ENE425 Sustainable Energy (and Development)

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Contents

Chapter 0

Introduction

During the last century, human activity has reshaped the world from an economic and environmental perspective introducing challenges for sustainability. In this part of the course, we study those challenges, and we provide some technological and political solutions to mitigate climate change. This manual provides the material that we will use during the course "ENE425 Sustainable Energy". **This manual is a copy and paste of the documents that appear in the biography in each chapter**.

The manual is organized in **three blocks** that complement each other.

1. The **first block** covers chapters 1, 2 and 3 where we **frame** the discussion by introducing the concepts of green economy, sustainable energy and sustainable development. We also introduce the **metrics** that help us to measure sustainable energy and sustainable development.

2. The **second block** covers chapters 4, 5, 6, 7, 8, 9. In that block, we study how the technological changes can contribute to develop a **sustainable energy** system.

3. The **third block** covers chapters 11, 12 and 13. In that block, we study how the technological changes studied in the second block can help to achieve the Sustainable Development Goals defined by the United Nations Development Program. We will not cover the last chapters that appear in the manual. However, we leave those chapters in case that some student could be interested in exploring those Sustainable Development Goals in the future.

The objective of the manual is to provide an **holistic view** by integrating the analysis of **sustainable energy** and **sustainable development** by, as Sharachchandra Lele proposes, moving beyond a “narrowed framing of the problem: **one value** (sustaining future generations), **one problem** (climate change), **one goal** (reduce carbon emissions) and **one solution** (renewables).”

For the first time in the last thirty years, in 2020, the United Nations introduces the footprint index to work out the Human Development Index. By doing that, the United Nations is connecting the sustainable energy with sustainable development. **That is exactly the objective of the manual and the course**.

The course is organized around the concepts of sustainable energy and development. To understand those concepts it is necessary to introduce some technical information about the technologies or other dimensions of energy. That part of the course appears in the **pink boxes** in some of the sections. Those boxes provide technical information that helps to understand the main concepts of the course, but are not the main part of the course. I have organized the course in that way, since I do not want to develop an engineering course. The technical information is a mean to understand the main concepts of the course, but it is not the main objective of the course.

In addition to the pink boxes, every chapter has also **green boxes**. Those boxes provide extra information about important concepts developed in that section or chapter.

To achieve the course objective of providing an holistic view, this manual is complemented by a **software application** to work out our **transport carbon emissions**. The objective is to explore how the **technology**, the **public policies** and our **personal decisions** could contribute to mitigate carbon emissions. That part of the course has been designed by **Gabriel Fuentes**.

Chapter 1

Frame: Green economy, sustainable energy and sustainable development

This chapter frames the content of the course by discussing key concepts as **green economy**, **sustainable energy** and **sustainable development**. We only provide and overview of those concepts. We will explore in detail the concepts of sustainable energy and sustainable development and their relationship in chapters 2 and 3. This chapter is based in McCormick et al. (2015).

1.1 Green economy concept

From an economic point of view, a “green economy” implies using taxes, subsidies and fees in a strategic and systematic way.

The term ”green economy” is based on multiple conceptual grounds. In fact green economy as a concept has evolved from, and been influenced by, many different schools of economic thought. This section provides a brief overview of how the concept has evolved.

The green economy concept is not new, but it became popular outside of academic circles right after the 2008-2009 global financial crisis.

The economic downturn that followed encouraged numerous pledges to reform current economic systems towards a path much less damaging to society, the environment and the financial system itself. As a result, numerous countries implemented green economy stimulus packages to reinvigorate production and consumption, particularly in the short term. At the time, the available definition of green economy was provided by UNEP. In its simplest expression, UNEP has argued that **“a green economy is low-carbon, resource efficient and socially inclusive”**.

The question remains - what does a green economy really entail? As mentioned earlier, conceptual choices about a green economy can cover a **wide spectrum**,

- from larger aspects of sustainability
- to narrow concerns about environmental pollution.

However, there also seems to be consensus about what a **green economy** should incorporate; and this points to

- job creation,
- poverty alleviation,

- reduction of greenhouse gas emissions,
- investments in natural capital and ecosystem services,
- improvements in social equity and human well-being,
- and also increases in resource efficiency.

For more information about the green economy watch the video: Green Economy - a film by Yann Arthus-Bertrand.

The term "green economy" is based on multiple conceptual grounds.

1. **Agricultural economics.** This was done during the so-called ”Green Revolution” in agriculture that occurred between 1940 and 1970.

   At that time, agricultural economists were studying and analysing the issues that the ”Green Revolution” brought to this economic sector, and they used the term green economy to refer to the positive impacts that **research and technology** development had on agricultural productivity.

2. **Welfare economics.** This school of economics is concerned with the effects of economic activities on welfare or well-being.

   From a general point of view, welfare or well-being is often understood as the state of being healthy, happy, or prosperous; either as individuals or as a group.

   Welfare economics also provides the basis for the **”market failure”** concept, which can be simply understood as the idea that if incorrect price signals are sent, market economies fail to achieve efficiency.

   Another aspect that is also captured by both welfare economics and the term green economy is **economic inequality**, that is, the uneven distribution of income and wealth.

3. **Natural resource economics.** This school of economics deals basically with the supply, demand, and distribution of renewable and depletable resources.

   A key objective for natural resources economics is to find ways **to manage resources efficiently and sustainably** so that they are available to future generations. In principle, a green economy should guarantee the capacity of natural capital that provides resources and environmental services in the long run.

4. **Environmental economics.** For environmental economists pollution is understood as a **negative externality**, take air pollution for example. If an economic activity is reducing air quality, the health or welfare of a third party may suffer as a consequence.

   Environmental economists attribute this to the absence of prices for environmental assets like clean air, biodiversity and clean water.

   Relying on the idea of sustainable development and also on the theory, the methods and the policy options provided by environmental and natural resource economics, Pearce, Markandya and Barbier framed the term green economy in the late 1990s around **technology innovation, resource efficiency natural capital, ecological risks and human development**.

5. **Energy economics** focuses on how the economic system can pursue growth by bringing together economic, environmental, social, and technological aspects through the expansion of clean energy production, distribution and consumption. Lately, there has been growing attention to the term ”green energy economy.”

6. **Ecological economics**, where priority is given to **sustainability and the economy as a subsystem of the ecosystem**.

   For instance aspects of ecological scarcity and social equity included in the green economy term have also been put forward by ecological economics.

   There is a growing body of knowledge that shows the rapid loss of ecosystems services. This situation has encouraged investment in and conservation of natural capital, which is also a critical aspect for the modern interpretation of the term green economy.

   Conventional or neoclassical economics, according to ecological economists, does not reflec adequately the value of essential factors such as clean air and water, species diversity, or social and generational equity. To address this, ecological economists advocate a transdiscplinary approach.

   Find out more about ecological economics: Interview with Robert Costanza (link)

1.2 Sustainable Energy

Sustainable energy is energy produced and used in such a way that it "meets the needs of the present without compromising the ability of future generations to meet their own needs." (Kutscher, 2019). It is similar to the concepts of green energy and clean energy in its consideration of environmental impacts, however formal definitions of sustainable energy also include economic and social impacts.

We will study the concept of sustainable energy and we will study the relation between **sustainable energy** and **sustainable development** in chapter 3.

For more information about sustainable energy visit: Sustainable energy (wikipedia).

For more information about sustainable development visit: Sustainable Development (wikipedia).

1.3 Bibliography

Kutscher, C. F., 2019, "Principles of sustainable energy systems," *Boca Raton, FL: CRC Press,* Chapter 1.

McCormick, K., Richter, J. L., and Pantzar, M., 2015, "Greening the Economy Compendium," *Lund University.*

Chapter 2

Metrics: Ecological footprint and biocapacity

In this chapter we study how to measure the ecological footprint per capita in every country. First, we define the concept. Second, we provide an overview of the concepts ecological footprint and biocapacity, Third, we present the methodology to work out the ecological footprint and the biocapacity. Finally, we present the historical trends of the ecological footprint and the biocapacity. The main text that we use in this chapter is Lin et al. (2019).

2.1 Definition

The Ecological Footprint is an account-based system of indicators whose underlying context is the recognition that Earth has a finite amount of biological production that supports all life on it. A widely recognized measure of sustainability, the Ecological Footprint provides an integrated, multiscale approach to tracking the use and overuse of natural resources, and the consequent impacts on ecosystems and biodiversity.

Ecological Footprint as an accounting system rather than a normative indicator.

How much of the biosphere's (or any region's) regenerative capacity does human activity ("activities" can refer to the entire consumption metabolism of humanity, the consumption of a given population (such as a city), a production process, or something as small and discreet as producing 1 kilogram of durum wheat spaghetti) demand? **How much of the planet's (or a region's) regenerative capacity does a defined activity require from nature?**

Footprint calculators:

There exist different online calculators to work out your personal footprint. To work out your footprint, and to know more about the methodology that they use to work out that footprint, you can visit:

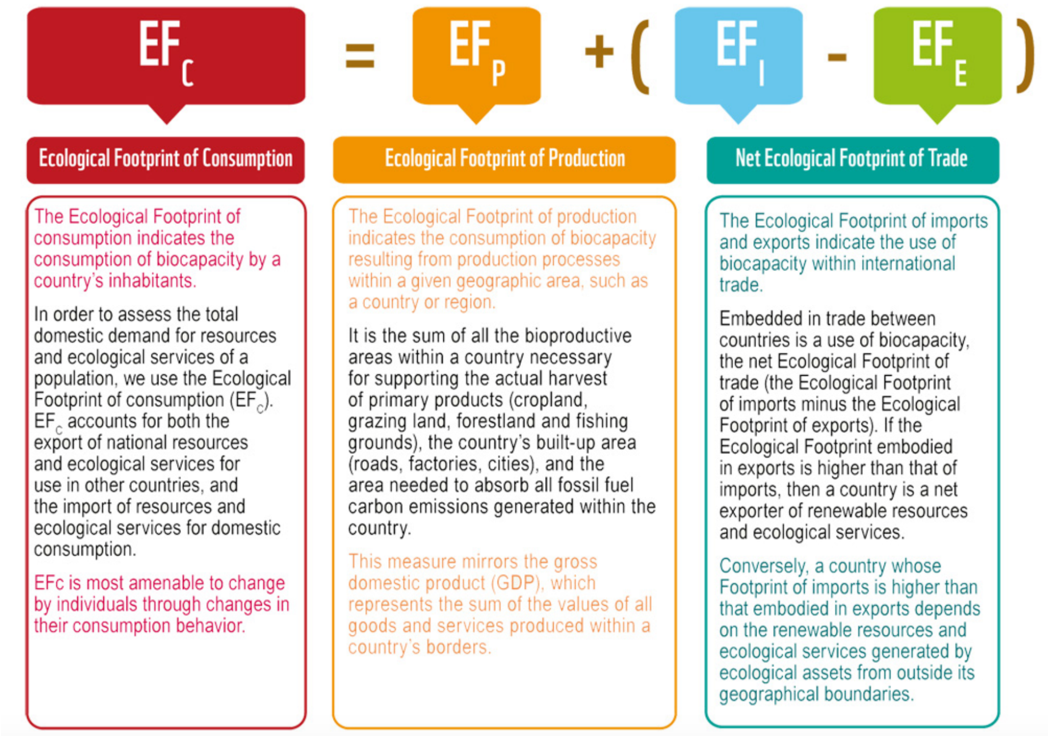
- Global Footprint Network calculator
- WWF calculator

Carbon calculators:

To work out your carbon emissions and to know more about projects to reduce carbon emissions visit: Carbon Footprint calculator.

To work out your **flight** carbon emissions visit: ICAO Carbon Emissions Calculator.

Figure 2.1: Footprint methodology



Source: footprintnetwork.org

2.1.1 Ecological footprint

The **Ecological Footprint** is derived by tracking how much biologically productive area it takes to provide for all the competing demands of people. These demands include space for food growing, fiber production, timber regeneration, absorption of carbon dioxide emissions from fossil fuel burning, and accommodating built infrastructure. A country's consumption is calculated by adding imports to and subtracting exports from its national production.

All commodities carry with them an embedded amount of bioproductive land and sea area necessary to produce them and sequester the associated waste. International trade flows can thus be seen as flows of embedded Ecological Footprint.

The Ecological Footprint uses yields of primary products (from cropland, forest, grazing land and fisheries) to calculate the area necessary to support a given activity.

2.1.2 Biocapacity

Biocapacity is measured by calculating the amount of biologically productive land and sea area available to provide the resources a population consumes and to absorb its wastes, given current technology and management practices. To make biocapacity comparable across space and time, **areas are adjusted proportionally to their biological productivity**. These adjusted areas are expressed in “global hectares”. Countries differ in the productivity of their ecosystems, and this is reflected in the Accounts.

Results from this analysis shed light on a country's ecological impact. A country has an ecological reserve if its Footprint is smaller than its biocapacity; otherwise it is operating with an ecological deficit. The former are often referred to as ecological creditors, and the latter ecological debtors.

Today, most countries, and the world as a whole, are running ecological deficits. In fact, today over 85% of the world population lives in countries with an ecological deficit. The world's ecological deficit is referred to as global ecological overshoot.

Earth Overshoot Day.

Earth Overshoot Day marks the date when humanity has exhausted nature's budget for the year. For the rest of the year, we are maintaining our ecological deficit by drawing down local resource stocks and accumulating carbon dioxide in the atmosphere. We are operating in overshoot.

For more information about the Earth Overshoot Day visit: Earth Overshoot Day (Global Footprint Network link).

2.2 National footprint and biocapacity accounts

National Footprint and Biocapacity Accounts (NFAs) provide the core data required for all Ecological Footprint analysis worldwide.

The Accounts measure the ecological resource use and resource capacity of nations over time. Based on approximately **15,000 data points per country per year**, the Accounts calculate the Footprints of more than 200 countries, territories, and regions from 1961 to the present.

The calculations in the National Footprint and Biocapacity Accounts are based on **United Nations or UN affiliated data sets**, including those published by the Food and Agriculture Organization, **United Nations Commodity Trade Statistics Database**, and the **UN Statistics Division**, as well as the **International Energy Agency**. Supplementary data sources include studies in peer-reviewed science journals and thematic collections. Of the countries, territories, and regions analyzed in the Accounts, 150 had populations over one million and typically have more complete and reliable data sets. For most of those, Global Footprint Network is able to provide time series of both **Ecological Footprint** and **biocapacity**.

For more information about the data used to work out the national footprint and biocapacity visit: The Global Footprint Network data (link).

2.3 Methodology

2.3.1 Overview

Figures 2.3 and 2.3 show an overview of the components and calculations that comprise the National Footprint and Biocapacity Accounts.

2.3.2 Basic equations

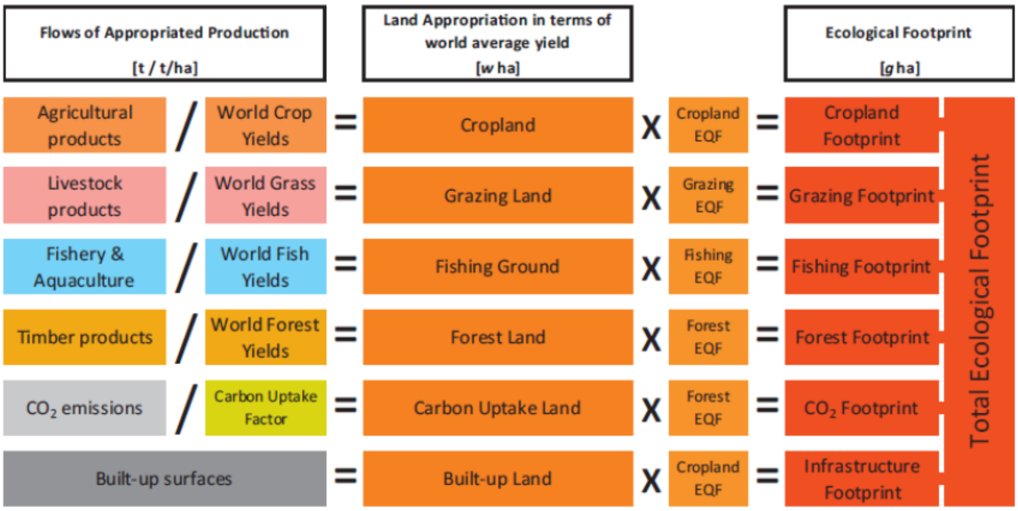
The **Ecological Footprint of consumption** is calculated as:

$$EF_{consumption} = EF_P + EF_I - EF_E \tag{2.1}$$

where:

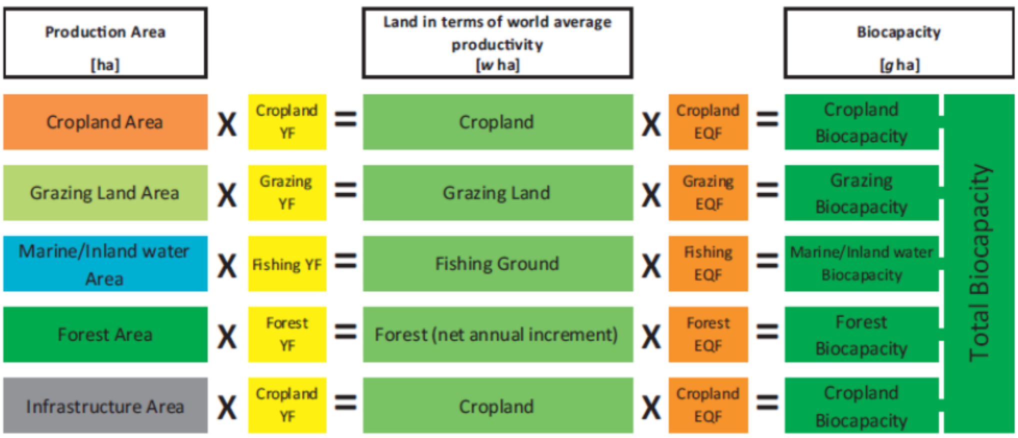
- EF_P is the is the Ecological Footprint of production,

Figure 2.2: Footprint methodology



Source: Boruckea et al.

Figure 2.3: Biocapacity methodology



Source: Boruckea et al.

- EF_I is the Ecological Footprint of imports, and
- EF_E is the Ecological Footprint of exports.

The Footprint of consumption of individual products or wastes are summed to obtain an aggregate Footprint of consumption for a given land use category. Adding together the Footprints of all of the major land use categories gives the Footprint of a country, or of the world.

Human-harvest or waste-production flow, imports, and exports are quantified in mass per time and translated into global hectares through the following equation:

$$EF_{production} = \frac{P}{Y_N} \cdot YF \cdot EQF \cdot IYF \tag{2.2}$$

where:

- $EF_{production}$ = Ecological Footprint associated with a product or waste, (gha)
- P = Amount of product extracted or waste generated, (t, yr^{-1})
- YN = National-average yield for product extraction or waste absorption, (t, nha^{-1}, yr^{-1})
- YF = Yield factor of a given land use type within a country, $(wha, nha - 1)$
- EQF = Equivalence factor for given land use type, (gha, wha^{-1})
- IYF= Intertemporal Yield factor of a given land use type, no units.

Notation:

- t: Metric tones
- nha: National-average hectares
- wha: World-average hectares
- gha: Global hectares

For each land-use type, the **EQF** is the ratio of a given land type's average global productivity divided by the average global productivity of the entire planet's productive surfaces. EQF makes it possible to compare the land used for a given product category with the average global bioproductive surface area, which may be of higher or lower average productivity.

For each country, the Ecological Footprint of production (EF_P) of a single footprint category is calculated by **summing all products of that footprint category** (such as rice, wheat, corn for cropland). The total EF_P of a country is the sum of the Ecological Footprint of all product categories combined.

Note that in Equation 2.2, because the yield factor is defined as national divided by world yield, the national-average yields cancel out. Thus, the basic Ecological Footprint formula can be expressed more succinctly in the following form:

$$EF_{production} = \frac{P}{Y_W} \cdot EQF \cdot IYF \tag{2.3}$$

where:

- Y_W = World-average yield for product extraction or waste absorption, $(t, wha - 1, yr - 1)$

Similarly, **biocapacity** can be measured in global hectares at any scale, from a single farm to the entire planet. The following formula details how biocapacity is calculated at the national level for each biocapacity land-use category:

$$BC = A_n \cdot YF \cdot IYF \cdot EQF \tag{2.4}$$

where:

- BC= biocapacity of a given land use type, (gha)
- A = Area of a given land use type within a country, (nha)
- YF = Yield factor of a given land use type within a country,($wha, nha - 1$)
- IYF = Intertemporal Yield factor of a given land use type for that year, no units
- EQF = Equivalence factor for given land use type, ($gha, wha - 1$)

Detailed equations and their application for each of the **six Ecological Footprint subcomponents** (cropland, grazing land, fishing grounds, forest for forest products, built-up land, and carbon footprint) can be found in (Lin et al., 2019). In the next subsection, we introduce briefly those subcomponents.

Carbon

The carbon Footprint represents the area of forest land required to sequester anthropogenic carbon dioxide emissions. The National Footprint Account workbook 2019 (NFA 2019) (Lin et al., 2019) calculates the Footprint of carbon dioxide emissions using several parameters including domestic fossil fuel combustion and electricity use, embodied carbon in traded items and electricity, a country's share of global international transport emissions, and non-fossil-fuel sources.

The total amount of carbon dioxide allocated to each country is converted into global hectares based on the **Footprint intensity of carbon**. This conversion factor is derived from the following:

- the yield of the productive land that is required to absorb the carbon dioxide emissions
- the amount of carbon absorbed by oceans
- an equivalence factor for carbon as a land type
- an adjustment factor for temporal changes in yield from the forest

The International Energy Agency (IEA) tracks carbon dioxide emissions from fossil fuel combustion across 45 different economic sectors. The IEA also publishes the total world emissions in international transport in the form of International Aviation bunker fuel and International Marine bunker fuels which are aggregated to "international transport emissions." These emissions are allocated to countries according to their respective domestic fossil fuel combustion by the proportion of national to world imports. Emissions from cement are attributed to the producing country; those from gas flaring emissions are distributed based on a country's percentage of World fossil fuel consumption.

Cropland Footprint

The cropland Footprint reflects the amount of land necessary to grow all crops consumed by humans and livestock. This includes agricultural products, market animal feed, and cropped grasses used as livestock feed.

Cropland yields are calculated for each crop type by dividing the amount of crop produced by the amount of area harvested. This differs from other land use types in that yields for cropland reflect an actual harvest yield, whereas other yields are calculated based on regeneration rates. Harvest yields and regeneration rates for crops are equal by definition, as humans manage all growth on cropland for harvest.

The NFA 2019 workbook tracks the production of 177 categories of agricultural products. The list of products, including both names and codes, has been generated from a complete list of all agricultural goods included in the UN's FAOSTAT ProdSTAT database as of 2015 (FAO ProdSTAT Statistical Database).

Grazing Land Footprint

The grazing land Footprint assesses demand for grazing land to feed livestock and the embodied demand for grazing land in traded goods. This is the most logically complex section of NFA 2019. The calculations estimate the total feed requirements of all livestock produced and the percentage of livestock energy requirements derived from concentrate feeds, forage crops, and crop residues. The difference between total feed requirement and total cropped feed supply is taken to equal the demand for grazing land.

The grazing land section of NFA 2019 relies on the methodology and data proposed by Haberl et al. (2007) for calculating human appropriation of net primary production (NPP). The calculation starts with the number of livestock in a country and their feed requirements. These feed requirements are partially filled through market feed (crops grown specifically to be fed to animals), residues (crop scraps that can be fed to livestock but not to humans), and cropped grasses (grasses that are grown on cropland and cut specifically to be fed to livestock). Once the feed demand satisfied by the above sources has been accounted for, the remaining amount of feed required is assumed to be provided by grazing land. The amount of grazing land required is based on dividing the grass feed required by the average grass yield of rangeland.

Fishing Grounds Footprint

The Fishing Grounds Footprint represents the demands of fisheries on aquatic ecosystems as the equivalent surface area required to sustainably support a country's catch.

The Fishing Grounds Footprint is calculated by dividing the amount of primary production consumed by an aquatic species over its lifetime by an estimate of the harvestable primary production per hectare of marine area. This harvestable primary production is based on a global estimate of the sustainable catch of several aquatic species (Pauly and Christensen, 1995). These sustainable catch figures are converted into primary production equivalents, and divided by the total area of continental shelf. This same calculation is currently used for inland fish as well.

NFA 2019 tracks the production of 1,941 marine and freshwater species, including fish, invertebrates, mammals, and aquatic plants. The Fishing Grounds Footprint includes all wild caught fish and production through aquaculture. The complete list of species corresponds to all species tracked in FishSTAT (FAO FishSTAT Fisheries Statistical Database).

Notes:

Calculations of the yield for fish are extremely sensitive to the estimated trophic level of the species. These estimates are drawn from average values from Froese and Pauly (2016), many of which have large standard errors. The uncertainty in the fisheries yields for individual species is thus large compared to other products in NFA 2019. The yields for fish catches are calculated by estimating the amount of primary production required, given the trophic level. This calculation considers only the raw primary production available to feed marine consumers, and not the dynamics of individual marine species stocks. To the extent that particular fisheries stocks are degrading or eroding over time at the species level, this analysis may overestimate the available biocapacity of fisheries each year.

A discard rate is used to scale the yield of each species downward to reflect the discarded primary production related to their harvest. This discard rate is currently assumed to be constant across all species. This will tend to underestimate the yields for species that do not have high discard rates associated with their fisheries, and overestimate the yield for species that have higher discard rates in their fisheries (e.g., prawns). Future NFA research is looking into ways to incorporate species and geographic variability, based on new data available through SeaAroundUs.

The Footprint of production of wild fish species uses data that track the total catch landed within a country, rather than of the fish caught within the waters of that country. This differs from the definition of Footprint of production for the other land use types, where the Footprint of production refers to all products extracted from land physically located within the country. Currently, the Footprint of production calculated for fishing grounds thus cannot be compared to the biocapacity of fishing grounds for a specific country to determine whether that country's own waters are, according to world average PPR, over-fished. However, Global Footprint Network researchers are exploring ways to refine this calculation.

For more information about fisheries visit: Sea Around Us webpage (link).

Forest Products Footprint

The forest products Footprint assesses human demand for the products of the world's forests. The forest products Footprint of production is comprised of two broad types of primary product: wood used for fuel; and timber and pulp used as a raw material to produce derived wood products.

The forest products Footprint represents the area of world average forest land needed to supply wood for fuel, construction, and paper. To calculate the Footprint of forest products, timber harvests are compared against the net annual growth rates of the world's forests.

The NFA 2019 workbook tracks the production of primary forest products and products derived from them. The complete list of products has been generated from a list of all forest products included in the UN's FAOSTAT ForeSTAT database as of 2015 (FAO ForeSTAT Statistical Database). The product names and codes correspond to those used in this database.

Built-up land

The built-up land Footprint represents bioproductive land that has been physically occupied by human activities.

The NFA 2019 workbook tracks infrastructure areas required for housing, transportation, and industrial production. The calculations assume that infrastructure area covers former cropland, and apply the yield and equivalence factors for cropland to the calculation of the Footprint.

Notes.

Based on the fact that human settlements historically developed and congregated on the most agriculturally fertile land, infrastructure areas are assumed to occupy former cropland and yield and equivalence factors for cropland are thus used in the Footprint calculation. This assumption will overestimate both the Footprint and biocapacity of infrastructure areas located on areas of formerly low productivity. However, since the Footprint and biocapacity of built-up land are equal, any inaccuracies in this assumption will equally affect both. Arid countries in particular may be subject to a systematic overestimate of their infrastructure Footprint and biocapacity.

The NFA 2019 workbook does not track imports and exports of built-up land, although built-up land is embodied in goods that are traded internationally (e.g., the physical area of a factory producing a given product for export) and thus should be counted as an export of Footprint embodied in that product. This omission likely causes an overestimate of the built-up Footprint of exporting countries, and an underestimate of the built-up Footprint of importing countries.

Since low-resolution satellite images are not able to capture dispersed infrastructure such as roads and houses, estimates of infrastructure areas have high levels of uncertainty. The NFA 2019 workbook likely underestimates the actual extent of impermeable surfaces overlaying productive land.

Biocapacity

Biocapacity refers to the amount of biologically productive land and water areas available within the boundaries of a given country. Biocapacity is calculated for each of the five major land use types: cropland, grazing land, fishing grounds (marine and inland waters), forest, and built-up land. Built-up land biocapacity is included here because, though built-up land does not generate resources, buildings and infrastructure occupy the biocapacity of the land they cover. The carbon Footprint does not have corresponding biocapacity because NFA 2019 assumes all carbon uptake as a demand on forest land biocapacity. Therefore, including carbon dioxide biocapacity in addition to forest land biocapacity would lead to double counting.

Notes.

There is no biocapacity figure for carbon uptake. All other land use types have a corresponding biocapacity calculation. Biocapacity for cropland is equal to the cropland Footprint of production because the yields are defined by human use.

Yield Factors

Yield factors reflect the relative productivity of national and world average hectares of a given land use type. Each country, in each year, has a yield factor for each land use type. Yield factors are used in biocapacity calculations when biocapacity is reported in global hectares. For land use types for which there are data on the average growth for primary production, yield factors are calculated using Equation 2.5 (Yield Factors Simple Calculation). This equation applies to grazing land, fishing grounds, and forest.

$$YF_N^L = \frac{Y_N^L}{Y_W^L} \tag{2.5}$$

where:

- YF_N^L = Yield factor for a given country and land use type, $(wha, nha - 1)$
- Y_N^L = Yield for a given country and land use type, $(t, nha - 1)$
- Y_W^L = World-average yield for a given land use type, $(t, wha - 1)$

Cropland produces more than one primary product. For this land use type, equation 2.6 (Yield Factors Extended Calculation) is used.

$$
\begin{aligned}
YF_N^L &= \frac{\sum A_W}{\sum A_N}, \text{ where} \\
A_N &= \frac{P_N}{Y_N}, \text{ and} \\
A_W &= \frac{P_W}{Y_W}
\end{aligned} \tag{2.6}
$$

where:

- YF_N^L =Yield factor for a given country and land use type, $(wha, nha - 1)$
- A_N = Area harvested for a given quantity of product in a given country, $(nha - 1)$
- A_W = Area that would be required to produce a given quantity of product using world average land, $(wha - 1)$
- P_N = Amount of given product extracted or waste generated in a country, $(t, yr - 1)$
- Y_N = National yield for product extraction, $(t, nha - 1, yr - 1)$
- Y_W = World-average yield for product extraction, $(t, wha - 1, yr - 1)$

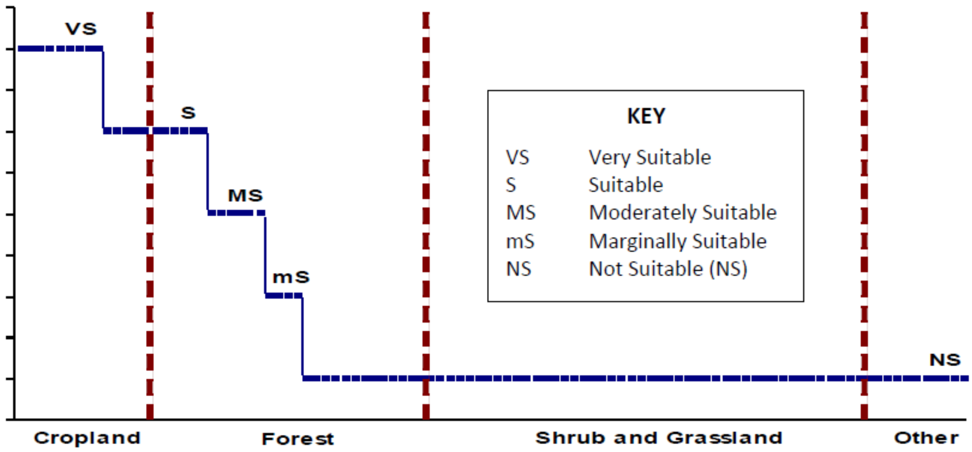
Equivalence Factors

Equivalence factors reflect the relative productivity of world average hectares of different land use types. Equivalence factors are the same for all countries, and change slightly from year to year. Equivalence factors are calculated in a satellite workbook to the NFA 2019 which is available upon request.

Equivalence factors are calculated using suitability indexes from the Global Agro-Ecological Zones (GAEZ) model, combined with information about actual areas of cropland, forest, and grazing area from FAOSTAT (Global Agro-Ecological Zones 2000; FAO ResourceSTAT Statistical Database). The GAEZ model divides all land globally into five categories, each of which is assigned a suitability score:

- Very Suitable (VS): 0.9
- Suitable (S): 0.7
- Moderately Suitable (MS): 0.5
- Marginally Suitable (mS): 0.3 ìtem Not Suitable (NS): 0.1

Figure 2.4: Equivalence factors



Source: Lin et al. (2019)

The equivalence factor calculation assumes that the most productive land is put to its most productive use. The calculations assume that the most suitable land available will be planted to cropland, the next most suitable land will be under forest, and the least suitable land will be grazing area. The equivalence factor is calculated as the ratio of the average suitability index for a given land use type divided by the average suitability index for all land use types.

The equivalence factor for built up area is set equal to the equivalence factor for cropland, reflecting the assumption that built up areas occupy former cropland.

The equivalence factor for marine area is calculated such that a single global hectare of pasture will produce an amount of calories of beef equal to the amount of calories of salmon that can be produced on a single global hectare of marine area. The equivalence factor for inland water is set equal to the equivalence factor for marine area.

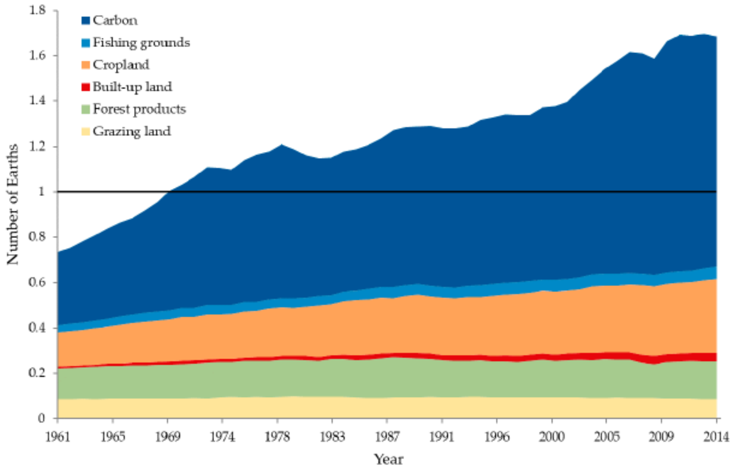
For more information about the Global Agro-Ecological Zones (GAEZ) model visit: GAEZ model webpage (link).

2.3.3 The accounting principles are:

- **Additivity:** Given that human life competes for biologically productive surfaces, these surface areas can be summed.
- **Equivalence:** Biologically productive areas vary in their ability to produce biological flows (i.e., biological resources and services used by people). Therefore, areas are scaled proportionally to their biological productivity.

Using these principles, Ecological Footprint accounting tracks the **supply (biocapacity)** and **demand (Ecological Footprint)** of renewable resources and ecosystem services. The expression of biological flows as **global hectares** allows for direct comparisons between them, making it possible to quantify human demand on the biosphere.

Figure 2.5: Footprint global trends



Source: Lin et al. (2018)

2.4 Analysis

Global trends:

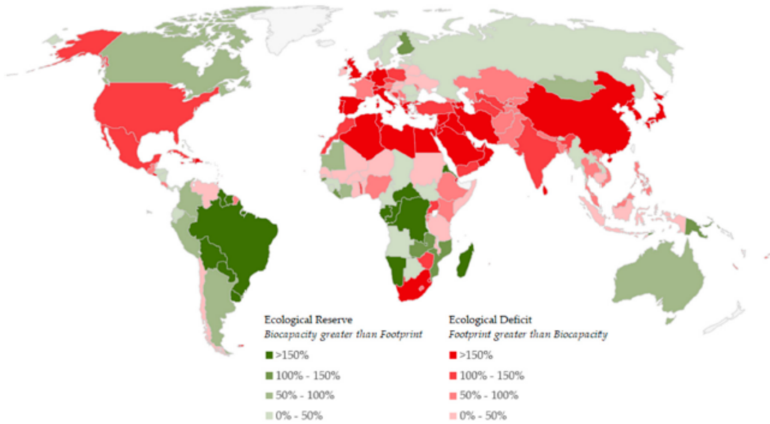
Humanity's total **Ecological Footprint** has been increasing steadily at an average of 2.1 percent per year (SD = 1.9) since 1961, nearly tripling from 7.0 billion gha in 1961 to 20.6 billion gha in 2014. The increase in Ecological Footprint has been **outpacing biocapacity** increases, which have increased at an average of 0.5 percent per year (SD = 0.7), from 9.6 billion gha in 1961 to 12.2 billion gha in 2014. Together, these results indicate that Earth's ecological overshoot began in the 1970s; further, ecological overshoot continues to grow at an average rate of 2.0 percent (SD = 2.3) per year. In 2014, humanity's Ecological Footprint was 69.6 percent greater than Earth's biocapacity.

During the same period, **per capita Ecological Footprint** increased by 24 percent (2.29 to 2.84 gha per person), while **per capita biocapacity** decreased by 46 percent (3.13 to 1.68 gha per person). The increase in total biocapacity and decrease in per capita biocapacity are indicative of a growing global population. More recently, the world Ecological Footprint per person decreased by 1.1 percent between 2010 and 2014, while biocapacity per person decreased by 2.4 percent over the same time period. In other words, although our individual share of the world's biocapacity is decreasing, we are also reducing our individual demand on nature.

The **carbon footprint** is the fastest growing Footprint component; in 2014, it comprised 60 percent of the world's total Ecological Footprint. This is a significant increase from the carbon Footprint in 1961, which contributed to 44 percent of the world's Ecological Footprint, or 150 years ago, when it was less than one percent of what it is today (figure 2.5). **Cropland footprint** was the next largest contributor to the world's Ecological Footprint in 2014, at 19.4 percent, followed by **forest-product** (9.8 percent), **grazing-land** (5.1 percent), **fishing-ground** (3.3 percent), and **built-up-land** (2.3 percent) Footprint types (figure 2.5).

Across **individual countries**, results show that most countries run a biocapacity deficit, where they have larger Ecological Footprints than biocapacity (figure 2.6). Countries that continue to have biocapacity reserves (where the biocapacity within a country's borders is greater than the Ecological Footprint of that country) tend to be located in forested regions, such as the

Figure 2.6: Ecological deficit and reserves



Source: Lin et al. (2018)

tropics and boreal latitudes.

<u>Sustainable development trends.</u>

National progress towards sustainable development can be assessed by comparing the NFA results to the United Nations' **Human Development Index (HDI)**, which aggregates education, longevity, and income into a single metric (figure 2.7).

The United Nations Development Program (UNDP) defines an **HDI score of 0.7 as the threshold for high development**. The **biocapacity available on the planet is calculated as 1.7 gha per person**. Combining these two thresholds gives clear minimum conditions for globally sustainable human development. Countries in the light-blue section of the lower right-hand box (figure 2.7) exhibit high levels of development with globally replicable resource demand. As of 2014, only two countries fit these criteria: Sri Lanka and the Dominican Republic. On average, the world is moving closer to the Global Sustainable Development Quadrant: HDI has increased consistently since the metric was developed in 1990, from 0.55 in 1990 to 0.69 in 2014 (weighted by the population of each country). In addition, the world's Ecological Footprint per person decreased from slightly from 2013 to 2014. However, the current world Ecological Footprint of 2.8 gha per person remains far above the 1.7 gha of biocapacity available to each person.

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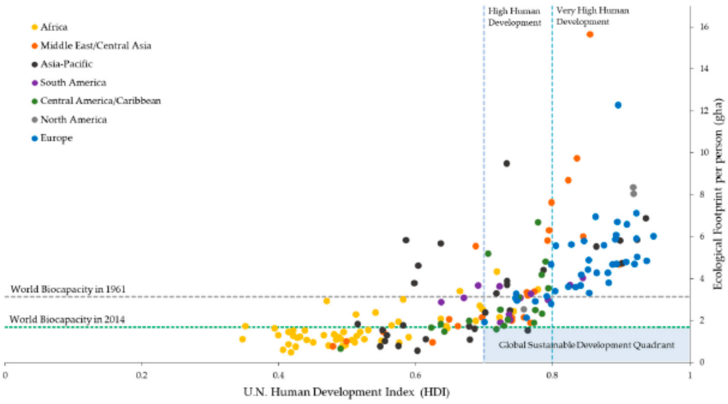
Figure 2.7: Sustainable development



Source: Lin et al. (2018)

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Chapter 3

Metrics: Human development for the Anthropocene

"Most 'classic' writings on sustainability present people as the problem, not as a collective source of strength. [... They] frame the discourse in terms of the Earth's finite resources and rising population. [...] We have moved away from framing it exclusively around limits to growth and conserving natural resources. Instead, we emphasize the connections between communities, ecosystems and social justice." Harini Nagendra

The **Anthropocene**: the age of humans. For the first time in our history the most serious and immediate, even existential, risks are human made and unfolding at planetary scale. This section argues that this new reality calls for reimagining the human development journey and leveraging the human development approach to support transformational social changes to ease pressures on the planet. We study the evolution of the Human Development Index during the last thirty years, and how to frame it in the context of the Anthropocene.

The Anthropocene is a proposed geological epoch dating from the commencement of significant human impact on Earth's geology and ecosystems, including, but not limited to, anthropogenic climate change.

As of July 2020, neither the International Commission on Stratigraphy (ICS) nor the International Union of Geological Sciences (IUGS) has officially approved the term as a recognised subdivision of geologic time, although the Anthropocene Working Group (AWG) of the Subcommission on Quaternary Stratigraphy (SQS) of the ICS voted in April 2016 to proceed towards a formal golden spike (GSSP) proposal to define the Anthropocene epoch in the geologic time scale and presented the recommendation to the International Geological Congress in August 2016. In May 2019, the AWG voted in favour of submitting a formal proposal to the ICS by 2021, locating potential stratigraphic markers to the mid-twentieth century of the common era. This time period coincides with the start of the Great Acceleration, a post-WWII time period during which socioeconomic and Earth system trends increase at a dramatic rate, and the Atomic Age.

Various start dates for the Anthropocene have been proposed, ranging from the beginning of the Agricultural Revolution 12,000–15,000 years ago, to as recent as the 1960s. The ratification process is still ongoing, and thus a date remains to be decided definitively, but the peak in radionuclides fallout consequential to atomic bomb testing during the 1950s has been more favoured than others, locating a possible beginning of the Anthropocene to the detonation of the first atomic bomb in 1945, or the Partial Nuclear Test Ban Treaty in 1963.

For more information about the Anthropocene visit: The Anthropocene (wikipedia).

For the **documentary**, the **book**, the **art project** "The Anthropocene" visit: The Anthropocene project.

Two more documentaries that explains The Anthropocene:

- The Anthropocene: Has earth shifted out of its Holocene state?
- The Anthropocene: The age of mankind

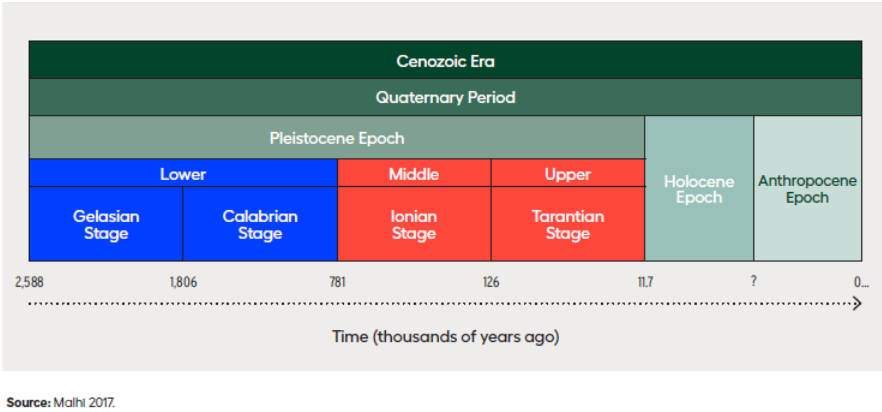
3.0.1 Enter the Anthropocene

"The world is a complex, nonlinear system, in which the living and non-living components are tightly coupled with important tipping points." Timothy M. Lenton (Lenton, 2019)

The story of the planet over time is told in the Geological Time Scale (figure 3.1). It records distinct periods in the Earth's history over timescales spanning thousands to millions of years, differentiated by characteristics ranging from climate to the emergence of life and stages in its evolution. Earth system scientists introduced the term Anthropocene at the turn of the 21st century. They confronted a range of observations of recent changes to the planet that contrasted with the palaeoenvironmental record of the Holocene (which is estimated to have started about 11,700 years ago) and indicated that the planet was operating in a no analogue state that is without precedent in the history of the planet.

The Anthropocene is not yet formally established as a new geological epoch, but several geologists and Earth system scientists propose dating its beginning to the mid-20th century with the growth in new anthropogenic materials as part of the evidence be hind their proposal. That

Figure 3.1: Geological Time Scale



Source: UNDP (2020)

would correspond to the Great Acceleration of human pressures on the planet that have the potential to leave a geological imprint (figure 3.2.

Drawing on interdisciplinary evidence and analysis, Earth systems science, geology and ecology characterize the Anthropocene from distinct perspectives (figure 3.3). Each brings something different, showing that considering diverse perspectives and approaches reveals the complexity and reach of the concept.

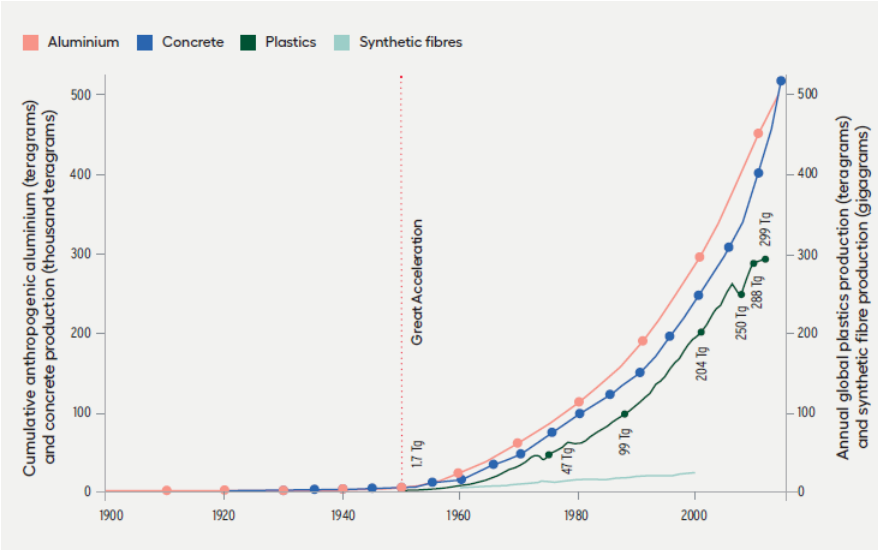
3.0.2 Understanding geological and ecological change

To specify the Anthropocene as a new geological epoch, geologists must identify a contemporary human-induced change that is significant and detectable over the timescales of Earth's history. Mining, landfills, construction and urbanization have resulted in the greatest expansion of new minerals that do not exist in the natural world as rocks (in the geological sense of having the potential for long-term persistence). Pure elemental aluminium is one of these materials, and as much as 98 percent of the aluminium on Earth has been produced since 1950. Another is plastics, whose current annual production equals the global human biomass. The disruptions of the global biogeochemical cycles of carbon and nitrogen also leave detectable signals visible in ice cores, reflecting rapid increases in the concentrations of carbon dioxide and methane. A unique and globally dispersed geological signature corresponds to the radioactive fallout from **atmospheric nuclear weapons** tested in the mid-20th century.

Geologists also consider **changes in flora and fauna**, both extinctions and the mixing of species across previously isolated continents and islands. Changes in periods in the geological timescale are often linked to sudden changes in the fossil record. While difficult to use as a marker for the Anthropocene with the precision of radionuclides, the magnitude and scale of the changes by humans to life on Earth may be the most enduring and obvious over the long term.

While Earth system science emphasizes the role of the biosphere on planetary functions and geologists look for markers, **ecologists and sustainability scientists** provide additional insights on human pressures by considering other fundamental changes to the diversity of life on the planet. **The Anthropocene biosphere corresponds to a third and fundamentally new stage in the evolution of life on Earth**. The first was dominated by simple single-cell microbial organisms —from approximately 3.5 billion to 650 million years ago. In the second stage complex multicellular life emerged, becoming widespread and diverse after the Cambrian

Figure 3.2: Beginning of the Anthropocene



Source: Waters and others 2016.

Source: UNDP (2020)

Figure 3.3: Perspectives from the natural sciences on the Anthropocene

Field	Focus	Evidence	Approaches and metrics
Earth system science	Planetary functions	Moving outside the range of variability of the Holocene → Climate change → Biogeochemical cycles disrupted (especially nitrogen and phosphorus) → Ocean acidification → Land use change → Biodiversity loss	→ Earth system tipping points and tipping elements → Planetary boundaries
Geology	Earth history	Identifying a contemporary change that is significant and detectable over Earth history timescales → Abundance of new materials of pure anthropogenic origin (aluminium, concrete, plastics) → Presence of radionuclides linked to atmospheric nuclear weapons testing	
Ecology	Biosphere	Altering the diversity, distribution, abundance and interactions of life on Earth → Conversion of ecosystems into agricultural or urban anthromes → Increasing species extinction rates → Habitat losses, overharvesting → Invasive species, global harmonization of flora and fauna	→ Biophysical reserve accounting (such as ecological footprint) → Human appropriation of net primary productivity → Rates of species extinction → Ecosystem services, nature's contributions to people

Source: Human Development Report Office based on Malhi (2017) and other sources in the text.

Source: UNDP (2020)

explosion 540 million years ago. **Four characteristics make the Anthropocene biosphere unlike anything that has ever existed on the planet**:

- Homogenization of flora and fauna through deliberate or accidental transfer of species across the globe.
- One species (humans) consuming 25–40 percent of land net primary productivity (that is, the biomass and energy made available by plants to all life on Earth).
- Human-directed evolution of plants and animals, marginalizing natural biomass—something unprecedented in the last 2.4 billion years.
- Increasing impact of new technologies as the biosphere interacts with the technosphere.

3.0.3 Bringing the Anthro into the Anthropocene

Along with the physical evidence this added dimension of the Anthropocene is essential to framing a new human development narrative. It places people's interactions with nature in historical, social and economic contexts, informed by insights from the natural sciences. This is reflected in new fields such as the climate-economy literature and in the resurgence of interest in environmental history.

Historical analysis places the current moment of the Anthropocene in perspective but also shows how much of human history has been influenced by occurrences in the natural world. In the words of historian Kristina Sessa, "The idea that objects, animals, and other non-human entities (volcanoes, oak trees and solar radiation, for instance) shape the development of human affairs, that they possess historical agency in some form, has forced scholars to **rethink** some of their basic assumptions about **government**, **power**, and **culture**." (Sessa, 2019)

Thus, many argue that rather than looking at the Anthropocene as a precisely dated geological period, it would be better to consider it a process, or a continuous Holocene/Anthropocene, in order to understand the long (and ongoing) transition of the dialectical relationship between cultural, political and economic systems and the natural world. Others reject the notion altogether, criticizing a narrative that lumps humanity together without attending to either existing inequalities or historical asymmetries in power and overexploitation of resources. One common line of criticism is that the notion of the Anthropocene, especially the more science-based formulations such as planetary boundaries, do not strike at the heart of the problem, which is seen as capitalist modes of production as well as longstanding historical legacies of colonization. Although Edward Barbier documents that the environmental record of centrally planned and collectivized economies has been no better than that of capitalist ones.

Some of these differences in perspective reflect differences between the social sciences and the humanities, on the one hand, and the natural sciences, on the other. The humanities see society and the economy as complex systems, with nature at best a contextual backdrop or something that can be analytically separated from societies, even if they are physically interdependent. The natural sciences take the reverse perspective, with natural systems as interdependent and complex and human agency de scribed in aggregate terms as causing generalized impacts or disturbances. Others oppose conceptualizing the Anthropocene as a process because they view the concept's power as signifying a rupture with the past, thus indicating a contemporary state of the world that urgently needs fundamental changes at the risk of catastrophic consequences for nature.

Where does this leave us? With the **notion that the Anthropocene is something novel in two ways**.

1. First, “the Anthropocene is an encapsulation of the concept that modern human activity is large relative to planetary processes, and therefore that human social, economic, and political decisions have become entangled in a web of planetary feedbacks. This global planetary entanglement is something new in human history and Earth history.”
2. Second, the Anthropocene is a catalyst for systematic thinking about the interdependence of people and nature, including the Earth system. It is informed by a diversity of disciplines, going beyond linear and simplified narratives of progress, and invites framing the options that face us today as more than a choice between impending catastrophe or an easy decoupling of economic activity from planetary pressures.

One implication of this understanding of the relationship between people and nature is the recent reframing of the conceptual approach of ecosystems as providers of services to acknowledge nature’s contributions to people. This reframing also presents anthropogenic drivers of changes in nature as being embedded in institutions and governance systems. It recognizes the intrinsic value of preserving nature.

3.1 Socioeconomic emplications of the Anthropocene

3.1.1 Confronting a new reality: People versus trees?

Unlike other concepts that have highlighted the impact of human pressures on the environment, the Anthropocene describes a state change in the Earth system, viewed as an interdependent, co-evolving social-ecological system, as well as a new way of thinking about our recent and current epoch. Anthropocene thinking takes us away from reductionist linear cause-effect analysis of equity and sustainability, to underline the fully intertwined character of human and ecological systems, and the co-evolving fates of sustainability and equity.” Melissa Leach, Belinda Reyers and others

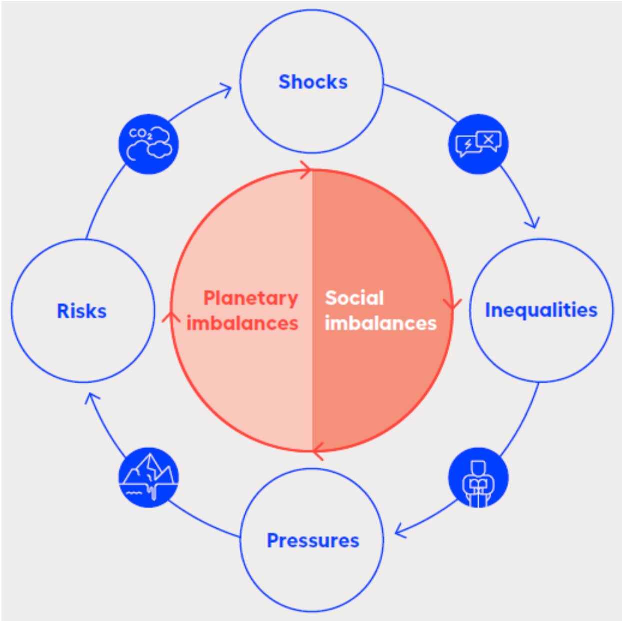
Our dependence on nature is not in question. Amartya Sen put it bluntly: “It is not so much that humanity is trying to sustain the natural world, but rather that humanity is trying to sustain itself. It is us that will have to ‘go’ unless we can put the world around us in reasonable order. The precariousness of nature is our peril, our fragility.” But there are **two new elements to consider**.

1. First, the notion of the Anthropocene has forced a **reframing of thinking** from standalone environmental and sustainability issues, such as climate change, to the recognition of a set of interdependent challenges resulting from underlying processes of planetary change driven by human pressures.

   As Sharachchandra Lele put it, we need to move beyond a “narrowed framing of the problem: **one value** (sustaining future generations), **one problem** (climate change), **one goal** (reduce carbon emissions) and **one solution** (renewables).” And that calls for a full understanding of the pressures we are putting on the planet and of our interdependence with nature.
2. Second, the notion of the Anthropocene emerges thanks to remarkable advances in **Earth system and sustainability sciences**. In addition to documenting and explaining the impacts of human activities, these new fields are stimulating interdisciplinary work, encompassing natural and social sciences and the humanities, providing insights into how to mitigate those impacts while improving people’s lives.

A key insight emerging from this vast and rapidly growing body of work is that **social and natural systems are best seen not only as interacting and interdependent but also**

Figure 3.4: Planetary and social imbalances reinforce each other



Source: UNDP (2020)

as embedded in each other. Moving beyond the notion of sustainable development as separable human development targets constrained by environmental or natural resource limits, to an inseparable socio-ecological systems perspective on sustainable development, offers a fresh perspective on sustainable development. It further offers a novel and expanded opportunity space from which to address the challenges of the Anthropocene.

Considering the complex and interdependent relationship between people and planet, between socio-economic and natural systems, points to the links between dangerous **planetary and social imbalances**, which interact and often reinforce each other. As long as planetary imbalances persist, they engender risks that can materialize in shocks to human development, just as the Covid-19 pandemic has done (figure 3.4).

Reframing the human development journey in the Anthropocene has the potential to break this cycle. **What does this mean for human development?**

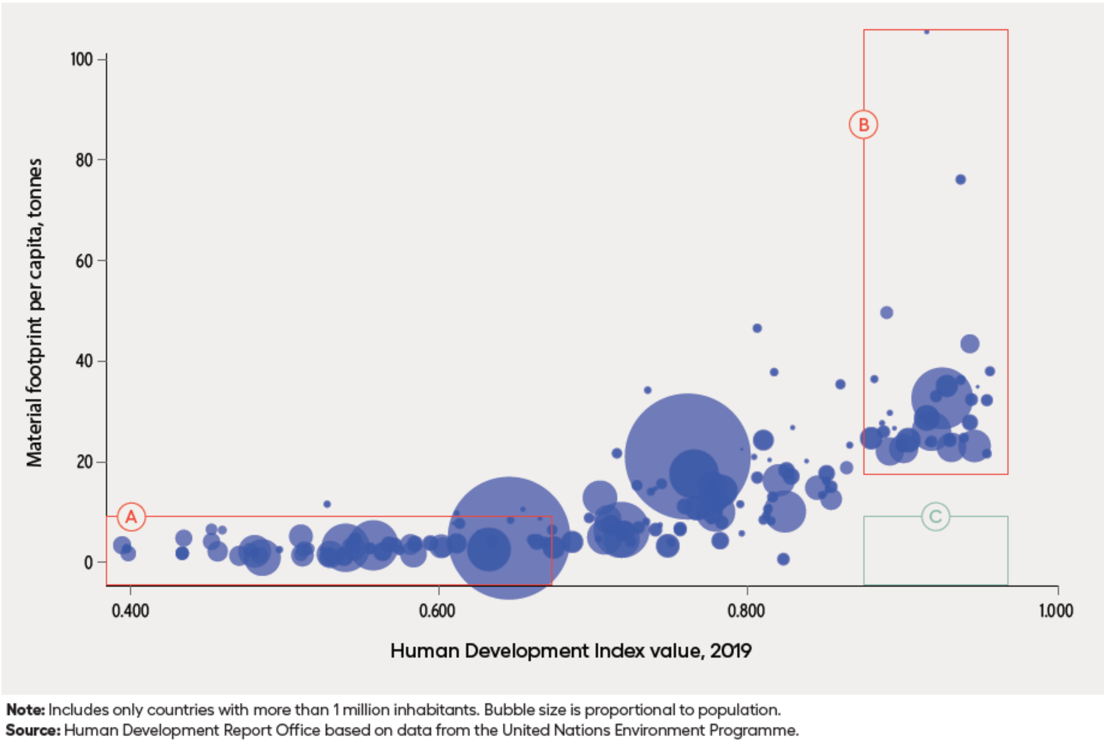
1. First, it presents a challenge as to how to imagine and pursue human development. Addressing social imbalances, the hemisphere on the right in figure 3.4, has always been at the core of the human development journey. But until now the other hemisphere, planetary imbalances, has not been systematically brought into the human development journey.

2. Second, the human development approach has not yet been fully leveraged to inform how to address the challenges in the hemisphere on the left in figure 3.4. It can offer fresh perspectives on making expanded capabilities and human agency central to easing pressures on the planet.

3.1.2 Reimagining the human development journey: Bringing the planet back in

Decoupling economic growth from emissions and material use is key to easing pressures on the planet while improving living standards. The debate on the extent to which this is sufficient and

Figure 3.5: Footprint and Human Development Index



Source: UNDP (2020)

feasible provides a natural starting point to explore whether decoupling helps rearticulate the human development journey in the Anthropocene.

Decoupling what?

The dominant view on decoupling is that green growth or green economy approaches hold promise by shifting towards more resource-efficient and less emission-intensive production and consumption, allowing for relative or absolute decoupling.

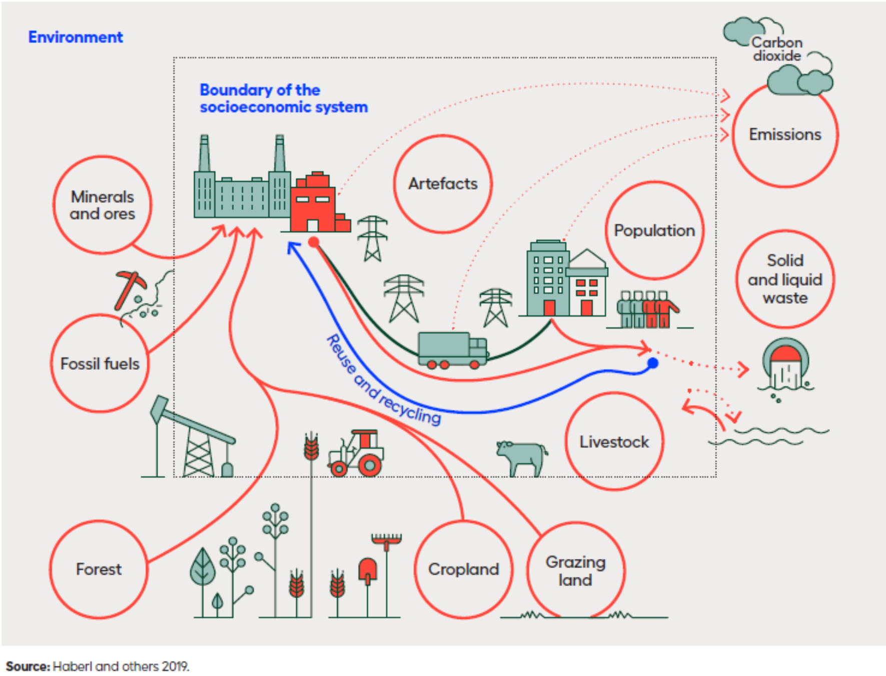
Roughly speaking, human development comprises capabilities that relate to wellbeing and agency.

1. Improvements in human development as measured by the HDI (which accounts only partially for agency) were fuelled by using resources that generated today's ecological crises (countries in **rectangle B** of figure 3.5.
2. So a reimagined human development journey cannot occur along the same path for low human development countries (in **rectangle A**), and high human development countries cannot remain where they are.
3. A reimagined human development journey thus calls on all countries to improve wellbeing equitably while easing pressures on the planet (moving to the empty **rectangle C**).

Mapping human societies' embeddedness in the biosphere: Energy and material flows.

Human societies are embedded in the biosphere and depend on it. But by extracting from it for economic activities that shape consumption and production patterns, they have

Figure 3.6: Human societies are embedded in the biosphere



Source: UNDP (2020)

also been depleting it. Much of this happens in the background and seems invisible to social and individual choices, similar to forgetting our dependence on the air we breathe. To make the interactions between social and ecological systems more visible, it is useful to look at material and energy flows in our societies and their impact on planetary processes (figure 3.6).

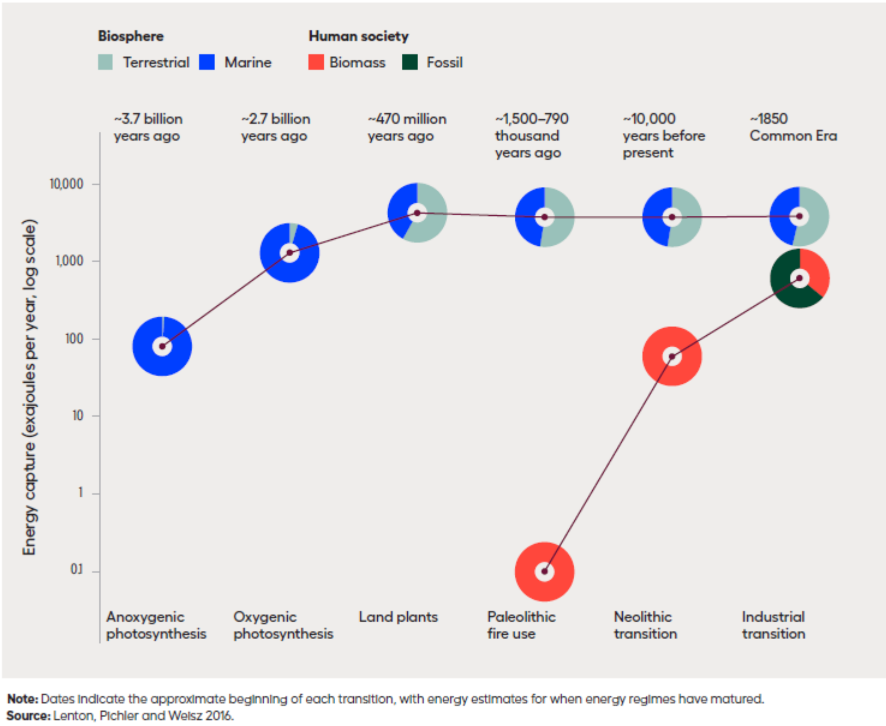
Transitions in human history have been driven by technological and institutional innovations, resulting in new forms of social and economic organization that have progressively expanded energy and material use. The intentional use of fire first allowed people to generate energy outside the human body but increased energy input above human physiological needs only by a factor of 2–4 (figure 3.7). The transition to agriculture represented a fundamentally new stage that raised human energy capture by three orders of magnitude (in around 1850, when it was the dominant mode of subsistence and the global population was around 1.3 billion). The higher flows of energy and population linked to farming boosted societies' material inputs and waste products and led to substantial local (and possibly global) ecological impacts due in part to the large-scale changes in forest cover often associated with fire regimes that spread and managed fire.

As some societies increased economic demands and evolved social structures to sustain those demands, the limiting conditions could be overcome by using fossil fuels for energy and through industrialization. This decoupled energy use from land and human labour. As a result, global human energy capture rose 10-fold between 1850 and 2000, as the population grew by a factor of 4.6 and GDP per person by a factor of 8.3. The total global energy flux through human societies is already one-third above the total that flows through all nonhuman and nonplant biomass.

3.1.3 Leveraging the human development approach for transformation: Beyond needs, beyond sustaining

The Brundtland approach to defining **sustainable development** as "development that meets the needs of the present without compromising the ability of future generations to meet their

Figure 3.7: Energy captured in the biosphere and human society



Source: UNDP (2020)

own needs" was a watershed moment (WCED, 1987). It brought together the ethical imperative of fulfilling the basic subsistence requirements of people today—putting poverty eradication squarely at the centre of the concept—with an obligation to our descendants rooted in **intergenerational justice**. It put people at the core, instead of defining what needed to be sustained for consumption or production. And rather than asking for the preservation of a pristine state of nature, it emphasized the ability of each generation to use resources, allowing for some fungibility across resources.

Where to go **beyond needs**? What can we expand, beyond focusing on sustaining? How to account for persistent inequalities that feeds social imbalances? The human development approach offers a path to address these questions.

Human development takes us beyond notions of sustainability based on needs fulfilment and away from notions based on instrumental objectives such as consumption or economic activity (measured by growth in GDP, for instance).

A focus on **needs** may lead to prioritizing social or economic floors, providing a minimum foundation to be shared by everyone, but it does not fully account for inequalities, and it downplays the potential of people as agents. For instance, the inspired and influential framework proposed by Kate Raworth sets a floor of essential human and social needs as a circle inside the planetary boundaries framework described in the next section. The resulting **"doughnut"** defines an operating space that is not only safe, from the Earth system sciences perspective, but also socially just.

There may not be a clear blueprint of what human development is and will be in the decades to come. Human development is permanently under construction, and the approach is open to new and emerging challenges and opportunities. This section has attempted to sketch a vision of the **human development journey in the Anthropocene** in order to navigate towards a better planet for people and the rest of life.

Brundtland Commission. Formerly known as the **World Commission on Environment and Development (WCED)**, the mission of the Brundtland Commission is to unite countries to pursue **sustainable development** together. The Chairperson of the Commission, Gro Harlem Brundtland, was appointed by United Nations Secretary-General Javier Pérez de Cuéllar in December 1983. At the time, the UN General Assembly realized that there was a heavy deterioration of the human environment and natural resources. To rally countries to work and pursue sustainable development together, the UN decided to establish the Brundtland Commission. Gro Harlem Brundtland was the former Prime Minister of Norway and was chosen due to her strong background in the sciences and public health. The Brundtland Commission officially dissolved in December 1987 after releasing Our Common Future, also known as the Brundtland Report, in October 1987.

The Report of the World Commission on Environment and Development: Our Common Future can be downloaded from the United Nations webpage (link).

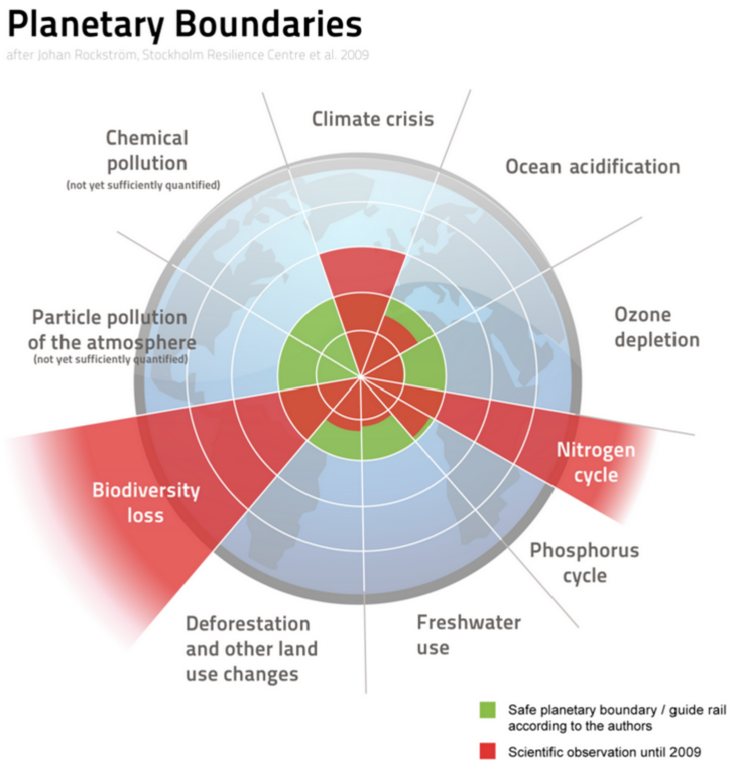
For more information about the Brudtland Commission visit the Brundtland Commission (wikipedia).

3.1.4 Learning from Earth system science: Something new under the sun

Over the past 2.6 million years the planet's temperature has oscillated sharply, leading to alternating warmer and colder periods. But the Holocene has been both warmer and more stable in temperature. The climate system has also been more stable, despite massive hydrological variability that has had radical implications at the regional scale. For instance, the Sahara has not always been the dry desert we see today, and the Amazon had to confront severe droughts earlier in the Holocene. In fact, an important characteristic of the climate system during the Holocene is the tight link between the whole web of life on the planet and in the atmosphere, regulating the carbon cycle. For instance, about a fifth of annual average precipitation falling on land is linked to plant-regulated water cycles, with many places now receiving half the precipitation from this type of cycle that they received before.

A prominent framework to summarize how changes in the Earth system and the biosphere underpin human prosperity in fundamental ways is the **planetary boundaries approach** 3.8. In 2009 Johan Rockström and colleagues identified what they denoted a **safe operating space for humanity**. This space is defined by several Earth system boundaries that, if transgressed, could undermine life-supporting conditions on our planet. This notion, refined over the years, remains one of the most influential framings for the challenges of the Anthropocene. Though the framework was designed explicitly for the **global level** only, there have been attempts to apply it at **lower scales**, even though that is neither encouraged nor supported by the original proponents.

Figure 3.8: Planetary boundaries



Source: Wikipedia

Planetary boundaries.

Planetary boundaries is a concept involving Earth system processes that contain environmental boundaries. It was proposed in 2009 by a group of Earth system and environmental scientists, led by Johan Rockström from the Stockholm Resilience Centre and Will Steffen from the Australian National University. The group wanted to define a "safe operating space for humanity" for the international community, including governments at all levels, international organizations, civil society, the scientific community and the private sector, as a precondition for sustainable development. The framework is based on scientific evidence that human actions since the Industrial Revolution have become the main driver of global environmental change.

According to the paradigm, "transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental-scale to planetary-scale systems." The Earth system process boundaries mark the safe zone for the planet to the extent that they are not crossed. As of 2009, two boundaries have already been crossed, while others are in imminent danger of being crossed.

For more information about planetary boundaries visit: Planetary boundaries (wikipedia).

Doughnut (economic model).

The Doughnut, or Doughnut economics, is a visual framework for sustainable development – shaped like a doughnut or lifebelt – combining the concept of planetary boundaries with the complementary concept of social boundaries. The name derives from the shape of the diagram, i.e. a disc with a hole in the middle. The centre hole of the model depicts the proportion of people that lack access to life's essentials (healthcare, education, equity and so on) while the crust represents the ecological ceilings (planetary boundaries) that life depends on and must not be overshot. The diagram was developed by Oxford economist **Kate Raworth** in the Oxfam paper A Safe and Just Space for Humanity and elaborated upon in her book Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist.

For more information about **Doughnut (economic model)** visit:

- https://www.kateraworth.com/
- Doughnut (economic model) (wikipedia).

For a video about **Doughnut (economic model)** visit: Kate Raworth (TED talk).

3.2 Towards a new generation of human development metrics for the Anthropocene

Human development is dynamic. So the way we measure it must be, too. Over the years, new dashboards and indices have been introduced. How do we measure human development in the Anthropocene?

In line with a central theme of this chapter, there is no one-size-fits-all tool or metric. Instead, this section introduces and explores a suite of possibilities, including an experimental **Planetary pressures adjusted Human Development Index**.

3.2.1 One index to rule them all?

Confronting the Anthropocene calls for a **new generation of human development metrics**. The Human Development Index (HDI) introduced in 1990 was intended to be a general index for global assessment and critique based on a minimal listing of capabilities focused on enjoying a basic quality of life. Clear and simple, and focused on **income**, **education** and **health**, it shaped public and political debate and reoriented objectives and actions. It has since been augmented by the **Inequality-adjusted HDI**, the **Gender Development Index**, the **Gender Inequality Index** and the **Multidimensional Poverty Index**.

The inclusion of **income** in the HDI was intended only as **a proxy for capabilities** other than **education** and **health**, as something instrumentally important for achievements in those other capabilities. But gross national income (GNI) does not account for **planetary pressures**. So this section considers possible **adjustments to the HDI's income component**, subtracting the **social costs of carbon** from GNI and discussing options to account for changes in total wealth that include **natural capital**.

The section also presents an adjustment to the HDI that uses indicators of **greenhouse gas emissions** and **material footprint**. The adjustment is made by multiplying the HDI by an **adjustment factor** that **accounts for planetary pressures**. This adjustment factor is calculated as the arithmetic mean of indices measuring carbon dioxide emissions per capita—which speaks to the challenge of shifting away from fossil fuels for energy—and the material footprint per capita—which relates to the challenge of closing material cycles. **This Planetary pressures–adjusted HDI provides a sense of the possibilities for achieving high HDI values with lower emissions and resource use**.

3.2.2 Broadening the vista on the Human Development Index: The income component and planetary pressures

This section builds on proposals to add environmental and sustainability dimensions to the HDI but explores **metrics** guided by the importance of going beyond sustaining. It focuses on the implications of accounting for planetary pressures by adjusting the income component of the HDI.

Accounting for the social cost of carbon

The HDI's indicator for the income dimension is GNI. "Gross" is the rogue word in this concept be cause it fails to account for the depreciation of capital assets and ignores **natural capital** and the **social costs** (borne by everyone) of environmental damage. **Other income-based indicators** take a broader view of net flows from capital and adjust for natural resource depletion and damage from emissions and pollution. Here we explore **a simpler and more direct adjustment to GNI by subtracting the social costs of carbon dioxide emissions**. Again, this is driven by the importance of encouraging a transformation in energy use to lower greenhouse gas emissions. This is not meant to accurately capture the full social costs of environmental damage or the overuse of resources not in GNI.

The social cost of carbon is the economic cost attributable to an additional tonne of carbon dioxide emissions or its equivalent. Estimates of this cost depend on several assumptions and parameter choices and span a wide range. The UNDP (2020) consider **two estimates**:

1. One proposed by the **International Monetary Fund** sets the cost of carbon in 2030 at $75 per tonne of carbon dioxide—in 2017 US dollars and covering all fossil fuels. It is based on a model showing that the impact of a global carbon tax at this level would be consistent with countries meeting their Paris Agreement pledges.

2. The other estimate is from a recent application of the **Dynamic Integrated Climate-Economy integrated assessment model**. It includes the latest climate science and reflects a broad range of expert recommendations on social discount rates—a key parameter in the model that weighs the value today of future benefits and costs. The median expert view on discount rates gives a carbon social cost of around $200 per tonne of carbon dioxide in 2020 (in 2010 international dollars).

Dynamic Integrated Climate-Economy model (DICE model).

The Dynamic Integrated Climate-Economy model, referred to as the DICE model or Dice model, is a neoclassical integrated assessment model developed by 2018 Nobel Laureate William Nordhaus that integrates in the economics, carbon cycle, climate science, and impacts allowing a weighing of the costs and benefits of taking steps to slow climate change.

For more information about **Dynamic Integrated Climate-Economy model (DICE model)** visit:

- Pedagogy in Action.
- (Wikipedia).

3.2.3 Adjusting the Human Development Index as a whole

The HDI is an example of what James Foster has called "intentional measurement." Its construction was driven by its intended purpose and desired characteristics. The purpose was to **shift objectives and action** towards a view of development that put people at the centre. Two of its main desired characteristics were clarity and simplicity.

So now is the chance to step back and reflect on the intent of adjusting the HDI. Put simply the intent is to have a measure that accounts for **how people are doing** and for the unprecedented **pressures people are imposing on the planet**.

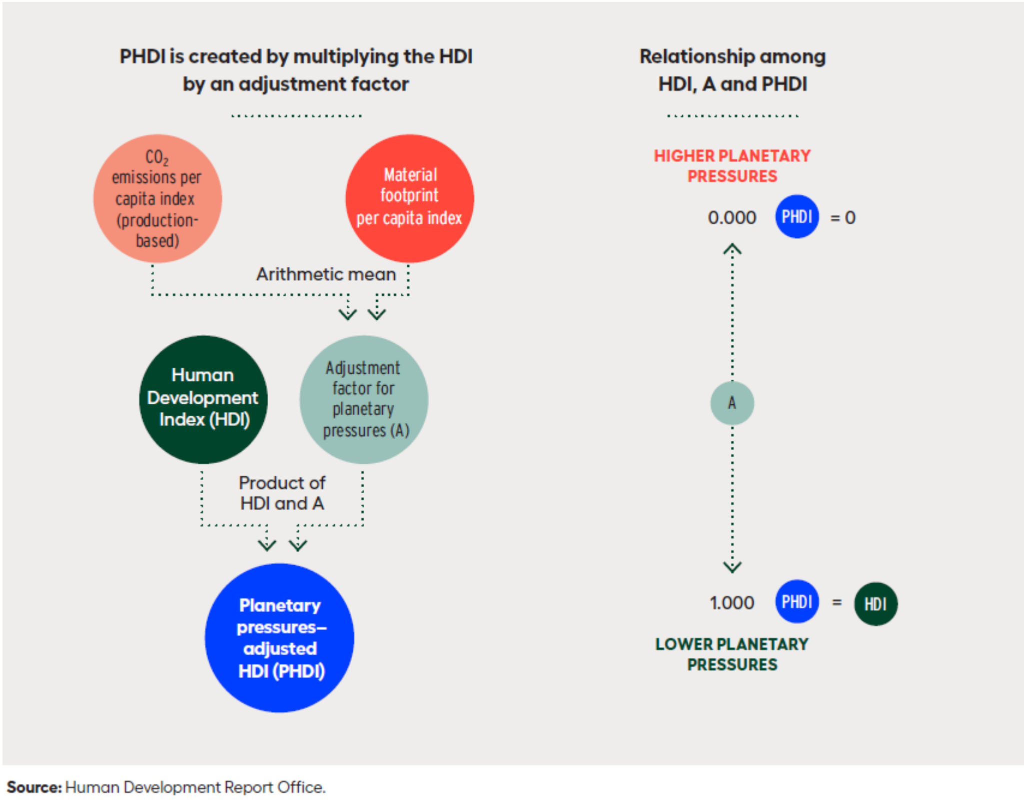
- To account for **capabilities**, the HDI is the obvious choice.
- And for the other component, the **biophysical and socioeconomic processes** that produce planetary pressures should inform the choice. We consider **two summary measures**:
  - **Carbon dioxide emissions**.
  - **Material footprint**, both on a per capita basis.

The adjustment to the HDI is a **signalling device** for positive change, encouraging the expansion of capabilities while reducing planetary pressures. The focus on greenhouse gases and material flows does not imply that all other environmental concerns are less important or urgent—as is the case for losses in biosphere integrity and several other urgent concerns, as reflected in the Sustainable Development Goals. But reductions in the flows of greenhouse gases and more efficient material use would eventually reflect the outcomes of the broader economic and societal transformation to ease planetary pressures.

The Planetary pressures–adjusted Human Development Index

The adjustment corresponds to multiplying the HDI by an adjustment factor, creating the Planetary pressures–adjusted HDI (PHDI) (figure 3.9). If a country puts no pressure on the planet, its PHDI and HDI would be equal, but the PHDI falls below the HDI as pressure rises. The **adjustment factor** is calculated as the arithmetic mean of indices measuring **carbon dioxide emissions per capita**, which speaks to the energy transition away from fossil fuels, and **material footprint per capita**, which relates to closing material cycles. A country's material footprint measures the amount of material extracted (biomass, fossil fuels, metal-ores (minerals) and nonmetal-ores) to meet domestic final demand for goods and services, regardless of where extraction occurs. It is a consumption-based measure that **accounts for international trade**.

Figure 3.9: Visual representation of the Planetary pressures–adjusted Human Development Index



Source: UNDP (2020)

It also indicates **pressures on the biosphere** exerted by socioeconomic activities, since it includes the use of biomass—thus indirectly reflecting impacts of actions such as land use change on the loss of biosphere integrity.

PHDI values are very close to HDI values for countries with an HDI value of 0.7 or lower (figure 3.10). Differences start to open up at higher HDI values, with wider divergence at very high HDI values.

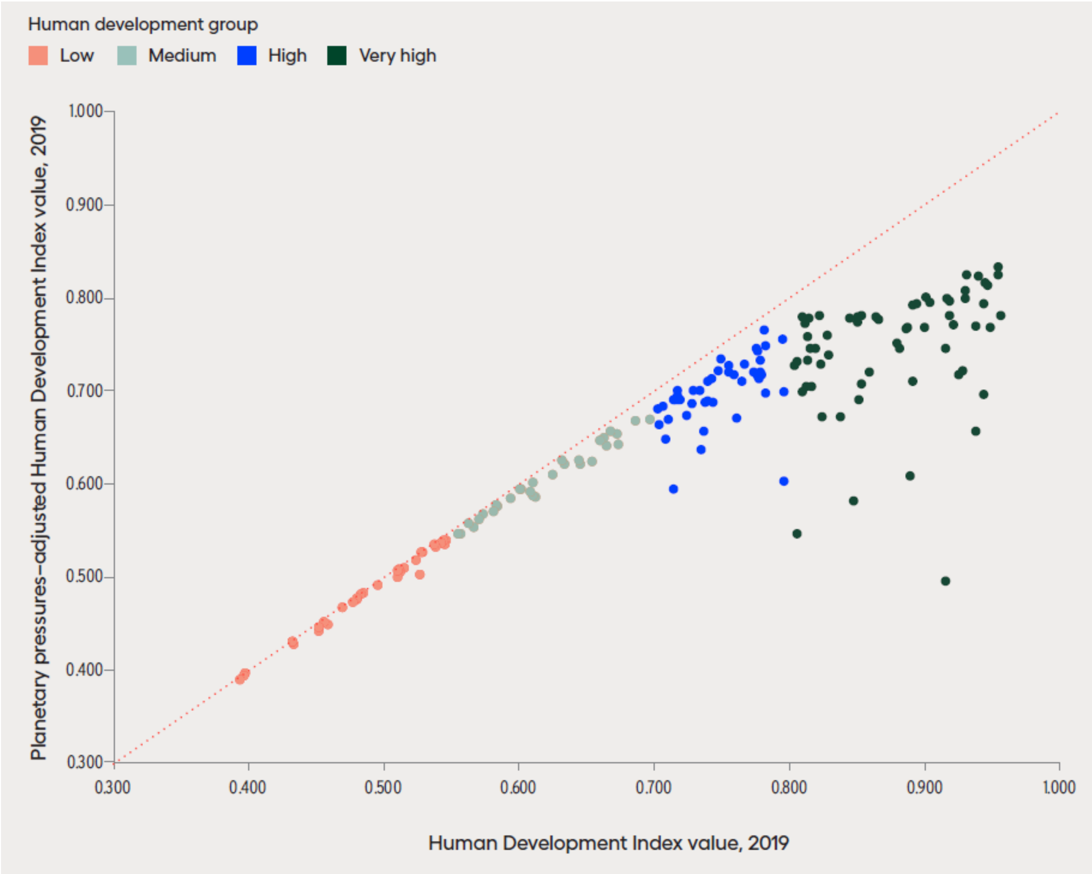
Human development progress based on the Planetary pressures–adjusted Human Development Index: A new lens

The global PHDI offers a summary view of the evolution in human development and the associated planetary pressures—the world has consistently increased planetary pressures per capita over the past three decades (left-hand side panel, figure 3.11). The PHDI is not only lower than the HDI; it is also growing more slowly (right-hand panel, figure 3.11). The gap between the conventional assessment of development (the HDI) and the new perspective to navigate the Anthropocene (the experimental PHDI) has been widening.

From a policy perspective the PHDI provides a guiding metric towards advancing human development while easing planetary pressures—a combination that today corresponds to an "empty corner" when human development is contrasted with indicators of planetary pressures (figure 3.5).

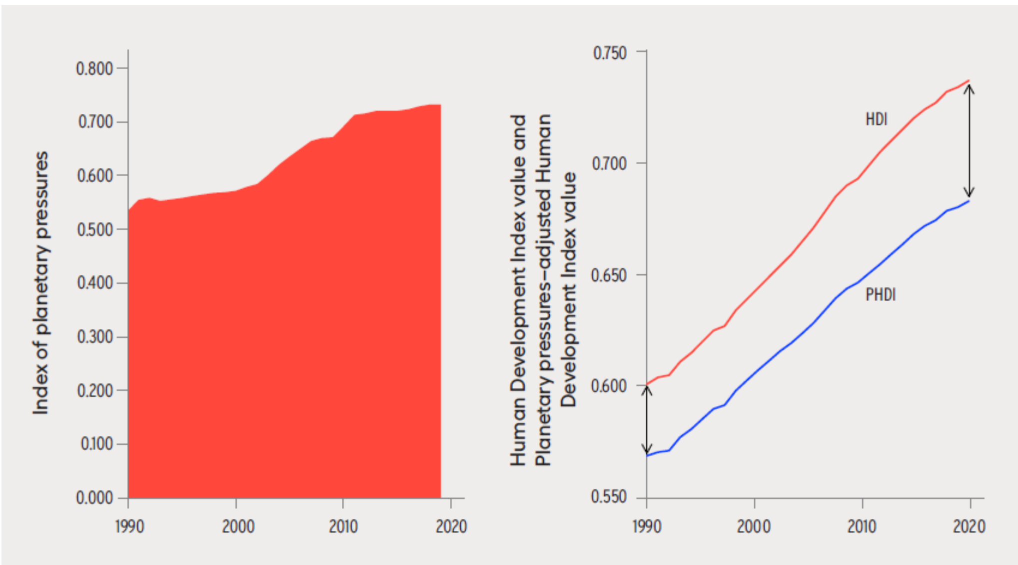
In figure 3.12 the horizontal axis shows the HDI, and the vertical axis shows the index of planetary pressures (which is one minus the adjustment factor for planetary pressures that is multiplied by the HDI to generate the PHDI). Also plotted are contour lines corresponding to

Figure 3.10: Human Development Index vs. Planetary pressures–adjusted Human Development Index



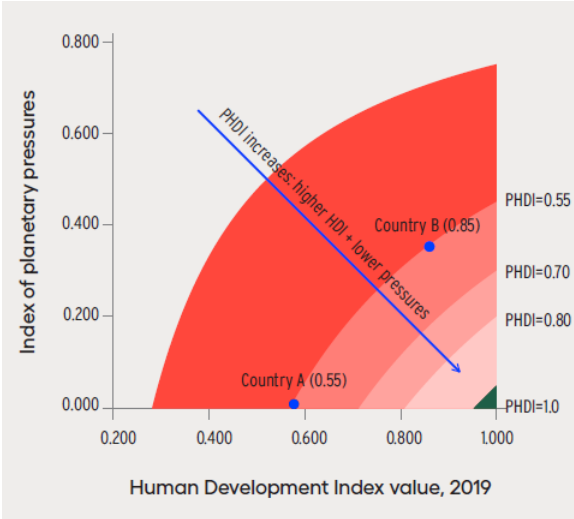
Source: UNDP (2020)

Figure 3.11: Planetary pressures have increased with gains on the Human Development Index



Source: UNDP (2020)

Figure 3.12: Contrasting progress in human development with planetary pressures



Source: UNDP (2020)

the same PHDI values that result from different combinations of the HDI and the index of planetary pressures (isoquants). PHDI values increase as these lines move towards the bottom right corner. This corner (highlighted in green in the figure) is the "empty space" identified in section 3.1 as the aspirational destination of the human development journey in the Anthropocene. For instance, countries in positions A and B have very different HDI values (0.55 and 0.85) but the same PHDI value (0.55) because the greater progress in HDI in country B has been coupled with much greater planetary pressures. This simple example shows the importance of a joint assessment of socioeconomic and planetary pressure indicators as part of a single framework.

Figure 3.13 shows how human development (in its traditional interpretation, characterized by the HDI) is intimately connected with planetary pressures. Of the more than 60 very high human development countries, **only 10 are still classified as very high human development on the PHDI**. And even in those 10 countries the PHDI is still far from the aspirational bottom-right corner.

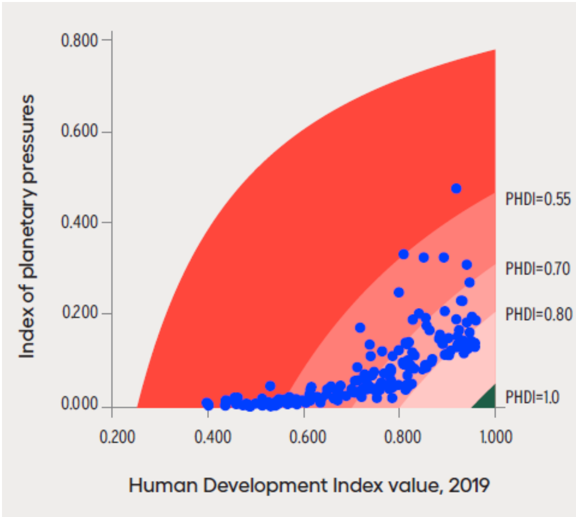
Looking at the trajectory of countries over the past three decades shows different paths across human development groups. Low and medium human development countries have been able to improve social and economic conditions substantially without a high burden on planetary pressures. But in high and very high human development countries, improvements on the HDI have been coupled with rising planetary pressures (left-hand side panel, figure 3.14).

Although absolute planetary pressures have been growing, **two aspects reflect some progress**:

1. First, after the 2008 global financial crisis a few developed countries have shown some **decoupling of human development gains from planetary pressures**. For instance, on average, the top 10 countries on the PHDI have increased their HDI value and reduced their planetary pressures over the last decade (right-hand side panel, figure 3.14).

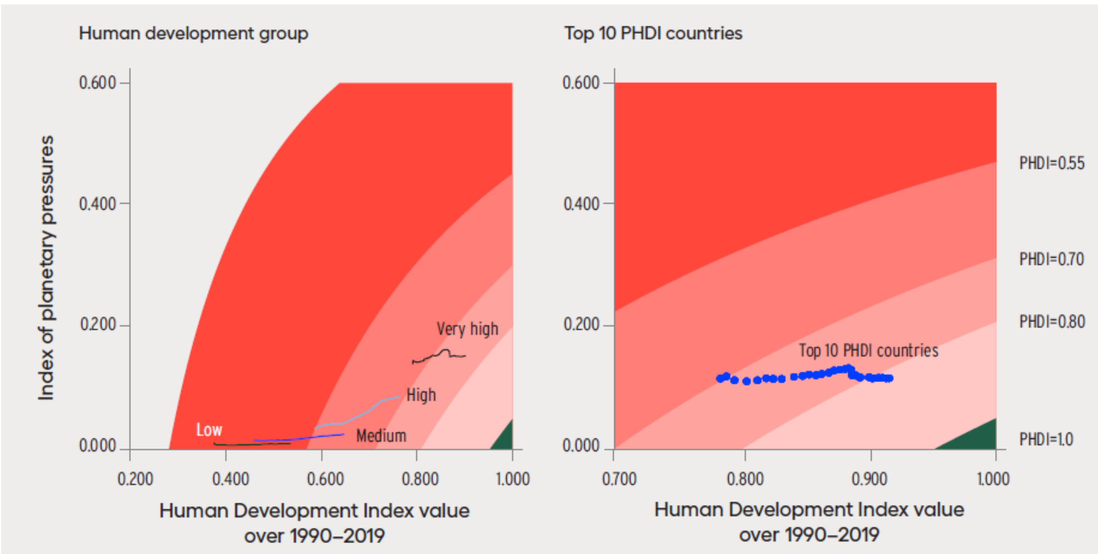
2. Second, there is some evidence **more broadly of relative decoupling**. The curve corresponding to the average performance on the HDI and planetary pressures for all countries moved slightly towards the bottom right-hand corner between 1990 and 2019 (figure 3.15.

Figure 3.13: Planetary pressures and Human Development Index by country



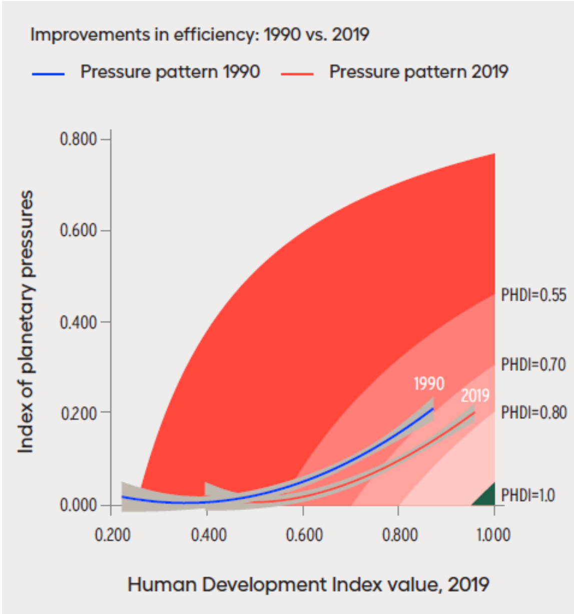
Source: UNDP (2020)

Figure 3.14: Planetary pressures and Human Development Index (time evolution)



Source: UNDP (2020)

Figure 3.15: Planetary pressures and Human Development Index (trends)



Source: UNDP (2020)

But the movement has been far too slow and modest. Further progress will require all countries to rapidly shift substantially towards the bot tom-right corner. The PHDI and the HDI can help assess and, more important, encourage choices towards a human development journey in the Anthropocene that move us all in the direction of advancing human development while easing planetary pressures.

3.3 Other measures of wellbeing

Efforts to measure societies' wellbeing have involved government, civil society, academia and international organizations, often working in collaboration. Though some initiatives have sought to measure wellbeing, others have assessed related concepts, including **progress**, **quality of life** or **sustainable development**. For the purposes here, there is little to choose among the measures used for these themes—each initiative has sought to provide an index, or set of indicators, that paints a broader picture of national wellbeing than GDP provides.

In 2005 the **Organisation for Economic Co-operation and Development (OECD)** began its Global Project on Measuring the Progress of Society to catalyse growing interest in going beyond GDP. In 2007 the OECD, along with the European Commission, the United Nations, the United Nations Development Programme (UNDP), the World Bank and others, cosigned a declaration on the importance of measuring the progress of societies. Later that year the European Union held a conference—**Beyond GDP**—on developing indicators that are as clear and appealing as GDP but more inclusive of environmental and social aspects of progress.

The OECD began developed the **Better Life Index** in 2011 to bring together internationally comparable measures of wellbeing.

Bhutan's Gross National Happiness work is a well known project from the Global South. What began as a remark by Bhutan's King—"Gross national happiness is more important than GNP"—gained traction as a policy goal, and the Centre for Bhutan Studies developed a survey to measure the population's overall wellbeing that covers **four pillars**:

- Promotion of sustainable development.
- Preservation and promotion of cultural values.
- Conservation of the natural environment.
- Establishment of good governance.

These four pillars consist of **nine general contributors to happiness**:

- Psychological wellbeing
- Health
- Education
- Cultural diversity and resilience
- Time use
- Community vitality
- Living standard
- Ecological diversity
- Resilience.

Central government agencies are also becoming interested in wellbeing. For example, the government of **New Zealand** recently made a strong political commitment to go beyond GDP, with its Treasury using the OECD's Living Standard Framework, which measures wellbeing, capital stocks, and risk and resilience to inform budget decisions. Its commitment to engaging with diverse communities within Aotearoa, New Zealand, will help transformation towards an even **richer conceptualization and measure of wellbeing**.

Around the world the development of wellbeing indicators for **children**, **older people**, **people with "disabilities" (special capacities)** and **indigenous communities** is ongoing, sometimes building on a long tradition of work. So too are wellbeing initiatives undertaken by local communities, such as indigenous communities, that are also undertaking socioenvironmental wellbeing surveys. These and other communities are developing wellbeing indicators to understand the **needs and aspirations of their communities in the widest sense**.

Better Life Index.

This index allows you to compare well-being across countries, based on topics the OECD has identified as essential, in the areas of material living conditions and quality of life.

For more information about the Better Life Index visit: Better Life Index (link).

Global Green Economy Index.

This index combines in-depth analysis of national green performance with perception of that performance. The index evaluates the green reputations of countries as judged by expert practitioners and benchmarks these perceptions against measures of national green performance.

For more information and data about the Global Green Energy Index visit: Global Green Energy Index, Dual Citizen (link).

For more information about sustainable lifestyles visit: The SPREAD Sustainable Lifestyles 2050 Project (link).

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Chapter 4

Sustainable energy. Global Energy Transformation. A road map to 2050

This chapter is based on the report entitled "Global Energy Transformation. A road map to 2050" (IREMA, 2019b). The report focuses its analysis on **two pathways** for the global energy system:

- **Reference Case:** This scenario considers current and planned policies of countries. It includes commitments made in Nationally Determined Contributions and other planned targets. It presents a perspective based on governments' current projections and energy plans.
- **REmap Case:** This scenario includes the deployment of low-carbon technologies, based largely on renewable energy and energy efficiency, to generate a transformation of the global energy system that limits the rise in global temperature to well below 2 degrees Celsius above pre-industrial levels. The scenario is focused on energy-related carbon dioxide emissions, which make up around two-thirds of global greenhouse gas emissions.

The **Reference Case** is an energy pathway set by current and planned policies. The **REmap Case** is a cleaner climate-resilient pathway based largely on more ambitious, yet achievable, uptake of renewable energy and energy efficiency measures, which limits the rise in global temperature to well below 2 degrees and closer to 1.5 degrees above pre-industrial levels and is aligned within the envelope of scenarios presented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C.

For more information about the REmap case and the data used in that case visit (link).

The analysis presented in this chapter (IREMA, 2018) is based in the **E3ME model**. E3ME is a macro-econometric model designed to assess global policy challenges. It is the most advanced econometric model in the world and is widely used for policy assessment, forecasting and research purposes. The model is owned and maintained by Cambridge Econometrics. For more information about E3ME model visit (link).

For more details and the **manual** of the model visit (link).

4.1 Highlights

1. **Electrification with renewable power** can start to reduce energy-related carbon dioxide ($CO2$) emissions immediately and substantially. The pairing has also other positive effects:

- Renewable energy is becoming cheaper than fossil fuel-based alternatives.
- It contributes to lower local air pollution and increases health benefits.
- It has a positive socio-economic benefits
- It will be a key enabler to build a connected and digitalised economy and society.

Electrification, when paired with renewables, goes hand-in-hand with energy efficiency, resulting in lower overall energy demand.

2. By 2050 **electricity** could become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share.

   - Renewable power will be able to provide the bulk of global power demand (86%).
   - The primary drivers for this increased electricity demand would be over 1 billion electric vehicles, increased use of electricity for heat and the emergence of renewable hydrogen.
   - Overall, renewable energy would supply two-thirds of final energy.

3. **Total investment** in the energy system would need to reach USD 110 trillion by 2050, or around 2% of average annual gross domestic product (GDP) over the period.

4. **Annual energy-related CO^2 emissions** in the REmap Case decline 70% below today's level. An estimated 75% of this reduction can be achieved through renewable energy and electrification technologies; if energy efficiency is included, then this share rises to over 90%.

   The report shows that emissions would need to be reduced by around 3.5% per year from now until 2050, with continued reductions after that time. Energy-related emissions would need to peak in 2020 and decline thereafter.

5. Any energy transition roadmap will interact with the evolution of the socio-economic system upon which it is deployed, producing a series of outcomes that can be understood as the **socio-economic footprint**.

   - By 2050, GDP increases by 2.5%, relative to the Reference Case.
   - The overall relative improvement over the Reference Case across the three dimensions of the welfare indicator (economic, social and environmental) is 17%, strongly driven by the improvements in health and environment.

6. **Climate damages**: For the end of the century (year 2100) global GDP reductions are estimated at around 20% for a 2°C global warming and 35% for a 5°C global warming are reported (Burke et al, 2018). In terms of GDP, by 2050, the relative improvement over the Reference Case increases from 2.5% to 5.3% when climate damages are factored into the macroeconomic analysis.

4.2 Main findings

1. **The transformation of the global energy system needs to accelerate substantially** to meet the objectives of the Paris Agreement. Those objectives are to keep the rise in average global temperatures "well below" 2 degrees Celsius (2°C) and ideally to limit warming to 1.5°C in the present century, compared to pre-industrial levels.

2. **Renewable energy supply**, increased electrification of energy services, and energy efficiency can deliver more than 90% of needed reductions to energy-related CO2 emissions. Renewable energy and electrification alone deliver 75% of emission reductions.

- Electricity would progressively become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share by 2050.
- Renewable power would be able to provide the bulk of global power demand (86%) economically. As a result, gross electricity consumption would more than double.

3. Changes in the energy system have impacts throughout the **economy**.
    - By year 2050, the REmap energy transition brings about relative improvements of GDP and whole-economy employment of 2.5% and 0.2% respectively.
    - In cumulative terms from 2019 to 2050 the GDP gains of the REmap Case over the Reference Case add up to 99 USD trillion.
    - The global welfare indicator measuring the improvement of REmap over the Reference Case reaches in 2050 a value of 17
4. Changes in the energy system have impacts in **employment**.
    - Across the world economy, overall employment increases between 2018 and 2050 for both the Reference and REmap cases, with CAGRi of 0.45% and 0.46% respectively.
    - The REmap Case produces more jobs than the Reference Case, with relative gains peaking around 2035 and remaining around 0.2% until 2050.
5. **Climate damages** will have a significant impact on the socio-economic footprint.
    - Macroeconomic performance under both the Reference and REmap cases is significantly impacted by climate damages, leading to a global GDP reduction of 15.5% and 13.2%, respectively, by 2050.
    - Despite this high impact, the global economy would still experience a significant growth due to the high growth rates achieved without climate damages under the considered socio-economic context: The CAGR between 2019 and 2050 with climate damages would be 1.8% and 2.0% for the Reference and REmap cases respectively, down from the 2.4% and 2.5%without climate damages.

4.3 A pathway for the transformation of the global energy landscape

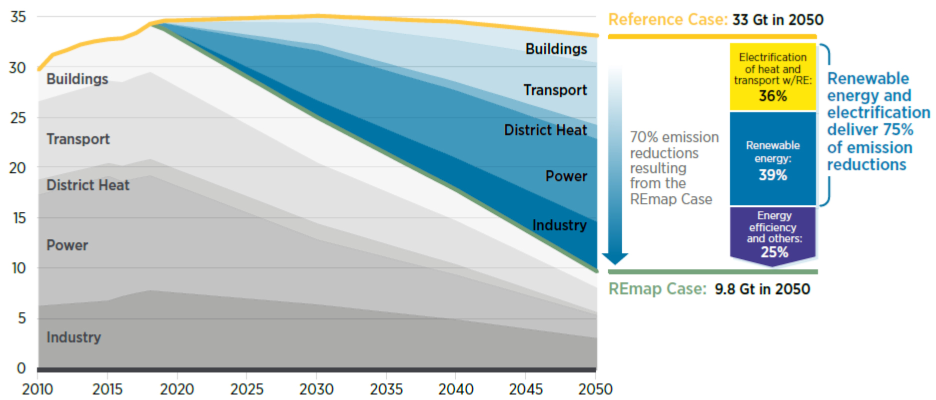
4.3.1 Energy-related CO2 emissions

Based on a carbon budget from the latest Intergovernmental Panel on Climate Change (IPCC) special report on the impacts of global warming of 1.5°C (IPCC, 2018), the Reference Case in this report shows that the global energy-related CO2 budget will run out at the latest by 2030 (based on the IPCC assessment of a 50% confidence level for 1.5°C). To set the world on a path way towards meeting the aims of the Paris Agreement, energy-related CO2 emissions would need to be scaled back by at least an additional 400 gigatonnes (Gt) by 2050 compared to the Reference Case; in other words, **annual emissions would need to be reduced by around 3.5% per year from now until 2050 and continue afterwards**.

Annual energy-related CO2 emissions under current and planned policies – the Reference Case – are expected to remain flat, at 33 Gt CO2 per year in 2050, but must be reduced by 70% to bring temperature rise to the well-below 2°C climate goal – as in the REmap Case. **Electrification**, **renewable energy** and **energy efficiency** measures provide over 90% of the reductions required by 2050. Renewable power and electrification of heat and transport alone reduce emissions by 75% (figure 4.1).

For more information about the Intergovernmental Panel on Climate Change (IPCC), visit: link.

Figure 4.1: Annual energy-related CO^2 emissions



Source: IRENA (2019)

In 2010 about 9 Giga-tons of Carbon (GtC) were emitted from burning fossil fuels as 33 Giga-tons of CO2 gas.

How much is 9 Giga-ton? 9 billion tons or 9.000.000.000.000.000 grams. 9 Giga-tons is the weight of about 132 billion people. The amount of carbon we are putting into the atmosphere each year is equal to 20 times the weight of the current world population.

For more information about **annual CO2 emissions** data visit:

- International Energy Agency (link).
- Global Monitoring Laboratory (link).

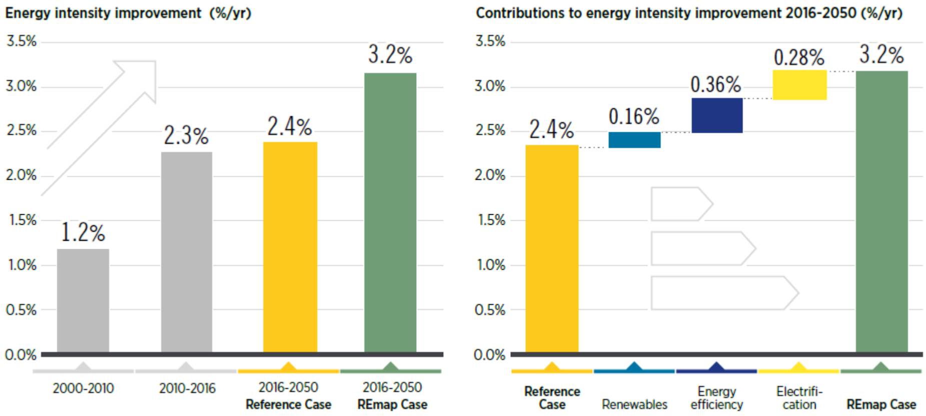
For more information about the **carbon cycle** and the **greenhouse effect** visit Global Monitoring Laboratory (link).

4.3.2 Energy intensity

The **energy intensity** improvement rate would need to increase to 3.2% per year. This is higher than the improvements in recent years (2.3%) or projected in the Reference Case (2.4%) (figure 4.2). The gap between the rate in the Reference Case and what is needed in REmap can be filled through several key means:

- Scaling up solar, wind and other renewables.
- Improving energy efficiency.
- Electrifying transport and heat.
- Structural change in transport and industry.

Figure 4.2: Energy Intensity



Source: IRENA (2019b)

Energy intensity is a measure of the energy inefficiency of an economy. It is calculated as units of **energy per unit of GDP**.

- **High energy intensities** indicate a high price or cost of converting energy into GDP.
- **Low energy intensity** indicates a lower price or cost of converting energy into GDP.

High energy intensity means high industrial output as portion of GDP. Countries with low energy intensity signifies labor intensive economy.

For more information about energy intensity, visit:

- Wikipedia (link 1).
- American Energy Department (link 2).

4.3.3 An electrified future

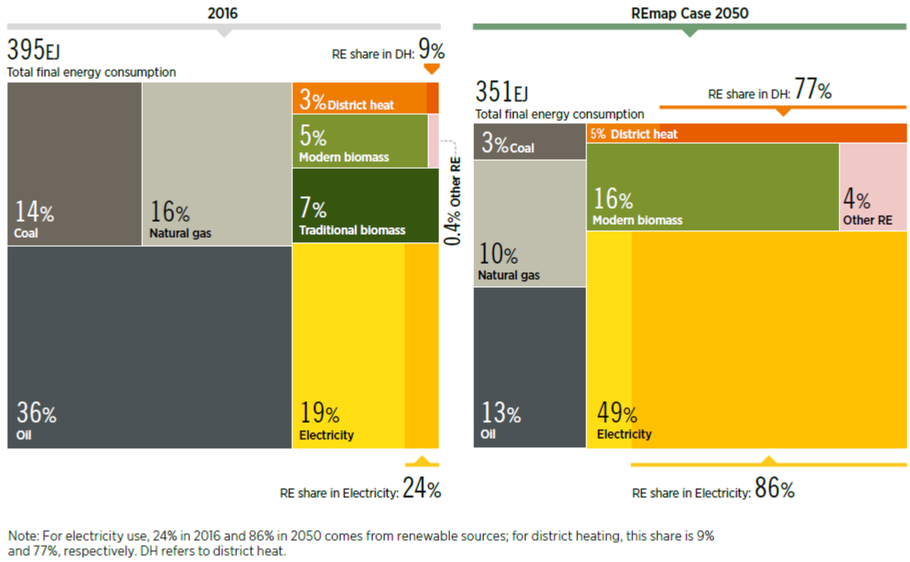
The increasingly electric energy system would transform how the power sector and demand interact. By 2050, 86% of electricity generation would be renewable, and 60% would come from solar and wind. Wind and solar PV would dominate expansion, with installed capacities of over 6 000 GW and 8500 GW, respectively, in 2050 (figure 4.3).

The share of electricity in final energy would increase from just 20% today to almost 50% by 2050 (figure 4.3). The share of electricity consumed in industry and buildings would double. In transport it would need to increase from just 1% today to over 40% by 2050.

4.3.4 The weight of renewables in electrification

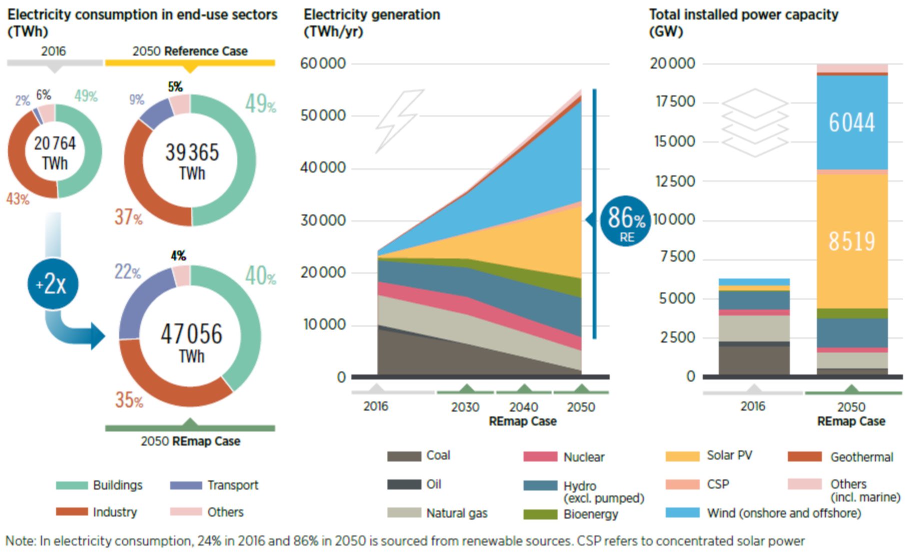
By 2050, solar power, with 8 500 GW installed capacity, and wind, with 6 000 GW, would account for three-fifths of global electricity generation. Electricity consumption in end-use sectors will more than double from today's level (figure 4.4).

Figure 4.3: Total final energy consumption breakdown by energy carrier (%)



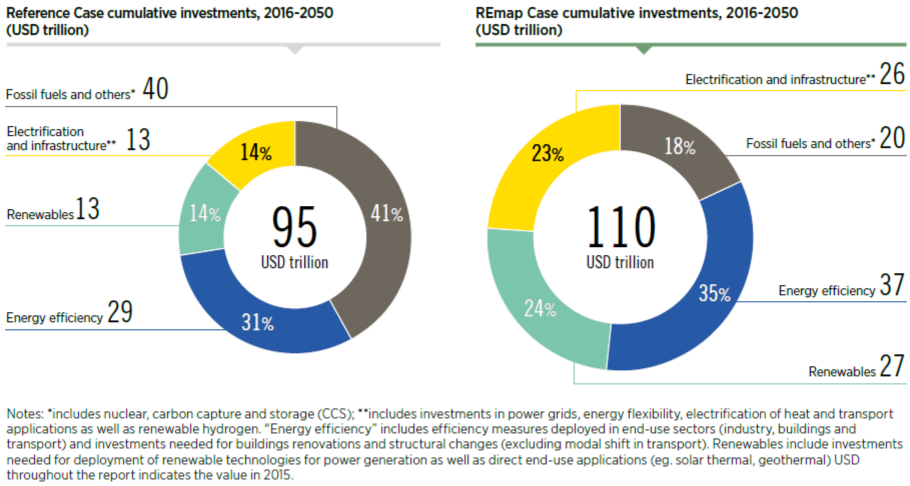
Source: IRENA (2019b)

Figure 4.4: Wind and solar dominate growth in renewable-based generation



Source: IRENA (2019b)

Figure 4.5: Investments



Source: IRENA (2019b)

4.3.5 Investments

Cumulative investments in the energy system to 2050, including infrastructure and efficiency, will total almost USD 95 trillion in the Reference Case, and would increase to USD 110 trillion in the REmap Case (figure 4.5).

Renewable power technologies are increasingly the least-cost electricity supply options available. The renewable energy market would grow quickly as costs continue to decline, as technologies improve and as innovation brings additional applications.

The REmap Case increases investments in the global energy system by USD 15 trillion, and shifts investment into electrification, renewable energy and energy efficiency technologies, which together, would make up four-fifths of the cumulative energy sector investments over the period to 2050.

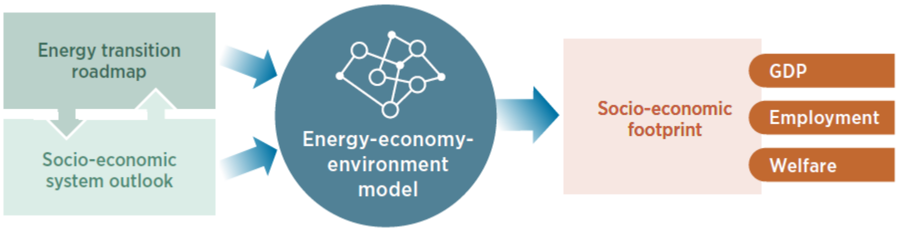
However, an energy system based heavily on renewables would be different than past systems and would require significant investments in **power grids**, complementary infrastructure and energy flexibility. In the Reference Case, investments for these would amount to USD 9 trillion. In the REmap Case, an additional USD 4 trillion would be required, for a total of USD 13 trillion.

4.4 Measuring the socio-economic footprint of the energy transition

The power and energy systems are embedded into the wider socio economic system, which in turn is embedded into the earth and its climate. In order to avoid dysfunctional outcomes, a holistic policy framework is needed to frame and support the transition (figure 4.6).

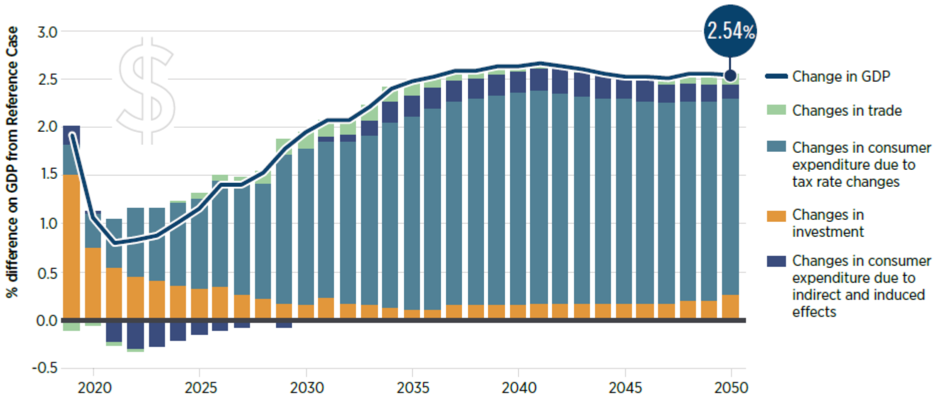
Both the energy and socio-economic systems will evolve during the transition, with multiple feedback loops between them. IRENA uses an integrated Energy-Economy-Environment model to evaluate the socio-economic footprint that results from the interactions among different combinations of the energy transition roadmap and the socio-economic outlook.

Figure 4.6: Energy transition and its socio-economic footprint



Source: IRENA (2019b)

Figure 4.7: Relative difference of global GDP between the REmap Case and the Reference Case, 2019-2050



Source: IRENA (2019b)

4.4.1 Energy-wide GDP and employment impacts

The analysis presented in this section builds on IRENA's body of work, which has focused on measuring the economics and benefits of the energy transition and on assessing renewable energy employment (IRENA, 2019a, 2018, 2017, 2016; IEA and IRENA, 2017). The analysis delves into macroeconomic variables to present the socio-economic footprint of the REmap roadmap, both at global and regional levels, as deployed within the current socio economic system.

In order to gain insights into the structural elements underpinning the socio-economic footprint, IRENA's macroeconomic analysis decomposes the outcomes in different drivers. The main macroeconomic drivers used to analyse the GDP and employment footprints include (figure 4.7):

- Investment.
- Trade.
- Tax changes.
- Indirect and induced effects.

In the short term, the net positive impact on global GDP is due mainly to a front-loaded **investment** stimulus in renewable energy generation capacity, energy efficiency, and energy system flexibility to support the transition. The overall impact of this driver gradually fades in importance as time progresses.

Gains in **consumer expenditure** due to tax rate changes become the dominant factor in the evolution of GDP between 2022 and 2050. This driver captures the impact of the changes in government income due to carbon taxes, fossil fuel phase-out, changes in fossil fuel royalties and other taxes.

The **employment** gains are expected to be less significant than for GDP because additional demand in the global economy also pushes up real wages. The additional wage volume available can be translated either as wage increases for all workers, or as an increase in the number of jobs, or a mix of both. Historical trends show that wage effects tend to dominate, leading to smaller increases in employment than GDP.

4.4.2 Climate damages and its impact on GDP

The literature suggests that very important impacts from climate change can be expected on the performance of the socio economic system both in terms of reducing global GDP and increasing inequality:

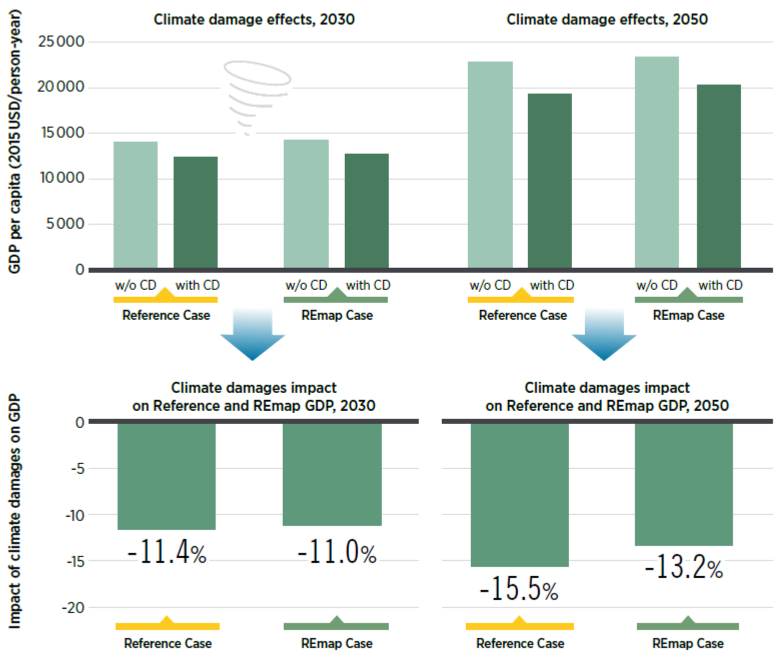
- For the end of the century (year 2100) global GDP reductions are estimated at around 20% for a 2°C global warming and 35% for a 5°C global warming are reported (Burke et al, 2018).
- Climate damages will lead to increased inequality because much higher impacts can be expected in warmer regions, which often correspond to poorer countries (Burke et al, 2015).

The upper graph in figure 4.8 presents per capita GDPs with and without climate damages. Clear green bars represent the per capita GDP without taking into account climate damages, while dark green bars represent the per capita GDP once climate damages are factored in. As it can be seen both REmap and Reference cases experience a significant reduction in GDP when climate damages are included in the macroeconomic modelling. To better understand these reductions, the lower graph in figure 4.8 presents the percentage reduction in GDP when climate damages are included, showing how important are the GDP reductions attributable to climate change.

What does the applied climate damage methodology does not include? The results obtained can be considered conservative, because there are several ways through which climate change can negatively impact the economy that are not captured by it:

- Sea level rise and increased incidence of extreme weather events (flooding, draughts, tropical cyclones, wildfires...).
- Disrupted trade and modified trade dynamics based on modified power positions, where regions with higher damages on GDP (Global South) experience losses in trade balance, and winners (Global North) use the advantageous situation to impose trade agreements.
- Social conflict effects associated to disruption and increasing inequality.
- Cross-country spillovers associated to climate change that would produce higher economic impacts (for example, supply chain interruptions/alterations, trade effects...)

Figure 4.8: Impact of climate damages on GDP results



Source: IRENA (2019b)

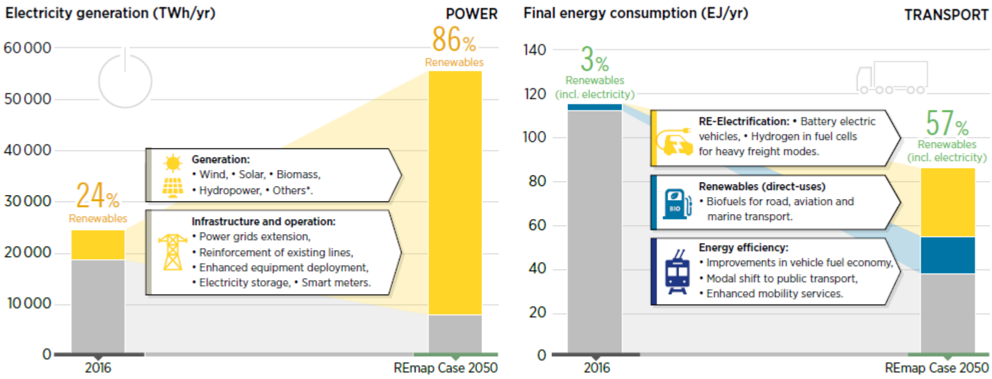
4.5 Action needed now

This chapter makes clear that an energy transition is urgently required, and that **renewable energy**, **energy efficiency** and **electrification** are the three cornerstones of that transition.

In this section, we present some of the key actions that are needed now to achieve the Paris agreement.

1. The **power sector** needs to be transformed to accommodate growing shares of variable renewables.
   - Develop power systems that provide a high level of technical **flexibility**.
   - Better **market signals** are needed to enable flexibility resources to come into play to cope with the uncertainty and variability of variable renewable energy (VRE) generation. Examples include real-time variable pricing and shorter trading intervals.
   - Power markets will need to be redesigned to enable the optimal investments for systems with high levels of VRE and enable sector coupling.
2. **Digitalisation** is a key enabler to amplify the energy transformation.
3. Accelerating the **electrification** of the transport and heating sectors is crucial for the next stage of energy transformation.
4. **Hydrogen** produced from renewable electricity could help to reduce fossil-fuel reliance.
5. **Supply chains** are key to meet growing demand for sustainable **bioenergy**.
   - **Bioenergy** must be produced in ways that are environmentally, socially and economically sustainable. There is a very large potential to produce bioenergy cost-effectively on existing farmland and grassland, without encroaching upon rainforests, and in addition to growing food requirements.

Figure 4.9: Sector level actions. Power and Transport sectors



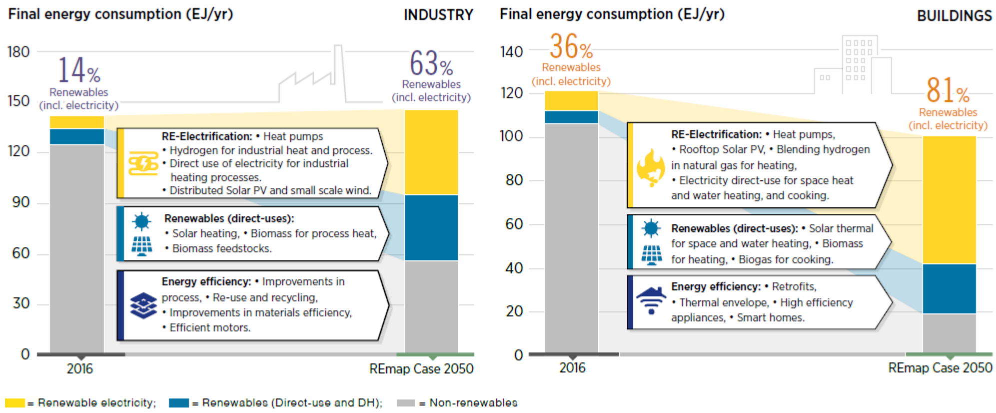
Source: IRENA (2019b)

- **Biomass-based industries** that generate ready-to-use biomass residues – such as pulp and paper, lumber and timber, and food – are fundamental in the transition.
- In sectors such as aviation, shipping and long-haul road transport, **biofuels** might be the main or only option for decarbonisation for years to come.

Actions in the power, industry, buildings and transport sectors are essential to realise the global energy transformation by 2050. Below, we present an overview of major actions at the sector level:

1. **Power (left-hand side panel, figure 4.9):**
   - Accelerate renewables capacity additions. In particular, identify and map renewable energy resources and develop a portfolio of financeable projects.
   - Plan for the power sector to accommodate increasing shares of variable renewable energy.
   - Support the deployment of distributed energy resources. In particular, incentivise energy consumers to become prosumers.
2. **Transport (right-hand side panel, figure 4.9):**
   - Reduce the energy need for transport. First, by deploying advanced digital communication technologies to reduce the transport needs (eg. teleconferencing over travelling) and to improve efficiency of transport by better utilizing the assets (eg. re-routing due to traffic). Second, by promoting mobility services, e.g., promote vehicle sharing and autonomous driving.
3. **Industry (left-hand side panel, figure 4.10):**
   - Reduce energy consumption in industries. First, by promoting actions towards circular economy (material recycling, waste management, improvements in materials efficiency and structural changes such as reusing and recycling). Second, by incentivising and adopting best available technologies (BAT) and efficiency standards.
   - Enable corporate sourcing of renewables by supporting a credible and transparent system for certification and tracking of renewable energy attributes.
   - Accelerate the deployment of low-carbon technologies in industrial process heating.

Figure 4.10: Sector level actions. Industry and Buildings sectors



Source: IRENA (2019b)

4. **Buildings (right-hand side panel, figure 4.10):**

   - Reduce energy consumption in buildings. First, by establishing and improve energy efficiency building codes and standards (incl. appliances (eg. air conditioners), lighting (eg. LED lights) and equipment (eg. efficient boilers)). Second, by adopting programmes for retrofitting/renovation including financing schemes.
   - Support and foster the deployment of distributed energy resources by removing regulatory barriers for prosumers that restrict them from taking an active role in the energy system transformation.
   - Scale up renewable share uptake in the building sector by promoting low-carbon heating technologies: heat pumps, solar heating, modern bioenergy for heating). Apply these renewable technologies for district heating.

Sector coupling refers to the idea of interconnecting (integrating) the **energy consuming sectors** - buildings (heating and cooling), transport, and industry - with the **power producing sector**. Making electricity the default form of energy in these sectors would be a step towards what is sometimes referred to as an “all-electric world.”

For more information about sector coupling visit:

- Journalism for the energy transition (link 1).
- IRENA, sector coupling (link 2).

Supply chain activities involve the transformation of natural resources, raw materials, and components into a finished product that is delivered to the end customer.
For more information about supply chains visit:

- Wikipedia (link 1).
- Investopedia (link 2).

4.6 Some questions to summarize the chapter

In this section, we propose some questions that could be useful to summarize the main points studied in this chapter.

1. Carbon emissions must be reduced to 10 GT per year in 2050. Which are the **three main ways to reduce carbon emissions**?

   Electrification, introduction of renewable energy and energy efficiency

2. Which are the **four sectors** where carbon emissions need to be more effective?

   Power sector, industry sector, transport sector and building sector

3. The share of electricity in the energy production will pass from 20% to 80%. Which **share of electric production will be renewable**?

   The 86% of the electricity will be produced by using renewable energy

4. Which will be the **share of electricity use by sector**?

   40% in the building sector, 33% in the industry sector, 22% in the transport sector

5. In the **power sector**, the renewable share will pass from 24% to 86%. Can you enumerate the main **sources of renewable production**?

   Solar, wind, biomass and hydropower

6. In the **transport sector**, the renewable share will pass from 3% to 57%. Can you enumerate the **main changes in that sector**?

   EV, hydrogen for heavy freight modes, biofuels for road, aviation and marine transport

7. In the **industry sector**, the renewable share will pass from 14% to 63%. Can you enumerate the **main changes in that sector**?

   Hydrogen for industrial heat and process; direct use of electricity and renewables for industrial heating processes

8. In the **building sector**, the renewable share will pass from 36% to 81%. Can you enumerate the **main changes in that sector**?

   Renewables for heating, and electricity; biogas for cooking; increase in efficiency

4.7 Questions: Competition Policy and European Green Deal

The video of the conference is in the this link. To motivate the discussion, I propose you some questions:

Frans Timmermans

1. Of the EU recoverage package, which proportion will be **invested** in **green energy (climate policy)** and **digitalization**?
   30% will be invested in green economy and 20% will be invested in digitalization. The rest will be invested in sectors that foster digitalization and the adoption of a green economy
2. Which are the main sectors that could be **more problematic to de-carbonize**?
   The building, the transport and the agriculture sectors
3. Which are some of the **policies** that could be implemented to green the economy?
   Price on carbon emissions, regulation predictability and long-term stability

Pedro Size Vieira

1. Which are the **four (five) main objectives** of the current Portuguese government?
   Demographic change, digitalization, inequalities, green economy and biodiversity
2. Which are the main **technologies** used to promote the electrification of the country? Which will be the **share of renewable energy** production and consumption in Portugal in the next years?
   The technologies to produce electricity will be hydroelectric, wind and solar. The share of renewables in production is the 60% and the share of renewables in consumption is 40%

Sven Giegold

1. To foster the adoption of green technologies, Sven Giegold introduces the concept of fair price. Could you explain which policies should by implemented to obtain **fair prices**?
   First, the subsidies on pollution technologies should by phased out. Second, the pollution technologies need to internalize their externalities on society
2. Which are the policies to be implemented to foster the **investments in green technologies**?
   First, state aids in critical technologies, that are still not mature to be competitive. Second, to ban the subsidies to fossil fuels, and fossil fuels infrastructure
3. Which are the policies to mitigate the **impact of digitalization on carbon emissions**?
   Digitalization should be treated as a "quasi-infrastructure" and should be taxed according with "quasi-infrastructure" taxation

Philippe Aghion

Philippe Aghion claims that **markets are not able to promote green innovation** by themselves, since firms tend to be conservative

1. Which are the main **State policies** to foster green innovation?
   Carbon taxes, carbon prices, subsidies and incentives similar to arpa-e in USA
2. Which are the **main driver in the civil society** that foster green innovation?
   The societies in which consumers demand "green products" creates the conditions for green innovations, since the firms need to compete to attract those consumers

Mechthild Wörsdörfer

1. Which are the share of **carbon emissions by sectors**?
   40% CO2 emissions in the power sector, 25% CO2 emissions in the transport sector, 20% in the industry sector, the rest in other sectors

2. Which are the **main four economy areas** to green the economy?
   First, EV sales should move from 3% nowadays to 100% in 2050. Second, the heating system need to be electrified. Third, energy intense industries (cement, steel, chemistry) need to be electrified. Fourth, the building stock need to increase its efficiency (currently, the 75% is inefficient)

3. Which are the policies to foster **green innovation**?
   The 50% of the 400 different types of technological innovations required to green the economy are still not mature to be competitive. It is necessary State aid to foster green innovation

4.8 Bibliography

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Chapter 5

Sustainable energy. Wind

5.1 Introduction

In this chapter, we will study the **main characteristics of wind energy from a technological perspective**, and we will connect that analysis with the **economic development of that technology**. The chapter is organized as follows:

1. Watch a video to **discuss** some important aspects of wind energy
2. Review the **history** and evolution of wind energy
3. Wind **technology** and its impact in wind production
4. Wind energy. **Key trends**: **Onshore** wind energy and **offshore** wind energy
5. **Questions** to summarize the chapter

5.2 Discussion

To motivate the chapter, we start by watching the video How Big Can Wind Turbines Get?

Based on that video, we discuss the next questions:

1. Which have been the evolution of **wind installed capacity** in the next 20 years?
2. Which is the **share energy production that come from wind energy** in Denmark in one year? And in a windy day?
3. Which has been the evolution of the **size of windmills** in the last years?
4. Which is the mathematical formula to work out **kinetic energy**? And **power** from that kinetic energy?
5. Based on those mathematical formulas, **why have increased the size of windmills**?
6. Which are the main **problems to continue increasing the size of windmills**?

5.3 Introduction

Wind power is one of the fastest-growing renewable energy technologies. Usage is on the rise worldwide, in part because costs are falling. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost 75 in the past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 564 GW by 2018, according to IRENA's latest data (link). Production of wind electricity doubled between 2009 and 2013, and in 2016 wind energy accounted for 16% of the electricity generated by renewables. Many parts of the world have strong wind speeds, but the best locations for generating wind power are sometimes remote ones. Offshore wind power offers tremendous potential.

Wind-turbine capacity has increased over time. In 1985, typical turbines had a rated capacity of 0.05 megawatts (MW) and a rotor diameter of 15 metres. Today's new wind power projects have turbine capacities of about 2 MW onshore and 3–5 MW offshore.

Commercially available wind turbines have reached 8 MW capacity, with rotor diameters of up to 164 metres. The average capacity of wind turbines increased from 1.6 MW in 2009 to 2 MW in 2014.

5.4 History

Wind turbines first emerged more than a century ago. Following the invention of the electric generator in the 1830s, engineers started attempting to harness wind energy to produce electricity. Wind power generation took place in the United Kingdom and the United States in 1887 and 1888, but modern wind power is considered to have been first developed in Denmark, where horizontal-axis wind turbines were built in 1891 and a 22.8-metre wind turbine began operation in 1897.

<u>People have been using wind energy for thousands of years.</u>

People used wind energy to propel boats along the Nile River as early as 5,000 BC. By 200 BC, simple wind-powered water pumps were used in China, and windmills with woven-reed blades were grinding grain in Persia and the Middle East.

New ways to use wind energy eventually spread around the world. By the 11th century, people in the Middle East were using wind pumps and windmills extensively for food production. Merchants and the Crusaders brought wind technology to Europe. The Dutch developed large windpumps to drain lakes and marshes in the Rhine River Delta. Immigrants from Europe eventually took wind energy technology to the Western Hemisphere.

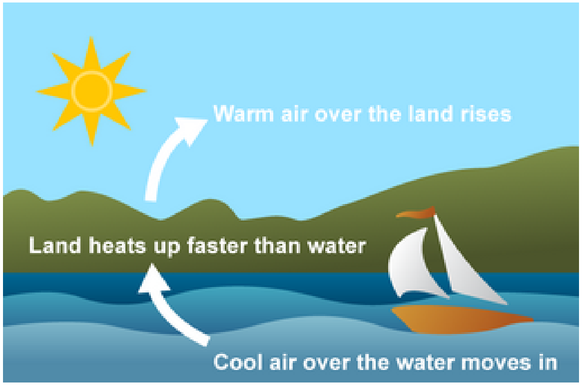
American colonists used windmills to grind grain, to pump water, and to cut wood at sawmills. Homesteaders and ranchers installed thousands of wind pumps as they settled the western United States. In the late 1800s and early 1900s, small wind-electric generators (wind turbines) were also widely used.

The number of wind pumps and wind turbines declined as rural electrification programs in the 1930's extended power lines to most farms and ranches across the country. However, some ranches still use wind pumps to supply water for livestock. Small wind turbines are becoming more common again, mainly to supply electricity in remote and rural areas.

<u>Wind energy use expanded in the wake of oil shortages and environmental concerns.</u>

The oil shortages of the 1970s changed the energy environment for the United States and the world. The oil shortages created an interest in developing ways to use alternative energy sources, such as wind energy, to generate electricity. The U.S. federal government supported research and development of large wind turbines. In the early 1980s, thousands of wind turbines were

Figure 5.1: How uneven heating of water and land causes wind



Source: EIA webpage

installed in California, largely because of federal and state policies that encouraged the use of renewable energy sources.

In the 1990s and 2000s, the U.S. federal government established incentives to use renewable energy sources in response to a renewed concern for the environment. The federal government also provided research and development funding to help reduce the cost of wind turbines and offered tax and investment incentives for wind power projects. In addition, state governments enacted new requirements for electricity generation from renewable sources, and electric power marketers and utilities began to offer electricity generated from wind and other renewable energy sources (sometimes called green power) to their customers. These policies and programs resulted in an increase in the number of wind turbines and in the amount of electricity generated from wind energy.

The share of U.S. electricity generation from wind grew from less than 1% in 1990 to about 7.3% in 2019. Incentives in Europe have resulted in a large expansion of wind energy use there. China has invested heavily in wind energy and is now the world's largest wind electricity generator. In 1990, 16 countries generated a total of about 3.6 billion kWh of wind electricity. In 2017, 129 countries generated a total of about 1.13 trillion kWh of wind electricity.

5.5 Technology

5.5.1 How wind turbines work.

Wind turbines use blades to collect the wind's kinetic energy. Wind flows over the blades creating lift (similar to the effect on airplane wings), which causes the blades to turn. The blades are connected to a drive shaft that turns an electric generator, which produces (generates) electricity.

5.5.2 Energy from moving air

Wind is caused by uneven heating of the earth's surface by the sun. Because the earth's surface is made up of different types of land and water, it absorbs the sun's heat at different rates. One example of this uneven heating is the daily wind cycle (figure 5.1).

<u>The daily wind cycle</u>

During the day, air above the land heats up faster than air over water. Warm air over land expands and rises, and heavier, cooler air rushes in to take its place, creating wind. At night, the winds are reversed because air cools more rapidly over land than it does over water.

In the same way, the atmospheric winds that circle the earth are created because the land near the earth's equator is hotter than the land near the North Pole and the South Pole. The global wind kinetic energy averaged approximately 1.50 MJ/m2 over the period from 1979 to 2010, 1.31 MJ/m2 in the Northern Hemisphere with 1.70 MJ/m2 in the Southern Hemisphere. The atmosphere acts as a thermal engine, absorbing heat at higher temperatures, releasing heat at lower temperatures. The process is responsible for the production of wind kinetic energy at a rate of 2.46 W/m2 sustaining thus the circulation of the atmosphere against frictional dissipation.

Wind is used to produce electricity using the kinetic energy created by air in motion. This is transformed into electrical energy using wind turbines or wind energy conversion systems. Wind first hits a turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the kinetic energy to rotational energy, by moving a shaft which is connected to a generator, and thereby producing electrical energy through electromagnetism.

The amount of power that can be harvested from wind depends on the size of the turbine and the length of its blades. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. Theoretically, when wind speed doubles, wind power potential increases by a factor of eight.

Mathematically, total **wind energy** flowing through an imaginary surface with area A during the time t is:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3 \tag{5.1}$$

where ρ is the density of air; v is the wind speed; Avt is the volume of air passing through A (which is considered perpendicular to the direction of the wind); $Avt\rho$ is therefore the mass m passing through A. $\frac{1}{2}\rho v^2$ is the kinetic energy of the moving air per unit volume.

Power is energy per unit time, so the wind power incident on A (e.g. equal to the rotor area of a wind turbine) is:

$$P = \frac{E}{t} = \frac{1}{2}A\rho v^3 \tag{5.2}$$

Energy:

As energy is defined via work, the International System of Units unit of energy is the same as the unit of work – the **joule (J)**, named in honor of James Prescott Joule and his experiments on the mechanical equivalenta of heat. In slightly more fundamental terms, **1 joule is equal to 1 newton metre** and, in terms of International System of Units base units:

$$1J = \left(1kg\frac{m}{s^2}\right)m = 1kg\left(\frac{m}{s}\right)^2 = 1\frac{kg \cdot m^2}{s^2} \tag{5.3}$$

Electricity is measured in Watts and kilowatts:

Electricity is measured in units of power called Watts, named to honor James Watt, the inventor of the steam engine. A Watt is the unit of electrical power equal to **one ampere under the pressure of one volt**.

One Watt is a small amount of power. Some devices require only a few Watts to operate, and other devices require larger amounts. The power consumption of small devices is usually measured in Watts, and the power consumption of larger devices is measured in kilowatts (kW), or 1,000 Watts.

Electricity generation capacity is often measured in multiples of kilowatts, such as megawatts (MW) and gigawatts (GW). One MW is 1,000 kW (or 1,000,000 Watts), and one GW is 1,000 MW (or 1,000,000,000 Watts).

Electricity use over time is measured in Watthours:

A Watthour (Wh) is equal to the energy of one Watt steadily supplied to, or taken from, an electric circuit for one hour. **The amount of electricity that a power plant generates or an electric utility customer uses is typically measured in kilowatthours (kWh)**. One kWh is one kilowatt generated or consumed for one hour. For example, if you use a 40-Watt (0.04 kW) light bulb for five hours, you have used 200 Wh, or 0.2 kWh, of electrical energy.

For more information about energy measures visit:

- Energy Information Administration (link).
- Wikipedia, wind power (link); wikipedia, units of energy (link); wikipedia, electric power (link).

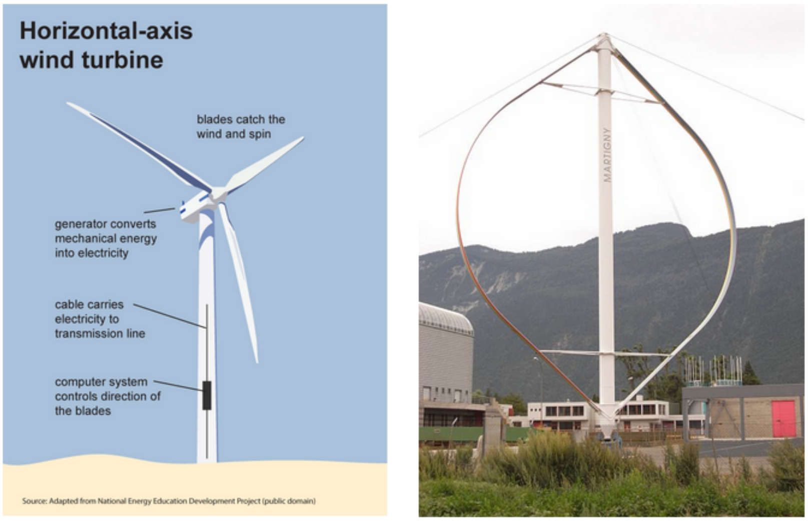
5.5.3 Types of wind turbines.

There are two basic types of wind turbines (figure 5.2):

- Horizontal-axis turbines
- Vertical-axis turbines

The size of wind turbines varies widely. The length of the blades is the biggest factor in determining the amount of electricity a wind turbine can generate. Small wind turbines that can power a single home may have an electricity generating capacity of 10 kilowatts (kW). The largest wind turbines in operation have electricity generating capacities of up to kilowatts (10

Figure 5.2: Types of wind turbines



Source: EIA webpage

megawatts), and larger turbines are in development. Large turbines are often grouped together to create wind power plants, or wind farms, that provide power to electricity grids.

Horizontal-axis turbines are similar to propeller airplane engines.

Horizontal-axis turbines have blades like airplane propellers, and they commonly have three blades. The largest horizontal-axis turbines are as tall as 20-story buildings and have blades more than 100 feet long. Taller turbines with longer blades generate more electricity. Nearly all of the wind turbines currently in use are horizontal-axis turbines.

Vertical-axis turbines look like egg beaters.

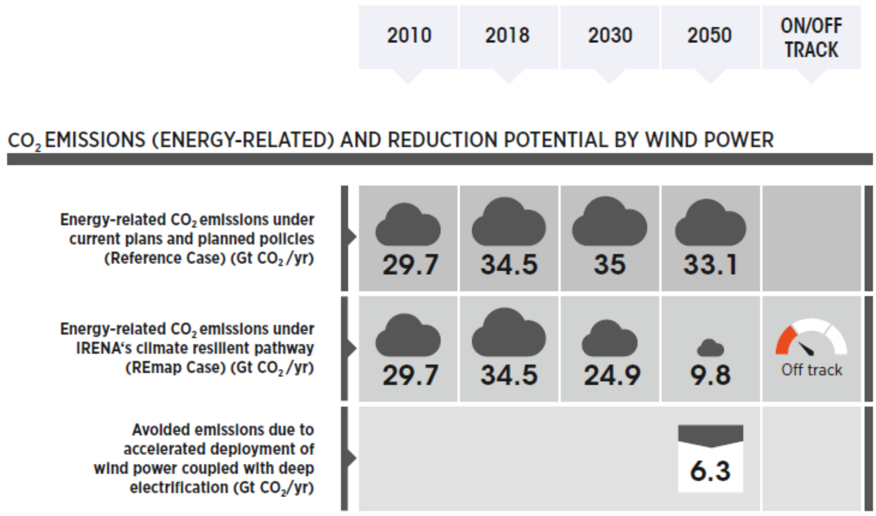
Vertical-axis turbines have blades that are attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus who patented the design in 1931—looks like a giant, two-bladed egg beater. Some versions of the vertical-axis turbine are 100 feet tall and 50 feet wide. Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines.

Two very useful videos to know more about **wind turbines**:

- How do wind turbines work: (link).
- Why Do Wind Turbines Have Three Blades? (link).

More information about **wind turbine generators** can be found in the Alternative Energy Tutorials webpage (link).

Figure 5.3: CO2 emissions (energy-related) and reduction potential by wind power



Source: IRENA (2019a)

The **Global Wind Atlas** is a web-based application developed to help policymakers and investors identify potential high-wind areas for wind power generation virtually anywhere in the world, and perform preliminary calculations.

It provides **free access to data on wind power density and wind speed at multiple heights** using the latest historical weather data and modeling, at an output resolution of 250 meters.

It was developed and is maintained by the **Wind Energy Department of the Technical University of Denmark (DTU Wind Energy)** in partnership with the **World Bank**, with funding provided by the Energy Sector Management Assistance Program (ESMAP).

For more information about the Global Wind Atlas visit (link).

5.6 Future of wind. Deployment, investment, technology, grid integration and socio-economic aspects

This section is based on IRENA (2019a).

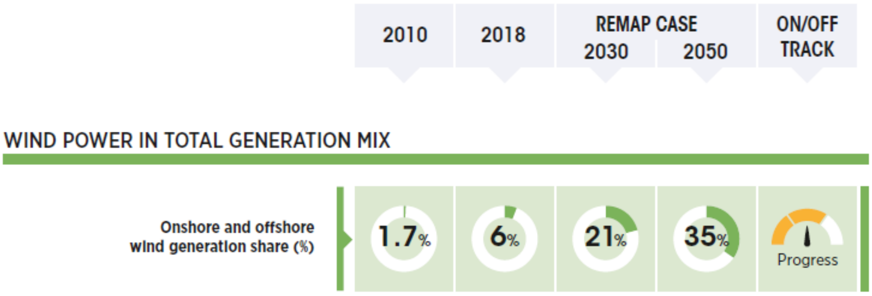
5.6.1 Key findings

1. Accelerated deployment of renewables, combined with deep electrification an increased energy efficiency, can achieve over 90% of the energy-related CO2 emissions reductions needed by 2050 to set the world on an energy patway towards meeting the **Paris climate targets**.

   Among all low-carbon technology options, accelerated deployment of wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed **(nearly 6.3 gigatonnes of carbon dioxide (Gt CO2) annually) in 2050** (figure 5.3).[1].

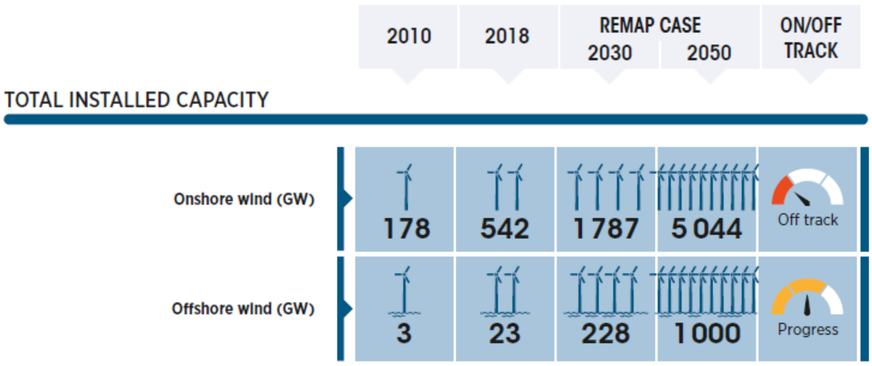
[1]For more information about CO2 emission visit section 4.3.1

Figure 5.4: Wind power in total generation mix



Source: IRENA (2019a)

Figure 5.5: Wind total installed capacity



Source: IRENA (2019a)

2. The achievement of the Paris climate targets is only possible by greatly **scaling up wind capacity installations** in the next three decades.

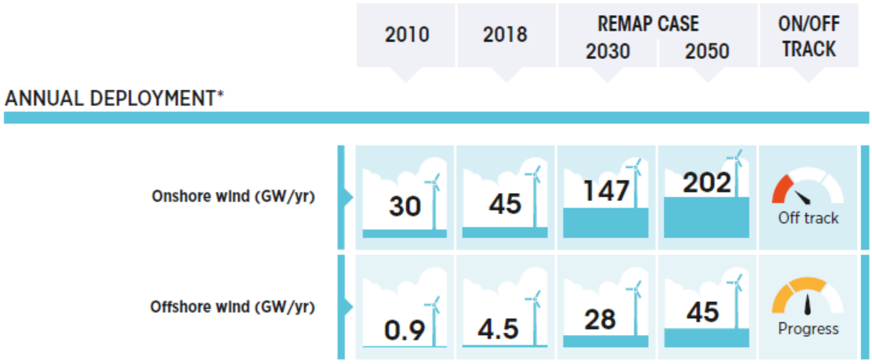
   This entails increasing the global cumulative installed capacity of **onshore wind power** more than three fold by 2030 (to 1 787 gigawatts (GW)) and nine-fold by 2050 (to 5 044 GW) compared to installed capacity in 2018 (542 GW). For **offshore wind power**, the global cumulative installed capacity would increase almost ten-fold by 2030 (to 228 GW) and substantially towards 2050, with total offshore installation nearing 1 000 GW by 2050 (figures 5.4 and 5.5).

3. **Annual capacity additions for onshore wind** would increase more than four-fold, to more than 200 GW per year in the next 20 years, compared to 45 GW added in 2018. Even higher growth would be required in **annual offshore wind capacity additions** – around a ten-fold increase, to 45 GW per year by 2050 from 4.5 GW added in 2018 (figure 5.6).

4. At a regional level, Asia would largely drive the pace of wind capacity installations, becoming the world leader in wind energy.

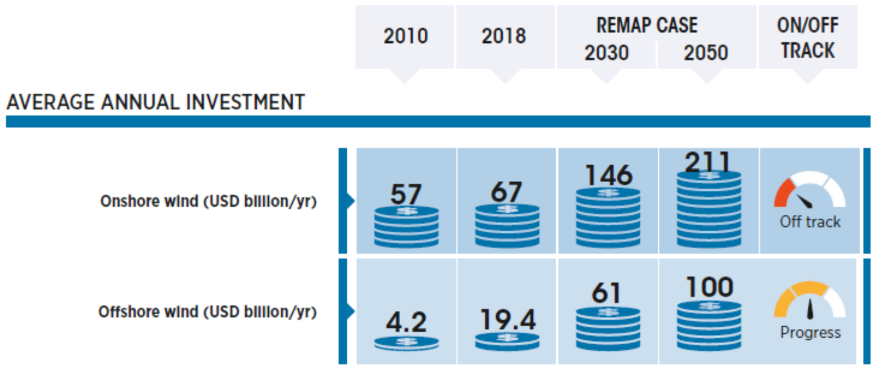
   - Asia (mostly China) would continue to dominate the **onshore wind** power industry, with more than 50% of global installations by 2050, followed by North America (23%) and Europe (10%).
   - For **offshore wind**, Asia would take the lead in the coming decades with more than 60% of global installations by 2050, followed by Europe (22%) and North America

Figure 5.6: Wind annual deployment



Source: IRENA (2019a)

Figure 5.7: Wind average annual investment



Source: IRENA (2019a)

(16%).

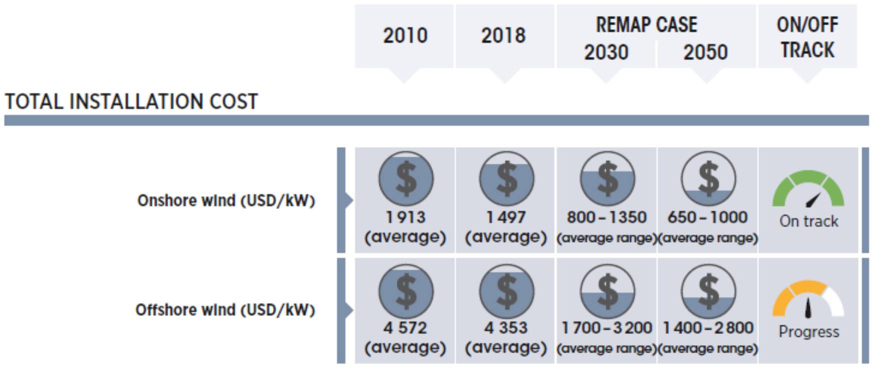
5. **Scaling up wind energy investments** is key to accelerating the growth of global wind power installations over the coming decades.

   - This would imply increasing global average annual **onshore wind** power investments by more than two-fold from now until 2030 (USD 146 billion/year) and more than three-fold over the remaining period to 2050 (USD 211 billion/year) compared to 2018 investments (USD 67 billion/year).
   - For **offshore wind**, global average annual investments would need to increase three-fold from now until 2030 (USD 61 billion/year) and more than five-fold over the remaining period to 2050 (USD 100 billion/year) compared to 2018 investments (USD 19 billion/year).

6. Increasing economies of scale, more competitive supply chains and further technological improvements will continue to reduce the **costs of wind power**.

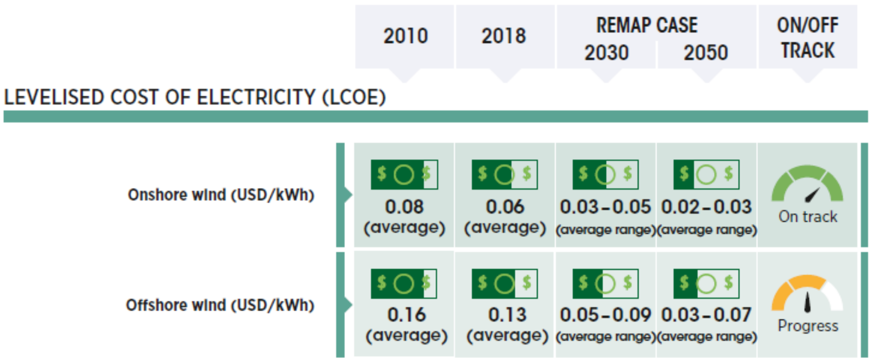
   (a) The **total installation cost** of **onshore wind projects** would continue to decline in the next three decades with the average cost falling in the range of USD 800 to 1 350 per kilowatt (kW) by 2030 and USD 650 to 1 000/ kW by 2050, compared to the global-weighted average of USD 1 497/kW in 2018. For **offshore wind projects**, the

Figure 5.8: Wind total installation cost



Source: IRENA (2019a)

Figure 5.9: Wind levelised cost of electricity (LCOE)



Source: IRENA (2019a)

average total installation cost would further drop in coming decades to between USD 1 700 and 3 200/kW by 2030 and between USD 1 400 and 2 800/kW by 2050.

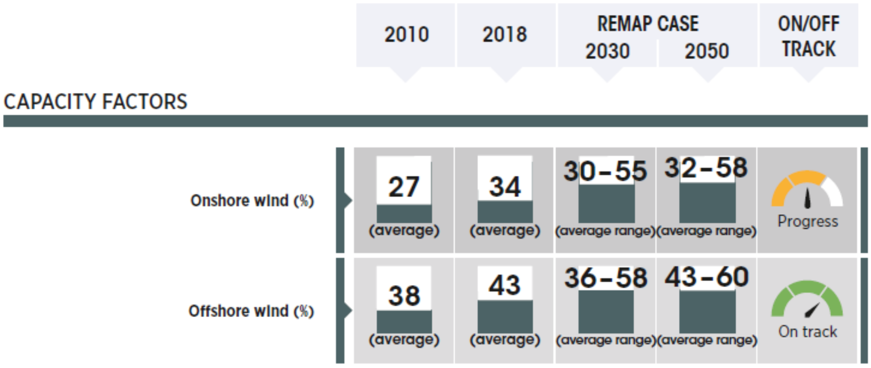
(b) The **levelised cost of electricity (LCOE)** for **onshore wind** will continue to fall from an average of USD 0.06 per kilowatt-hour (kWh) in 2018 to between USD 0.03 to 0.05/kWh by 2030 and between USD 0.02 to 0.03/kWh by 2050. The LCOE of offshore wind would drop from an average of USD 0.13/kWh in 2018 to an average between USD 0.05 to 0.09/kWh by 2030 and USD 0.03 to 0.07/kWh by 2050.

7. Ongoing **innovations** and **technology enhancements** towards larger capacity turbines as well as increased hub heights and rotor diameters help improve yields for the same location.

   - For **onshore wind plants**, global weighted average capacity factors would increase from 34% in 2018 to a range of 30% to 55% in 2030 and 32% to 58% in 2050.
   - For **offshore wind farms**, even higher progress would be achieved, with capacity factors in the range of 36% to 58% in 2030 and 43% to 60% in 2050, compared to an average of 43% in 2018.

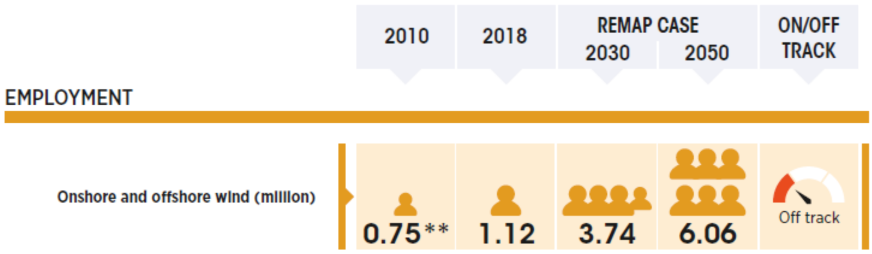
8. Technological developments in **wind turbine foundations** are a key factor enabling the accelerated deployment of offshore wind permitting access to better wind resources. By 2030, industry experts estimate that around 5 GW to 30 GW of floating offshore capacity

Figure 5.10: Wind capacity factors



Source: IRENA (2019a)

Figure 5.11: Wind employment



Source: IRENA (2019a)

could be installed worldwide and that, based on the pace of developments across various regions, floating wind farms could cover around 5% to 15% of the global offshore wind installed capacity (almost 1 000 GW) by 2050.

9. The wind industry can employ 3.74 million people by 2030 and more than 6 million people by 2050, a figure nearly three times higher and five times higher respectively than the 1.16 million jobs in 2018.

The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered. The LCOE is used to compare different methods of electricity generation on a consistent basis. The LCOE "represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generating plant during an assumed financial life and duty cycle." Inputs to LCOE are chosen by the estimator. They can include cost of capital, "fuel costs, fixed and variable operations and maintenance costs, financing costs, and an assumed utilization rate.

The LCOE is calculated as:

$$LCOE = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where,

- I_t: Investment expenditure in the year t.
- M_t: Operations and maintenance expenditures in the year t.
- F_t: Fuel expenditures in the year t.
- E_t: electrical energy generated in the year t.
- r: Discount rate
- n: Expected lifetime of system or power station.

For more information about the levelized cost of energy (LCOE) visit:

- Wikipedia (link).
- Energy Information Administration (link).

The **net capacity factor** is the unitless ratio of an actual electrical energy output over a given period of time to the maximum possible electrical energy output over that period. The capacity factor is defined for any electricity producing installation, such as a fuel consuming power plant or one using renewable energy, such as wind or the sun. The average capacity factor can also be defined for any class of such installations, and can be used to compare different types of electricity production.

The Danish offshore wind farm Horns Rev 2 has a nameplate capacity of 209.3 MW. As of January 2017 it has produced 6416 GWh since its commissioning 7 years ago, i.e. an average annual production of 875 GWh/year and a **capacity factor of**:

$$\frac{875.000 MW \cdot h}{(365\text{days })(24\text{hours/day})(209.3\text{MW})} = 0.477 = 47.7\% \tag{5.4}$$

Sites with lower capacity factors may be deemed feasible for wind farms, for example the onshore 1 GW Fosen Vind which as of 2017 is under construction in Norway has a projected capacity factor of 39%. Feasibility calculations may be affected by seasonality. For example in Finland, capacity factor during the cold winter months is more than double compared to July. While the annual average in Finland is 29.5%, the high demand for heating energy correlates with the higher capacity factor during the winter.

For more information about the capacity factor visit wikipedia (link).

The capacity factor of a wind turbine measures actual production relative to possible production, it is unrelated to **Betz's coefficient** of $16/27 \simeq 59.3\%$, which limits production vs. energy available in the wind.

Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. It was published in 1919 by the German physicist Albert Betz. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than $16/27 \simeq 59.3\%$ of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient. Practical utility-scale wind turbines achieve at peak $75-80\%$ of the Betz limit.

For more information about the capacity factor visit wikipedia (link).

5.6.2 Onshore wind outlook to 2050

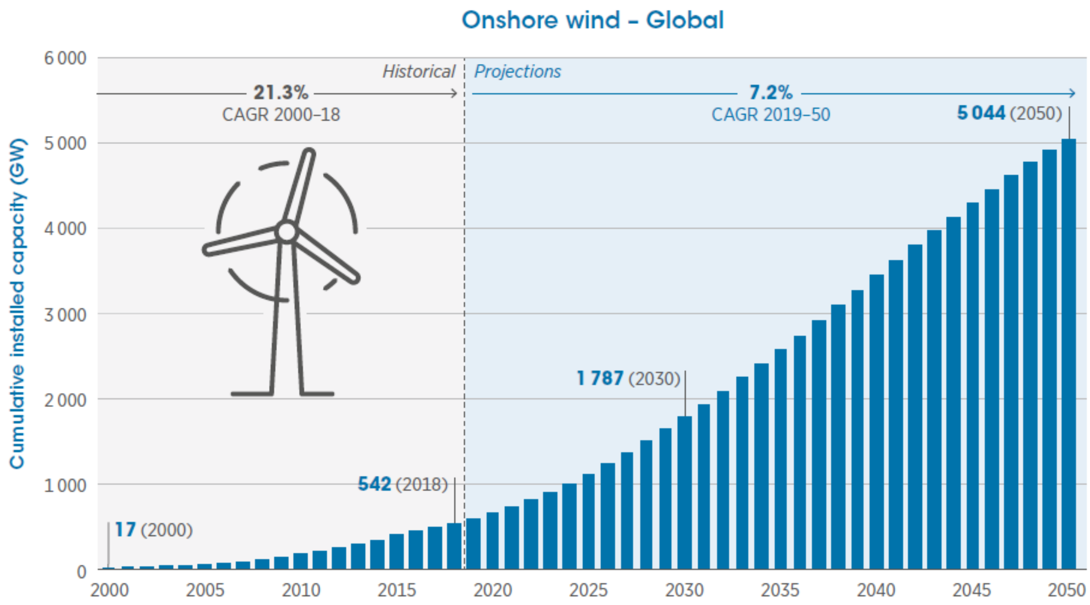
The global installed capacity of onshore wind power would increase three-fold by 2030 (to 1 787 GW) and ten-fold by 2050 (to 5 044 GW) compared to installations in 2018 (542 GW) (figure 5.12).

Deployment strategies by regions (countries)

Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050 (figure 5.13).

After Asia, significant onshore wind power deployments would occur in **North America** (mainly the US, at more than 850 GW), where the installed capacity would grow more than ten-fold from 2018 levels, reaching around 1 150 GW by 2050 (figure 5.13).

Figure 5.12: Onshore wind - Global



Source: IRENA (2019a)

Africa would be a key market for rapid onshore wind deployment in the next three decades installing onshore wind capacity of more than 500 GW by 2050 (figure 5.13).

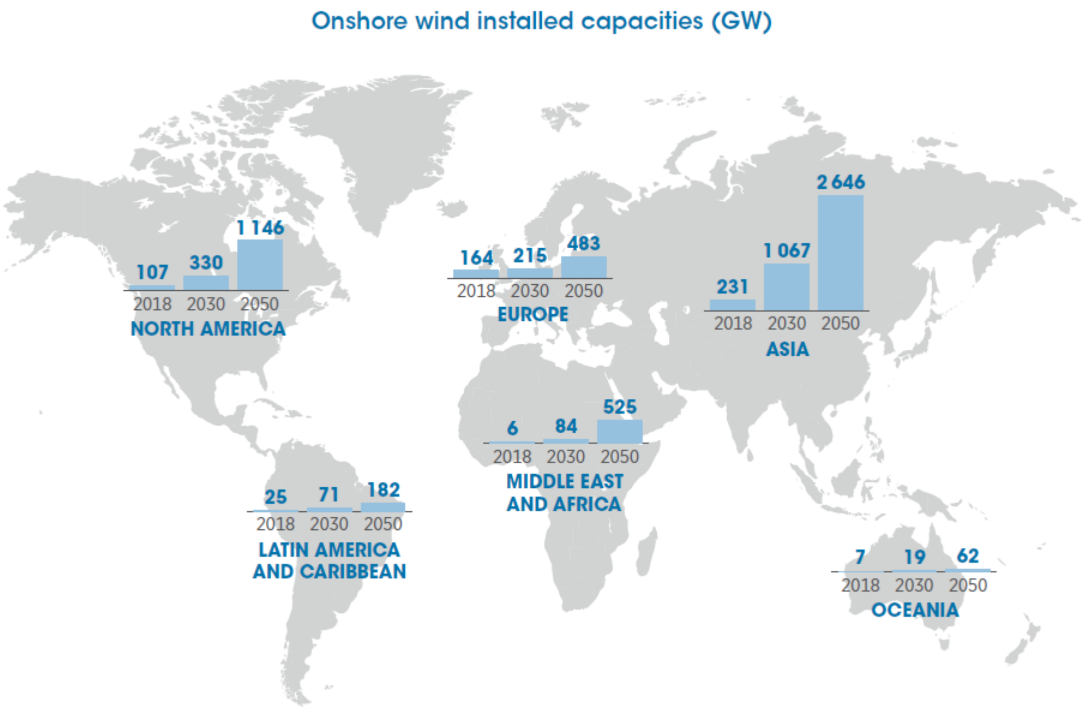
A detail analysis by regions (countries).

China: China's onshore wind installed capacity would grow from 205 GW in 2018 (CWEA, 2019) to almost 2 150 GW in 2050. This represents nearly a quarter of China's total land-based wind potential, which is estimated at around 8 800 GW considering an average wind turbine height of 80 metres (figure 5.14). In particular, China's northern regions have abundant onshore wind potential. The provinces of Qinghai, Xinjiang and Inner Mongolia, and the country's north east, have the highest power density (average values between 400 and 600 watts per square metre (W/m^2)),

The onshore wind installed capacity in the 3.5 million km^2 of land excluding protected areas, **US** would grow from 94 GW in 2018 to almost cities and water This massive potential is mostly 857 GW by 2050 (figure 5.15). According to the National concentrated in a central area of the country Renewable Energy Laboratory (NREL), the total land-based wind potential in the country is more than 10 000 GW, equivalent to almost 3.5 million km^2 of land excluding protected areas, cities and water This massive potential is mostly concentrated in a central area of the country from Minnesota/North-Dakota to Texas, which is likely to see the most deployment of future in land wind installations (NREL, 2018).

After China and the US, **Europe** is the third largest market for onshore wind in the coming three decades. The installed onshore capacity is expected to increase more than two-fold by 2050 compared to the 161 GW installed as of the end of 2018 (figure 5.16). The region's total land-based wind potential is an estimated 13 900 GW (EEA, 2009). The best sites for onshore installations are in northern and central continental Europe as well as in the UK (EEA, 2009).

Figure 5.13: Onshore world wind installed capacities (GW)



Source: IRENA (2019a)

Figure 5.14: Onshore wind China

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
8 800	2 150	24%

Source: IRENA (2019a)

Figure 5.15: Onshore wind US

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
10 000	857	8.5%

Source: IRENA (2019a)

Figure 5.16: Onshore wind Europe

TECHNICAL POTENTIAL [GW]	IRENA'S REMAP CASE BY 2050 [GW]	% OF TECHNICAL POTENTIAL
13 900	406	3%

Source: IRENA (2019a)

Cost reductions and capacity factore improvement

The breakthrough in renewable capacity additions over the past few years has been achieved largely because of the significant cost reductions in renewables driven by technology improvements, specialisation and standardisation, broader and more competitive supply chains, economies of scale, competitive procurement and a wide base of experienced, internationally active project developers. In particular, in production, a combination of improved **wind turbine technologies**, deployment of **higher hub heights** and **longer blades** with larger swept areas has led to increased capacity factors for a given wind resource. As a consequence, the total installation cost and the levelised cost of wind energy will decrease during the next three decades (figures 5.8 and 5.9).

Investment needs

Scaling up onshore wind investments is key to facilitate the uptake of the onshore wind market. In particular, global average annual onshore wind power investment needs to scaled up a factor of more than two until 2030 (USD 146 billion/year) and more than three over the remaining period to 2050 (USD 211 billion/year), compared to 2018 investment (USD 67 billion/year) (figure 5.7).

Ongoing and future innovations

1. **Wind turbine technology:** The key parameters that denote the improvements in wind turbine technologies are the rotor diameter and the hub height to access more power from wind turbines, even in areas with lower wind speeds. Larger rotors aid in decreasing specific power, which eventually boosts capacity factors and opens up low-wind areas to more wind. The maximum size of turbines added in 2018 was 4.3 MW, up from 3.3 MW in 2015 (figure 5.17). GE Renewable Energy is now offering improved onshore turbine technologies rated at 4.8 MW and 5.3 MW, respectively (Wind Power Monthly, 2018). Siemens-Gamesa presented its 5.8 MW, 170-metre rotor diameter model, which is larger than the largest offshore turbine currently available in the market (Vestas's V164 10 MW) (Wind Power Monthly, 2019).

2. **Optimised power electronics:** Optimising the power inverters reliability and dimensions could reduce turbine installation and operation costs.

3. **"Smart/Intelligent" wind turbines:** The digital revolution is affecting wind energy with new technologies for turbine monitoring and controls.

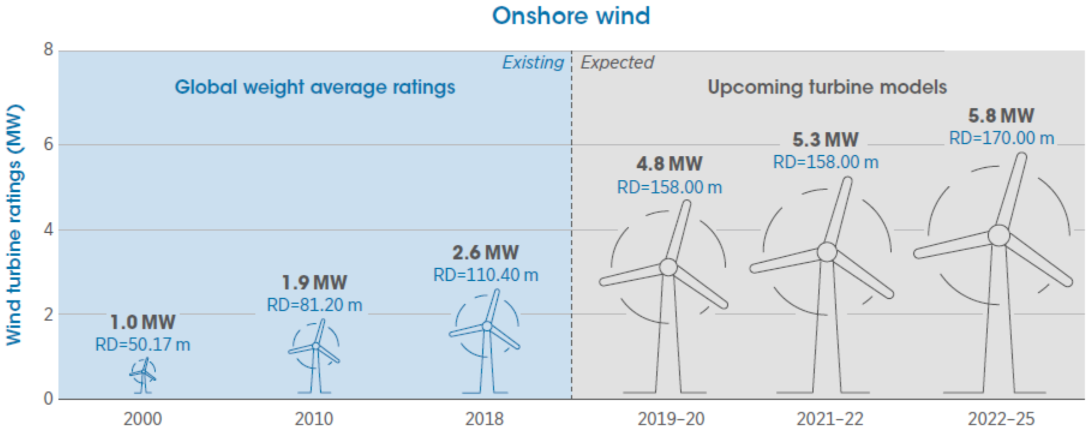
4. Recycling of materials: Currently, nearly 2.5 million tonnes of composite materials are in use in the wind energy sector (RECYCLING, 2019). In Europe alone, almost 12 000 wind turbines are expected to be decommissioned in the next five years (RECYCLING, 2019).

> For more information about market developments, legislation, technical issues, new products and technologies, management knowledge in the recycling sector visit the webpage of the RECYCLING Magazine (link).

5.6.3 Offshore wind outlook to 2050

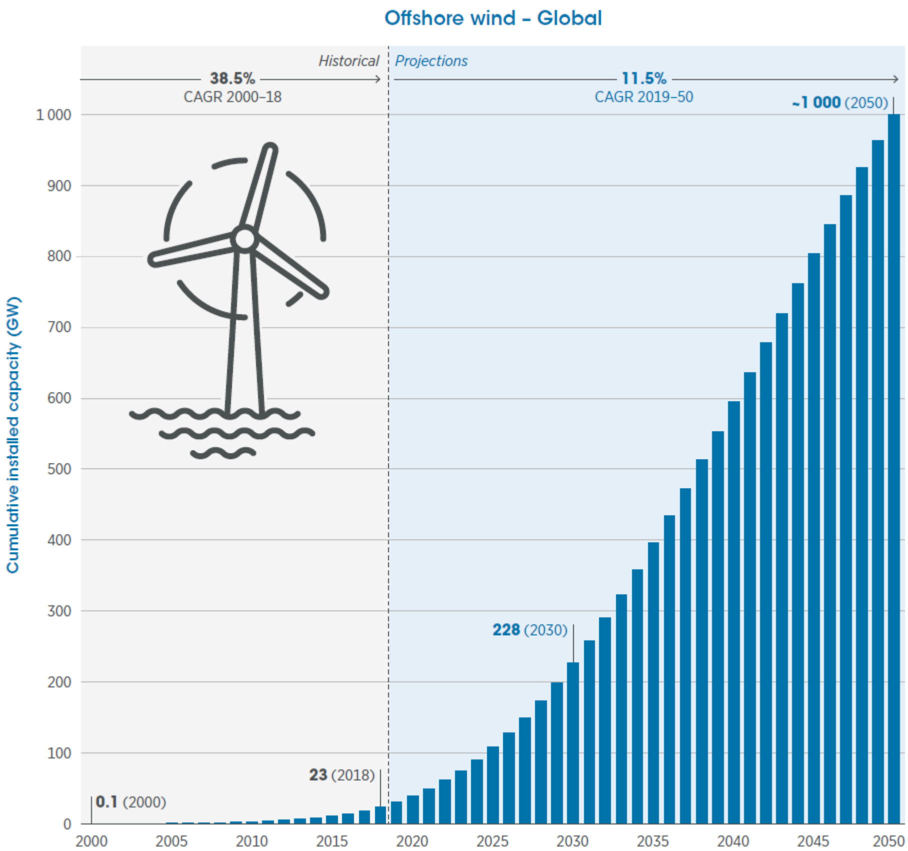
Global cumulative offshore wind capacity would increase almost ten-fold by 2030 (to 228 GW) and even more towards 2050, with total offshore installation nearing 1 000 GW by 2050 (figure 5.18).

Figure 5.17: Onshore wind turbines improvements



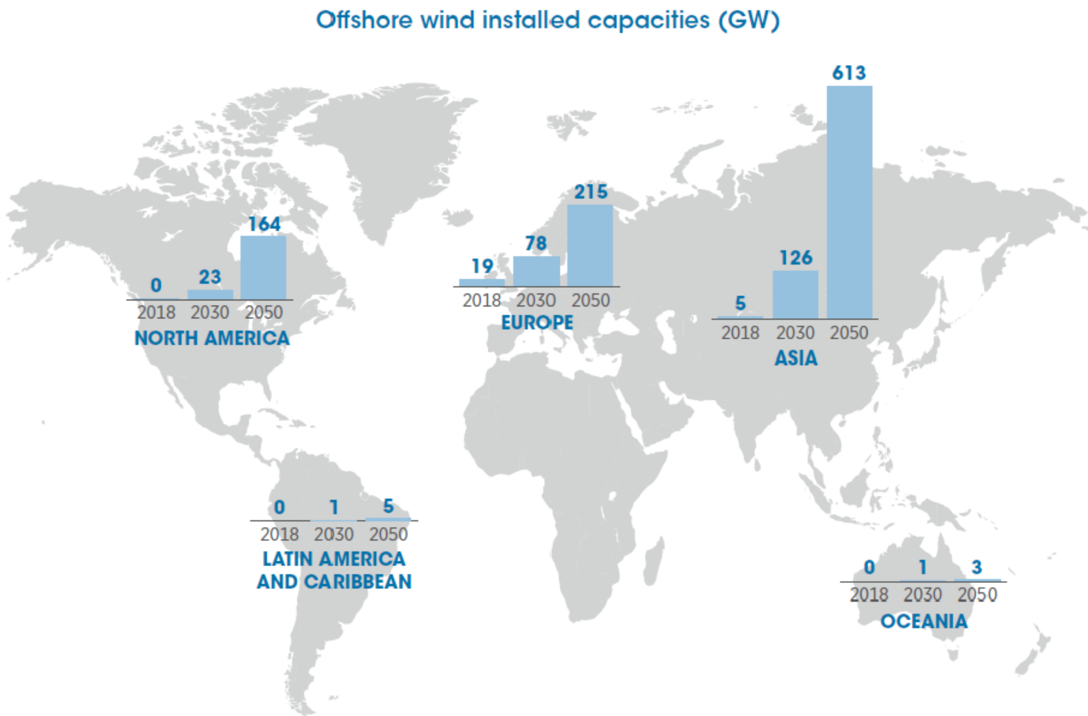
Source: IRENA (2019a)

Figure 5.18: Offshore wind - Global



Source: IRENA (2019a)

Figure 5.19: Offshore world wind installed capacities (GW)



Source: IRENA (2019a)

Deployment strategies by regions (countries)

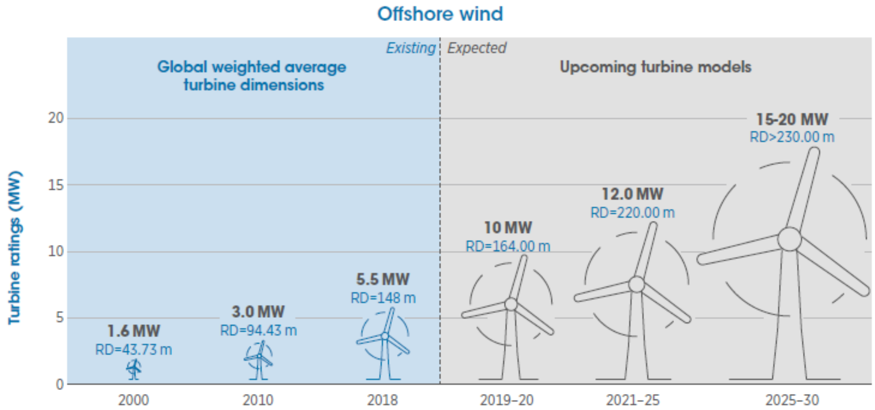
Moving forward, a prominent shift in deployment would happen in Asian waters (mostly in China, India, Chinese Taipei, the Republic of Korea, Japan, Indonesia, the Philippines and Viet Nam) in the next three decades. **Asia** would eventually dominate global offshore wind power installations with a total capacity exceeding 100 GW by 2030 and 600 GW by 2050 (figure 5.19). Within Asia, significant offshore wind deployment would occur in China, where the installed capacity would reach around 56 GW by 2030 and 382 GW by 2050.

China would dominate offshore wind installations, outpacing Europe in less than two decades from now. **Europe** would continue to dominate offshore wind installations for a decade or so, with total offshore wind capacity growing four-fold to 78 GW by 2030 and more than eleven-fold to 215 GW by 2050, compared to 19 GW in 2018 (figure 5.19). After Asia and Europe, **North America** would be another emerging offshore wind market. In the US, offshore wind installed capacity would grow more strongly, from less than 1 GW today to almost 23 GW by 2030 and 164 GW by 2050 (figure 5.19).

Cost reductions and capacity factors

The growth in turbine size helps to increase wind farm output. Larger turbines with greater swept areas yield higher capacity factors for the same resource quality. The cost reductions for offshore wind farms have been driven by technology improvements that have raised capacity factors, as well as by declines in total installed costs, operation and management costs and the cost of capital as project risk has declined. As a consequence, the total installation cost and the levelised cost of wind energy will decrease during the next three decades (figures 5.8 and 5.9).

Figure 5.20: Offshore wind turbines improvements



Source: IRENA (2019a)

Investment needs

Globally, investment in offshore wind would need to grow substantially over the next three decades, with overall cumulative investment of over USD 2 750 billion from now until 2050. In annual terms, global average annual offshore wind investment would need to increase more than three-fold from now until 2030 (USD 61 billion/year) and five-fold during the last two decades to 2050 (USD 100 billion/year) compared to investment in 2018 (USD 19.4 billion/year) (figure 5.7).

Ongoing and future innovations

Future generation turbines.

Developments in blade, drivetrain and control technologies, in particular, would enable the development of larger, more reliable turbines with higher capacity ratings. Turbine sizes have increased rapidly in recent decades and the technological changes make that the turbine size will increase even more in the next years (figure 5.20).

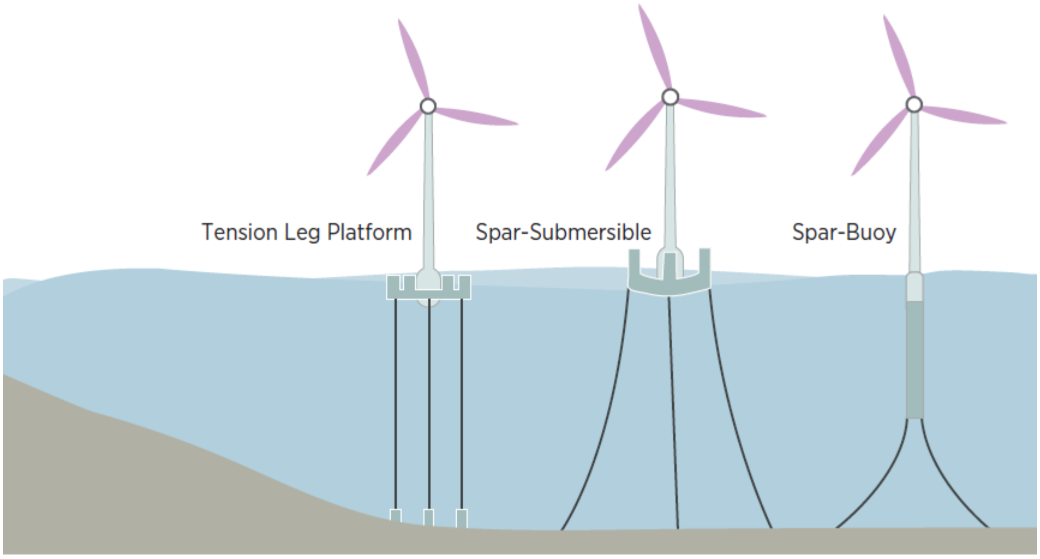
Floating foundations.

Technological developments in wind turbine foundations are one of the key factors enabling the accelerated deployment of offshore wind, permitting access to better wind resources. Turbines are now routinely being installed in water depths of up to 40 metres and as far as 80 kilometres from shore. These turbines, rooted in the seabed by monopile or jacket foundations, are currently restricted to waters less than 60 metres deep. This is a major limitation, as some of the largest potential markets for offshore wind, such as Japan and the US, have few shallow-water sites.

In such cases, floating foundations may be a better choice. Floating wind farms are one of the most exciting developments in ocean energy technologies. Floating foundations offer the offshore wind industry **three important opportunities**:

1. They allow access to sites with water deeper than 60 metres.
2. They ease turbine set-up, even for mid-depth conditions (30–50 metres) and may in time offer a lower-cost alternative to fixed foundations.

Figure 5.21: Offshore wind turbine foundation technologies



Source: IRENA (2019a)

3. Floating foundations generally offer environmental benefits compared with fixed-bottom designs due to less-invasive activity on the seabed during installation.

Three main designs are under development and have been tested: spar-buoys, spar-submersibles and tension-leg platforms (figure 5.21).

The ability of floating offshore wind turbines to unlock areas of deep water close to shore and large population centres, notably in Japan and the US, could greatly expand offshore wind deployment. Floating technologies can also be applied intensively in south-east Asia, Oceania and Northern Europe. Floating foundations therefore are potentially a "game-changing" technology to effectively exploit abundant wind potential in deeper waters and thus are leading the way for rapid future growth in the offshore wind power market.

Integrated turbine and foundation installation.

Most offshore installation operations can be eliminated through the development of technologies and processes that enable assembling and precommissioning of wind turbines in a harbour followed by installation of the complete, integrated turbine (including rotor, tower and foundation) in a single operation offshore.

Commercialisation is anticipated around 2025, but technology developments would need to continue to meet the needs of larger turbines.

HVDC technology.

For projects far offshore, high-voltage direct current (HVDC) transmission is preferable to high-voltage alternating current (HVAC) transmission in order to overcome the reactive resistance (capacitance) caused by the export cables in a long grid connection (offshore and onshore).

Today, HVDC infrastructure is used to connect two points, but it cannot be used to create a multi-nodal network. However, commercialisation of HVDC infrastructure for wind farms is under way, with point-to-point grid connections used on a few projects in European waters.

Direct current (DC).

Direct current (DC) is the one directional or unidirectional flow of electric charge. An electrochemical cell is a prime example of DC power. Direct current may flow through a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current (AC).

Alternating current (AC).

Alternating current (AC) is an electric current which periodically reverses direction and changes its magnitude continuously with time in contrast to direct current (DC) which flows only in one direction. Alternating current is the form in which electric power is delivered to businesses and residences.

Transmission, distribution, and domestic power supply.

Electrical energy is distributed as alternating current because AC voltage may be increased or decreased with a transformer. This allows the power to be transmitted through power lines efficiently at high voltage, which reduces the energy lost as heat due to resistance of the wire, and transformed to a lower, safer, voltage for use. Use of a higher voltage leads to significantly more efficient transmission of power. The power losses (P_w) in the wire are a product of the square of the current (I) and the resistance (R) of the wire, described by the formula:

$$P_w = I^2 R$$

This means that when transmitting a fixed power on a given wire, if the current is halved (i.e. the voltage is doubled), the power loss due to the wire's resistance will be reduced to one quarter.

The power transmitted is equal to the product of the current and the voltage (assuming no phase difference); that is,

$$P_t = IV$$

Consequently, power transmitted at a higher voltage requires less loss-producing current than for the same power at a lower voltage. Power is often transmitted at hundreds of kilovolts on pylons, and transformed down to tens of kilovolts to be transmitted on lower level lines, and finally transformed down to 100 V – 240 V for domestic use.

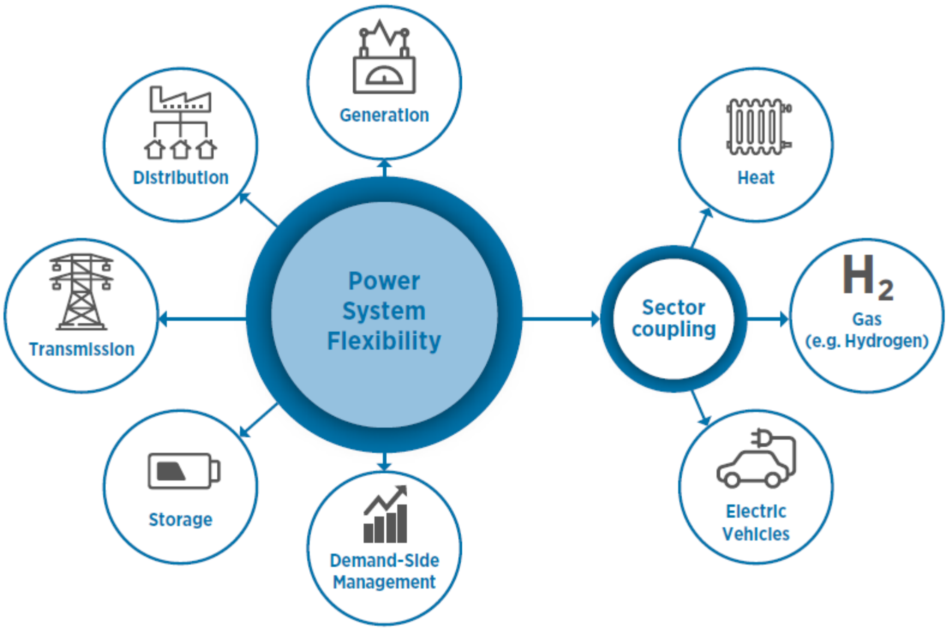
High-Voltage Direct Current (HVDC).

A **high-voltage, direct current (HVDC)** electric power transmission system (also called a power superhighway or an electrical superhighway) uses direct current (DC) for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems.

Most HVDC links use voltages between 100 kV and 800 kV. A 1,100 kV link in China was completed in 2019 over a distance of 3,300 km with a power of 12 GW. With this dimension, intercontinental connections become possible which could help to deal with the fluctuations of wind power and photovoltaics.

For more information about power electronics visit EEPOWER textbook (link), or the Wikipedia.

Figure 5.22: Power system flexibility enablers in the energy sector



Source: IRENA (2019a)

5.6.4 Power system flexibility to integrate rising shares of variable renewable energy

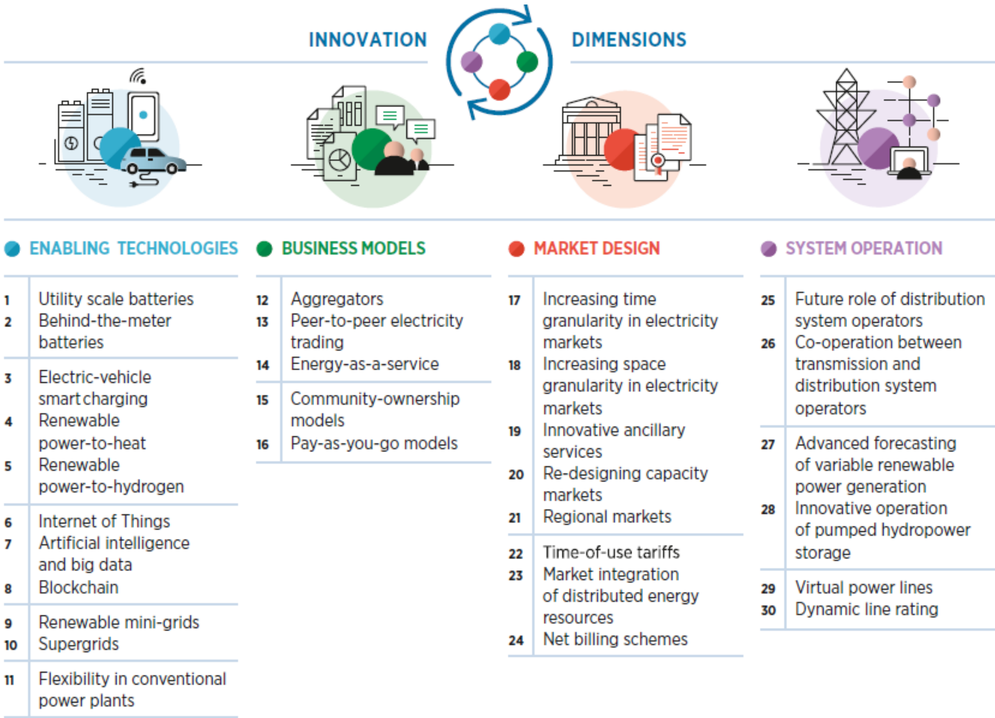
To effectively manage large-scale variable renewable electricity (VRE), flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (**demand-side management** and **sector coupling**) (IRENA, 2018) (figure 5.22).

In conventional power systems, **flexibility has been provided mainly by generation**, with dispatchable generators adjusting their output to follow demand and, if available, pumped hydropower dealing with inflexible baseload and reducing the need for power plants to cover peak demand. Important progress has been made in recent years towards increasing the flexibility of conventional power plants, as the demand side was largely unresponsive and provided very little flexibility. Emerging innovations are not only further increasing flexibility on the supply side but are now also widening the availability of flexibility to all segments of the power system, including grids and the demand side (IRENA, 2018).

Electric vehicles (EV) lead the way to unleash synergies between low-carbon transport modes and renewable electricity generation, contributing to sector coupling. The EV fleet could be used as an electricity storage option contributing to improved flexibility of power systems with raising shares of variable renewable sources. If unleashed starting today, the use of EVs as a flexibility resource especially via smart charging approaches would reduce the need for additional investment in flexible, but carbon-intensive, fossil-fuel power plants to balance the system with renewables (IRENA, 2019b).

Hydrogen contributes to "Sector Coupling" between the electricity system and industry, buildings and transport, increasing the level of flexibility while facilitating the integration of VRE into the power system. The gas grid can also be decarbonised via renewable hydrogen by taking advantage of low electricity prices, providing seasonal storage for solar and wind, and

Figure 5.23: The four dimensions of innovation



Source: IRENA (2019a)

providing grid services from electrolysers. The deployment of hydrogen requires specific efforts such as targeted applications, dedicated supply system and conversion pathways (IRENA, 2019d).

For more information about power system flexibility enablers and clustering with other low-carbon technologies hybrid systems visit the experience of the Danish island of Bornholm (link).

5.6.5 Innovation landscape to integrate high shares of variable renewable energy

IRENA's work confirms that there is no single game-changing innovation. No innovation, in isolation, may have a significant impact, but rather it needs to be accompanied by innovations in all segments of the power sector. IRENA has investigated the landscape of abundant innovations that can facilitate the integration of high shares of VRE into the power system, identifying and clustering 30 transformative innovations across four dimensions: enabling technologies, business models, market design and system operation (IRENA, 2019c) (figure 5.23).

Enabling technologies: Battery storage, demand-side management and digital technologies are changing the power sector, opening doors to new applications that unlock system flexibility. Electrification of end-use sectors is emerging as a new market for renewables but could also provide additional ways of flexing demand, if applied in a smart way.

Business models: Innovative business models are key to monetising the new value created by these technologies and therefore enable their uptake. At the consumer end, numerous innovative business models are emerging, alongside innovative schemes that enable renewable electricity supply in places with limited options, such as offgrid or densely populated areas.

Market design: Adapting market design to the changing paradigm – towards low-carbon power systems with high shares of VRE – is crucial for enabling value creation and adequate revenue streams.

System operation: With new technologies and sound market design in place, innovations in system operation are also needed and are emerging in response to the integration of higher shares of VRE in the grid. These include innovations that accommodate uncertainty and the innovative operation of the system to integrate distributed energy resources.

5.7 Some questions to summarize the chapter

1. Can you explain briefly how the wind turbines **transform wind into electricity**?

Wind first hits a turbine's blades, causing them to rotate and turn the turbine connected to them. That changes the **kinetic energy to rotational energy**, by moving a shaft which is connected to a generator, and thereby producing electrical energy through **electromagnetism**.

The amount of power that can be harvested from wind depends on the **size of the turbine** and the **length of its blades**.

The output is proportional to the **dimensions of the rotor** and to the **cube of the wind speed**.

Theoretically, when **wind speed doubles**, wind **power potential increases by a factor of eight**.

An useful video to know more about **wind turbines**: How do wind turbines work: (link)
More information about **wind turbine generators** can be found in the Alternative Energy Tutorials webpage (link).

2. Can you formulate **mathematically** the concept of wind energy?

Mathematically, total **wind energy** flowing through an imaginary surface with area A during the time t is:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3$$

where ρ is the density of air;
v is the wind speed; Avt is the volume of air passing through A (which is considered perpendicular to the direction of the wind);
$Avt\rho$ **is therefore the mass** m **passing through** A

$\frac{1}{2}\rho v^2$ is the kinetic energy of the moving air per unit volume

3. Can you formulate **mathematically** the concept of power from wind energy?

Power is energy per unit time, so the wind power incident on A (e.g. equal to the rotor area of a wind turbine) is:

$$P = \frac{E}{t} = \frac{1}{2} A \rho v^3$$

4. Can you formulate **mathematically** the concept of energy?

Energy:

As energy is defined via work, the International System of Units unit of energy is the same as the unit of work – the **joule (J)**, named in honor of James Prescott Joule and his experiments on the mechanical equivalenta of heat. In slightly more fundamental terms, **1 joule is equal to 1 newton metre** and, in terms of International System of Units base units:

$$1J = \left(1kg\frac{m}{s^2}\right) m = 1kg \left(\frac{m}{s}\right)^2 = 1\frac{kg \cdot m^2}{s^2}$$

5. Can you formulate **mathematically** the concept of power in electricity?

Electricity is measured in Watts and kilowatts:

Electricity is measured in **units of power** called Watts, named to honor James Watt, the inventor of the steam engine. A Watt is the unit of electrical power equal to **one ampere under the pressure of one volt**.

6. In which amount **carbon emissions** will decrease due to wind energy?

Wind power when coupled with deep electrification would contribute to more than one-quarter of the total emissions reductions needed **(nearly 6.3 gigatonnes of carbon dioxide (Gt CO2) annually) in 2050**

7. Which should be the **share of wind production in 2050** to satisfy the Paris Agreement?

35% of the electricity needs to be produced with wind energy

8. Which should be the **wind production capacity** in 2050 to satisfy the Paris Agreement?

The global cumulative installed capacity of **onshore wind power** should increase more than three fold by 2030 (to 1 787 gigawatts (GW)) and nine-fold by 2050 (to 5 044 GW) compared to installed capacity in 2018 (542 GW)

For **offshore wind power**, the global cumulative installed capacity would increase almost ten-fold by 2030 (to 228 GW) and substantially towards 2050, with total offshore installation nearing 1 000 GW by 2050

9. Which should be the **wind capacity additions** in 2050 to satisfy the Paris Agreement?

Annual capacity additions for onshore wind would increase more than four-fold, to more than 200 GW per year in the next 20 years, compared to 45 GW added in 2018

Even higher growth would be required in **annual offshore wind capacity additions** – around a ten-fold increase, to 45 GW per year by 2050 from 4.5 GW added in 2018

10. At a regional level. Which will be the **investment trends in wind energy**?

Onshore wind at a regional level

Asia – mainly China (at more than 2 000 GW) and India (at more than 300 GW) – would continue to lead global onshore wind power installations, with the region accounting for more than half (2 656 GW) of the total global capacity by 2050.

After Asia, significant onshore wind power deployments would occur in **North America** (mainly the US, at more than 850 GW), where the installed capacity would grow more than ten-fold from 2018 levels, reaching around 1 150 GW by 2050.

Africa would be a key market for rapid onshore wind deployment in the next three decades installing onshore wind capacity of more than 500 GW by 2050.

Offshore wind at a regional level

Asia would eventually dominate global offshore wind power installations with a total capacity exceeding 100 GW by 2030 and 600 GW by 2050.

China would dominate offshore wind installations, outpacing Europe in less than two decades from now

Europe would continue to dominate offshore wind installations for a decade or so, with total offshore wind capacity growing four-fold to 78 GW by 2030 and more than eleven-fold to 215 GW by 2050, compared to 19 GW in 2018.

After Asia and Europe, **North America** would be another emerging offshore wind market. In the US, offshore wind installed capacity would grow more strongly, from less than 1 GW today to almost 23 GW by 2030 and 164 GW by 2050.

11. Which should the aggregate **investment trends in wind energy**?

Investments in **Onshore wind** power should increase by more than two-fold from now until 2030 (USD 146 billion/year) and more than three-fold over the remaining period to 2050 (USD 211 billion/year) compared to 2018 investments (USD 67 billion/year).

For **offshore wind**, global average annual investments would need to increase three-fold from now until 2030 (USD 61 billion/year) and more than five-fold over the remaining period to 2050 (USD 100 billion/year) compared to 2018 investments (USD 19 billion/year).

12. Which will be the evolution of **total wind installation cost**?

The **total installation cost** of **onshore wind projects** would continue to decline in the next three decades with the average cost falling in the range of USD 800 to 1 350 per kilowatt (kW) by 2030 and USD 650 to 1 000/ kW by 2050, compared to the global-weighted average of USD 1 497/kW in 2018.

For **offshore wind projects**, the average total installation cost would further drop in coming decades to between USD 1 700 and 3 200/kW by 2030 and between USD 1 400 and 2 800/kW by 2050 (figure, next slide).

13. Which will be the evolution of **levelised cost of electricity for wind energy**?

The **levelised cost of electricity (LCOE)** for **onshore wind** will continue to fall from an average of USD 0.06 per kilowatt-hour (kWh) in 2018 to between USD 0.03 to 0.05/kWh by 2030 and between USD 0.02 to 0.03/kWh by 2050.

The LCOE of **offshore wind** would drop from an average of USD 0.13/kWh in 2018 to an average between USD 0.05 to 0.09/kWh by 2030 and USD 0.03 to 0.07/kWh by 2050.

14. Which will be the evolution of **wind capacity factors**?

Ongoing **innovations** and **technology enhancements** towards larger capacity turbines as well as increased hub heights and rotor diameters help improve yields for the same location.

- For **onshore wind plants**, global weighted average capacity factors would increase from 34% in 2018 to a range of 30% to 55% in 2030 and 32% to 58% in 2050
- For **offshore wind farms**, even higher progress would be achieved, with capacity factors in the range of 36% to 58% in 2030 and 43% to 60% in 2050, compared to an average of 43% in 2018

15. Can you define the **levelized cost of energy**?

The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime

The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered

16. Can you define the **capacity factor of energy**?

The **net capacity factor** is the unitless **ratio** of an **actual electrical energy output over a given period of time** to the **maximum possible electrical energy output over that period**

The capacity factor is defined for any electricity producing installation, such as a fuel consuming power plant or one using renewable energy, such as wind or the sun

The average capacity factor can also be defined for any class of such installations, and can be used to compare different types of electricity production.

17. Can you define the **the Betz' coefficient**?

The capacity factor of a wind turbine measures actual production relative to possible production, it is unrelated to **Betz's coefficient** of $16/27 \simeq 59.3\%$, which limits production vs. energy available in the wind.

Betz's law indicates the maximum **power that can be extracted from the wind**, independent of the design of a wind turbine in open flow

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Chapter 6

Sustainable energy. Solar Energy

6.1 Introduction

In this chapter we study the main characteristics of solar energy. We study the main features of solar energy and solar panels, and we analyze the future development of this technology. The chapter is organized as follows:

1. Watch a video to **discuss** some important aspects of wind energy.
2. Review the **history**, **evolution** and **types** of solar energy.
3. Study solar panels **technology**, solar cell efficiency and the architecture of solar panels at home.
4. Analyze the **key trends** in solar energy: Materials and modules; applications; operation and maintenance; end-of-life management.
5. **Questions** to summarize the chapter

6.2 Discussion

To motivate the chapter, we start by watching the video The Rise Of Solar Power

Based on that video, we discuss the next questions:

1. Which has been the **main driver** of the increase of solar energy in the last decade?
2. The video proposes **three sizes of solar installations**: Solar installations in houses, big-size installations and mid-size installations. Can you explain some of the advantages and disadvantages of each type of installation?
3. According with the video **big companies as Facebook or Apple** could play a crucial role fostering the investments in solar energy. Could you explain why?
4. According with the video, solar energy + storage could be more profitable than gas power plants. Which should be the **proportion of storage capacity over solar production** to make that solar energy becomes more profitable than gas power plants?

6.3 Solar Energy

This section is based in the information from three main sources:

- Solar Energy Industries Association.
- National Renewable Energy Laboratory (NREL).
- Solar Energy (wikipedia).

6.3.1 Introduction

Solar energy is radiant light and heat from the sun that is harnessed using a range of ever-evolving technologies such as **solar heating**, **photovoltaics**, **solar thermal energy**, **solar architecture**, **molten salt power plants** and **artificial photosynthesis**.

It is an essential source of renewable energy, and its technologies are broadly characterized as either **passive solar** or **active solar** depending on how they capture and distribute solar energy or convert it into solar power.

- **Active solar** techniques include the use of photovoltaic systems, concentrated solar power, and solar water heating to harness the energy.
- **Passive solar** techniques include orienting a building to the Sun, selecting materials with favorable thermal mass or light-dispersing properties, and designing spaces that naturally circulate air.

6.3.2 History

In 1878, at the Universal Exposition in Paris, Augustin Mouchot successfully demonstrated a **solar steam engine**, but couldn't continue development because of cheap coal and other factors.

In 1897, Frank Shuman, a US inventor, engineer and solar energy pioneer built a small demonstration solar engine that worked by reflecting solar energy onto square boxes filled with **ether**, which has a lower boiling point than water and were fitted internally with black pipes which in turn powered a steam engine. In 1908 Shuman formed the Sun Power Company with the intent of building larger solar power plants. He, along with his technical advisor A.S.E. Ackermann and British physicist Sir Charles Vernon Boys, developed an improved system using mirrors to reflect solar energy upon collector boxes, increasing heating capacity to the extent that water could now be used instead of ether. Shuman then constructed a full-scale steam engine powered by **low-pressure water**, enabling him to patent the entire solar engine system by 1912.

Shuman built the world's first solar thermal power station in Maadi, Egypt, between 1912 and 1913. His plant used parabolic troughs to power a 45–52 kilowatts engine that pumped more than 22,000 litres of water per minute from the Nile River to adjacent cotton fields. Although the outbreak of World War I and the discovery of cheap oil in the 1930s discouraged the advancement of solar energy, Shuman's vision, and basic design were resurrected in the 1970s with a new wave of interest in solar thermal energy.

6.3.3 Potential. Global Solar Atlas

The Earth receives 174 petawatts (PW) of incoming solar radiation (insolation) at the upper atmosphere.Approximately 30% is reflected back to space while the rest is absorbed by clouds, oceans and land masses. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. Most of the world's population live in areas with **insolation levels** of 150–300 watts/m2, or 3.5–7.0 kWh/m2 per day.

The total solar energy absorbed by Earth's atmosphere, oceans and land masses is approximately 3,850,000 exajoules (EJ) per year. This is more energy in **one hour** than the world used in one year.

Photosynthesis captures approximately 3,000 EJ per year in biomass. The amount of solar energy reaching the surface of the planet is so vast that in **one year** it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined.

The potential solar energy that could be used by humans differs from the amount of solar energy present near the surface of the planet because factors such as geography, time variation, cloud cover, and the land available to humans limit the amount of solar energy that we can acquire.

The World Bank and the International Finance Corporation, collectively The World Bank Group, have provided the **Global Solar Atlas** in addition to a series of global, regional and country data layers and poster maps, to support the scale-up of solar power in their client countries. This work is funded by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank and supported by 13 official bilateral donors. It is part of a global ESMAP initiative on Renewable Energy Resource Mapping that includes **biomass**, **small hydro**, **solar** and **wind**.

More information about Global Solar Atlas in their official webpage (link)

In World Bank (2020) can be found complete report about solar energy at a country level.

6.3.4 Solar energy production technologies

Solar thermal collector

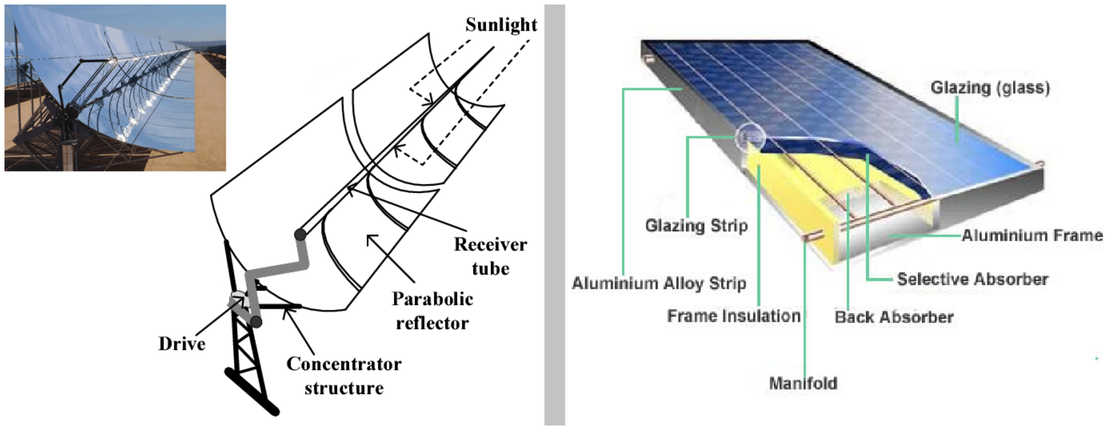
A solar thermal collector collects heat by absorbing sunlight. The term "solar collector" commonly refers to a device for solar **hot water heating**, but may refer to large power generating installations such as solar parabolic troughs and solar towers or non water heating devices such as solar air heaters.

Solar thermal collectors are either **non-concentrating** or **concentrating**.

- In **non-concentrating collectors**, the aperture area (i.e., the area that receives the solar radiation) is roughly the same as the absorber area (i.e., the area absorbing the radiation). A common example of such a system is a metal plate that is painted a dark color to maximize the absorption of sunlight. The energy is then collected by cooling the plate with a working fluid, often water or glycol running in pipes attached to the plate (right-hand side, figure 6.1).

- **Concentrating collectors** have a much larger aperture than the absorber area. The aperture is typically in the form of a mirror that is focussed on the absorber, which in most cases are the pipes carrying the working fluid. Due to the movement of the sun during the day, concentrating collectors often require some form of solar tracking system, and are sometimes referred to "active" collectors for this reason (left-hand side, figure 6.1).

Figure 6.1: Solar thermal collectors



Non-concentrating collectors are typically used in residential and commercial buildings for space heating, while **concentrating collectors** in concentrated solar power plants generate electricity by heating a heat-transfer fluid to drive a turbine connected to an electrical generator.

More information about solar thermal collectors in the **solar thermal collector webpage** (wikipedia).

Photovoltaics

Photovoltaics (PV) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. The photovoltaic effect is commercially utilized for electricity generation and as photosensors.

A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop mounted, wall mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky.

PV has become the cheapest source of electrical power in regions with a high solar potential, with price bids as low as 0.01567 US/kWh in 2020. Panel prices have dropped by the factor of 10 within a decade.

We analyze in detail photovoltaic energy in section 6.4.

Solar thermal energy

Solar thermal energy (STE) is a form of energy and a technology for harnessing solar energy to generate thermal energy for use in industry, and in the residential and commercial sectors.

Solar thermal collectors are classified by the United States Energy Information Administration as low-, medium-, or high-temperature collectors. Low-temperature collectors are generally unglazed and used to heat swimming pools or to heat ventilation air. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use.

High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric

Figure 6.2: Concentrated Solar Power

power production. Two categories include Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries, and Concentrated Solar Power (CSP) when the heat collected is used for power generation (figure 6.2).

> More information about solar thermal energy in the **Concentrating Solar Power webpage** (The National Renewable Energy Laboratory (NREL)).

Solar architecture

Solar architecture is an architectural approach that takes in account the Sun to harness clean and renewable solar power. It is related to the fields of optics, thermics, electronics and materials science. Both active and passive solar housing skills are involved in solar architecture.

The use of flexible thin-film photovoltaic modules provides fluid integration with steel roofing profiles, enhancing the building's design. Orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air also constitute solar architecture.

Initial development of solar architecture has been limited by the rigidity and weight of standard solar power panels. The continued development of photovoltaic (PV) thin film solar has provided a lightweight yet robust vehicle to harness solar energy to reduce a building's impact on the environment.

> More information about solar architecture in the **solar architecture webpage** (wikipedia)

6.4 Solar panels

6.4.1 History solar cells.

In **1839**, the ability of some materials to create an electrical charge from light exposure was first observed by Alexandre-Edmond Becquerel. Though the premiere solar panels were too inefficient for even simple electric devices they were used as an instrument to measure light. The observation by Becquerel was not replicated again until **1873**, when Willoughby Smith discovered that the charge could be caused by light hitting selenium. After this discovery, William Grylls Adams and Richard Evans Day published "The action of light on selenium" in **1876**, describing the experiment they used to replicate Smith's results.

In **1881**, Charles Fritts created the first commercial solar panel, which was reported by Fritts as "continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight." However, these solar panels were very inefficient, especially compared to coal-fired power plants. In **1939**, Russell Ohl created the solar cell design that is used in many modern solar panels. He patented his design in 1941. In **1954**, this design was first used by Bell Labs to create the first commercially viable silicon solar cell. In **1957**, Mohamed M. Atalla developed the process of silicon surface passivation by thermal oxidation at Bell Labs. The surface passivation process has since been critical to solar cell efficiency.

6.4.2 How does solar energy work?

Photovoltaic modules use light energy (photons) from the Sun to generate electricity through the photovoltaic effect. Most modules use wafer-based crystalline silicon cells or thin-film cells. The structural (load carrying) member of a module can be either the top layer or the back layer. Cells must be protected from mechanical damage and moisture. Most modules are rigid, but semi-flexible ones based on thin-film cells are also available. The cells are connected electrically in series, one to another to the desired voltage, and then in parallel to increase amperage. The wattage of the module is the mathematical product of the voltage and the amperage of the module. The manufacture specifications on solar panels are obtained under standard condition which is not the real operating condition the solar panels are exposed to on the installation site.

A PV junction box is attached to the back of the solar panel and functions as its output interface. External connections for most photovoltaic modules use MC4 connectors to facilitate easy weatherproof connections to the rest of the system. A USB power interface can also be used.

Module electrical connections are made in series to achieve a desired output voltage or in parallel to provide a desired current capability (amperes) of the solar panel or the PV system. The conducting wires that take the current off the modules are sized according to the ampacity and may contain silver, copper or other non-magnetic conductive transition metals.

To understand how solar panels (and batteries) work, it is important to understand how electricity works, and to be familiar with the concepts of volts, amperes and watts. We explain both concepts in the next box:

1. **What is electricity?** For more information about electricity in the video (What is electricity? - Electricity Explained - (1)).

Based on the video, answer the next questions:

1. Can you explain which particles are in the **nucleus** of an element? An in the **orbit**?
2. Can the same element have a different number of **neutrons**? And **electrons**?
3. What does mean that an atom is **positively charged**? and **negatively charged**? How this is related to **electricity**?

2. To complete our understanding about how does electricity work, it is important to be familiar with the concepts of **volts, amperes and watts**. The next three videos provide intuitive explanations of those concepts:

- Electricity Explained: Volts, Amps, Watts, Fuse Sizing, Wire Gauge, AC/DC, Solar Power and more!
- What are VOLTs, OHMs and AMPs?
- What is an amp? - Electricity Explained - (2)

Based on the videos, answer the next questions:

1. Can you define the concept of **volt**? This is related with the concept of **pressure**
2. Can you define the concept of **ampere**? This is related with the concept of **wideness** of the wire
3. Can you define the concept of **watt**? This is related with the concept of **volume** of electricity
4. Can you define the concept of **ohm**? This is related with the concept of **resistance** of an electricity system
5. Why these concepts are **important**? these concepts are related to the **transport** of electricity (DC/AC); the **compatibility** of different systems; the **structure** of solar plants, wind farms...

3. How is electricity **transported**? Difference between Direct Current and Alternate Current (**DC/AC**). Edison vs. Tesla: link.

Based in the information from the previous box, we can explain how do **solar cells** and **solar panels** work:

4. To understand how **solar cells** and **solar panels** works, we use the next two videos:

- How do Solar cells work?
- How do solar panels work? - Richard Komp

Based on the previous videos and boxes, we explain the **photovoltaic process**:

1. Initially, the silicon atoms are in balance.

2. Electrons are injected in one layer of the silicon cell (**N-type doping**). some electrons are free to move (randomly).
3. Boron with three valance electrons are injected in the opposite layer of the silicon cell (**P-type doping**). There will be a free hole for each atom.
4. By placing together the N-type and the P-type layers is generated a **depletion region** with no free electrons.
5. **Photons enter in the depletion region** making that electrons move to the N-type layer and holes move to the P-type region. An electric field is created.
6. By **connecting the extremes of the two layers** by using a wire, an electric current is formed.
7. The **performance** of the electric cell **can be increased** by:
    a. Making the N-layer thin and heavily doped.
    b. Making the P-layer thick and poorly doped.
    c. The depletion region becomes thicker and that increase the electron-hole pairs increasing the electric field.
8. Solar panels can be connected by suing **parallel or series circuits**. This is related to the concepts of volts, amps, and watts and have important implications in the design of solar farms.
9. There are two types of solar cells depending on the alignment of silicon atoms: **Polycrystalline** and **monocrystalline**. Monocrystalline silicon cells perform better, but are more expensive.

6.4.3 Solar cell efficiency

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.

The efficiency of the solar cells used in a photovoltaic system, in combination with latitude and climate, determines the annual energy output of the system. For example, a solar panel with 20% efficiency and an area of 1 m2 will produce 200 kWh/yr at Standard Test Conditions if exposed to the Standard Test Condition solar irradiance value of 1000 W/m2 for 2.74 hours a day. Usually solar panels are exposed to sunlight for longer than this in a given day, but the solar irradiance is less than 1000 W/m2 for most of the day. A solar panel can produce more when the sun is high in the sky and will produce less in cloudy conditions or when the sun is low in the sky. The sun is lower in the sky in the winter. In a high yield solar area like central Colorado, which receives annual insolation of 2000 kWh/m2/year, such a panel can be expected to produce 400 kWh of energy per year. However, in Michigan, which receives only 1400 kWh/m2/year, annual energy yield will drop to 280 kWh for the same panel. At more northerly European latitudes, yields are significantly lower: 175 kWh annual energy yield in southern England under the same conditions. Schematic of charge collection by solar cells. Light transmits through transparent conducting electrode creating electron hole pairs, which are collected by both the electrodes. The absorption and collection efficiencies of a solar cell depend on the design of transparent conductors and active layer thickness.

Several factors affect a cell's conversion efficiency value, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values. Because these parameters can be difficult to measure directly, other parameters are measured instead, including **quantum efficiency**, **open-circuit voltage (V_{OC}) ratio**, and **fill factor**. Reflectance losses are accounted for by the quantum efficiency value, as they affect "external quantum efficiency." Recombination losses are accounted for by the quantum efficiency, V_{OC} ratio, and fill factor values. Resistive losses are predominantly accounted for by the fill factor value, but also contribute to the quantum efficiency and V_{OC} ratio values. In 2019, the world record for solar cell efficiency at 47.1% was achieved by using multi-junction concentrator solar cells, developed at National Renewable Energy Laboratory, Golden, Colorado, USA. This is above the standard rating of 37.0% for polycrystalline photovoltaic or thin-film solar cells

For more information about **solar cell efficiency** visit:

- Solar cell efficiency (wikipedia)
- NREL cell efficiency

For more information about **panel efficiency** visit: NREL panel efficiency

Quantum efficiency:

The term quantum efficiency (QE) may apply to incident photon to converted electron (IPCE) ratio of a photosensitive device.

For more information about quantum efficiency visit: (Quantum efficiency (wikipedia)).

Open-circuit voltage (V_{OC}):

Open-circuit voltage (V_{OC}) is the difference of electrical potential between two terminals of a device when disconnected from any circuit. There is no external load connected. No external electric current flows between the terminals. Alternatively, the open-circuit voltage may be thought of as the voltage that must be applied to a solar cell or a battery to stop the current. It is sometimes given the symbol V_{OC}. In network analysis this voltage is also known as the Thévenin voltage.

For more information about open-circuit voltage (V_{OC}) visit: Open-circuit voltage (wikipedia).

Fill factor (FF):

The fill factor is the available power at the **maximum power point** (P_m) divided by the **open circuit voltage** (V_{OC}) and the **short circuit current** (I_{SC}):

$$FF = \frac{P_m}{V_{OC} \cdot I_{SC}}$$

For more information about fill factor (FF) visit: Solar cell efficiency (wikipedia).

6.4.4 Solar panels at home (hybrid solar system)

In hybrid solar systems, rooftop solar panels are connected to both a solar battery and the electric grid. This reduces your reliance on the utility while also providing backup power when needed. The architecture of an hybrid solar system is represented in figure 6.3. In the previous sections

Figure 6.3: Solar panels at home (hybrid solar system architecture)

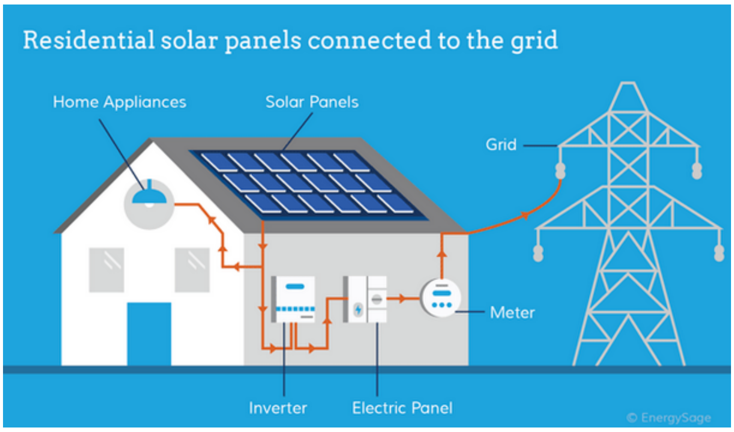
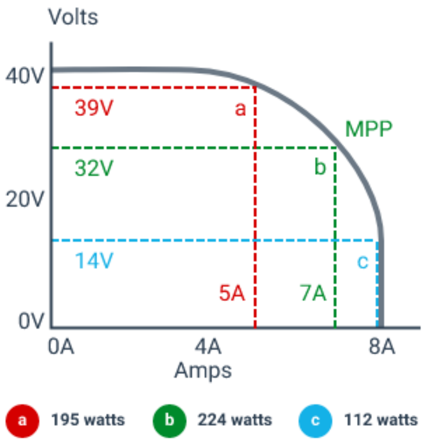


Figure 6.4: Maximum Power Point (MPP) curve



we have studied the main features of solar panels. In this section, we study the role of inverters, since they play an important role in hybrid solar systems.

Solar inverters are an integral part of every solar power system. They perform two key functions:

1. **DC to AC conversion:** All solar panels generate Direct Current (DC); a solar inverter is required to convert this into Alternating Current (AC), the form of electricity usable by your home.

2. **MPP tracking:** The operating conditions of solar panels - sunlight intensity and panel temperature - fluctuate throughout the day. This means that the possible solar panel voltage and current are always changing as well. In a process called Maximum Power Point (MPP) tracking, the solar inverter dynamically selects the exact combination of the two that will produce the most power (figure 6.4).

Types of solar inverter.

There are two categories to consider when deciding on the right solar inverter type: **the solar inverter technology**, and **the type of solar power system the inverter is for**.

1. **Solar inverter technology.**

- **String inverter:** A string inverter is a single, standalone unit that converts power from a whole string (or strings) of solar panels. String inverters are cheap and convenient, but tend to be the least efficient.
- **String inverter + power optimizer:** Power optimizers are attached to each individual panel. They perform MPP tracking at the module level; the optimized DC power is then sent to the string inverter for conversion into AC power. Combining string inverters with power optimizers will increase your cost but allow your system to handle issues like shading better.
- **Microinverter:** Microinverters are also attached to individual panels. They perform both MPP tracking and power conversion at the module level, allowing each panel to output usable AC power. They're good at dealing with shade (like power optimizers), and have the additional advantage of making your solar system easy to expand. They are, however, the most expensive type of inverter.

2. **The type of solar power system the inverter is for**. The solar inverter will need to be compatible with the solar system:

   - **Grid-tied inverters** are meant for grid-tied solar systems, the most common system type. They manage a two-way relationship with the grid, exporting solar power to it, and importing utility power from it as required.
   - **Hybrid inverters** are designed to work with hybrid solar systems (aka solar-plus-storage systems). They have the same functionality as a grid-tie inverter, but can also charge and draw power from a battery setup.
   - **Off-grid inverters** are used in off-grid solar systems, i.e. fully independent solar power systems, giving you back up power when the grid is down. An off-grid inverter requires a battery backup to function, and cannot be connected to the grid.

For a complete video that illustrates how **solar hybrid systems** work visit: Hybrid solar systems

For more information about **solar inverters** visit:

- Power inverter (wikipedia).
- Solar Reviews.

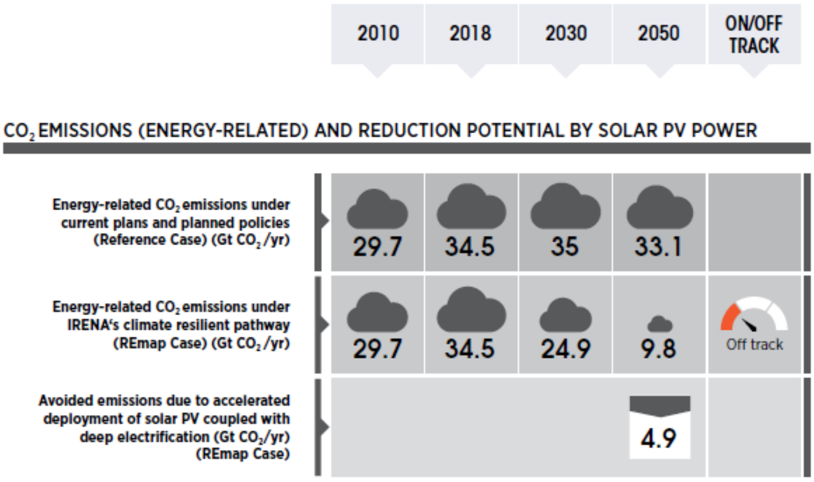
6.5 Future of solar photovoltaic. Deployment, investment, technology, grid integration and socio-economic aspects

6.5.1 Key findings

1. Accelerated deployment of renewables, combined with deep electrification and increased energy efficiency, can achieve over 90% of the energy-related **carbon dioxide (CO2) emission reductions** needed by 2050 to set the world on an energy pathway towards meeting the Paris climate targets. Among all low-carbon technology options, accelerated deployment of solar PV alone can lead to significant emission reductions of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector (figure 6.5).

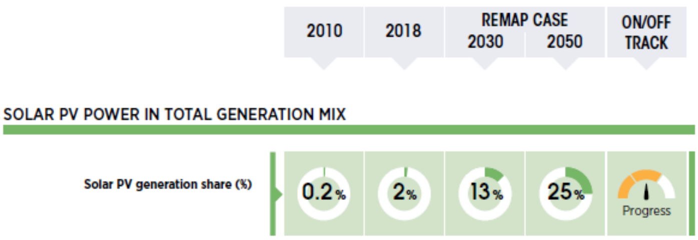
2. Achieving the Paris climate goals would require significant acceleration across a range of sectors and technologies. By 2050 solar PV would represent the second-largest power generation source, just behind wind power and lead the way for the transformation of the global electricity sector. **Solar PV would generate a quarter** (25%) **of total**

Figure 6.5: CO2 emissions (energy-related) and reduction potential by wind power



Source: IRENA (2019a)

Figure 6.6: Solar power in total generation mix



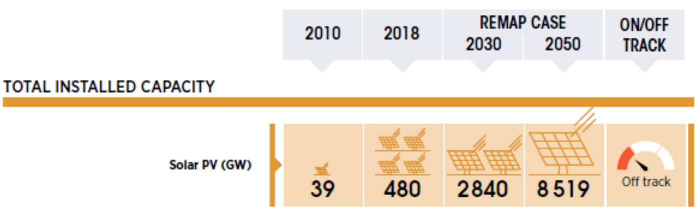
Source: IRENA (2019a)

electricity needs globally, becoming one of prominent generations source by 2050 (figure 6.6).

3. Such a transformation is only possible by significantly **scaling up solar PV capacity in next three decades**. This entails increasing total solar PV capacity almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels (figure 6.7).

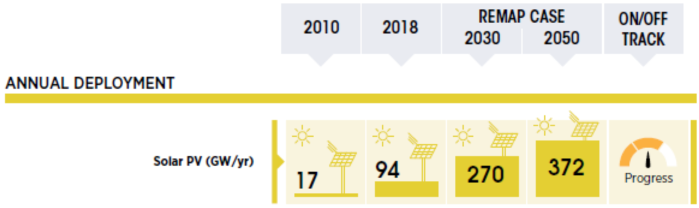
4. The solar PV industry would need to be prepared for such a significant growth in the market over the next three decades. In annual growth terms, an almost threefold rise in yearly solar PV **capacity additions** is needed by 2030 (to 270 GW per year) and a fourfold rise by

Figure 6.7: Solar total installed capacity



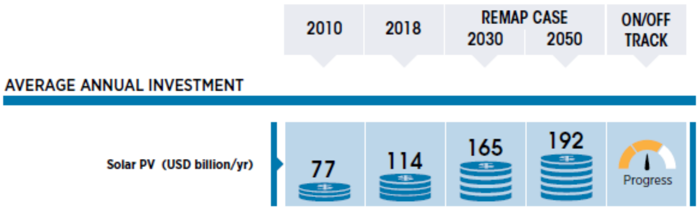
Source: IRENA (2019a)

Figure 6.8: Solar annual deployment



Source: IRENA (2019a)

Figure 6.9: Solar average annual investment



Source: IRENA (2019a)

2050 (to 372 GW per year), compared to current levels (94 GW added in 2018) (figure 6.8).

Thanks to its modular and distributed nature, solar PV technology is being adapted to a wide range of off-grid applications and to local conditions. In the last decade (2008–18), the globally installed capacity of off-grid solar PV has grown more than tenfold, from roughly 0.25 GW in 2008, to almost 3 GW in 2018. Off-grid solar PV is a key technology for achieving full energy access and achieving the Sustainable Development Goals.

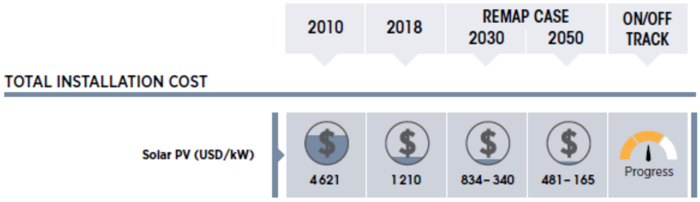
5. At a regional level, Asia is expected to drive the wave of solar PV capacity installations, being the world leaders in solar PV energy. Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by North America (20%) and Europe (10%).

6. Scaling up solar PV energy investment is critical to accelerating the growth of installations over the coming decades. Globally this would imply a 68% increase in **average annual solar PV investment** from now until 2050 (to USD 192 billion/yr). Solar PV investment stood at USD 114 billion/yr in 2018 (figure 6.9).

7. Increasing economies of scale and further technological improvements will continue to reduce the costs of solar PV. Globally, the **total installation cost of solar PV projects** would continue to decline in the next three decades. This would make solar PV highly competitive in many markets, with the average falling in the range of USD 340 to 834 per kilowatt (kW) by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018 (figure 6.10).

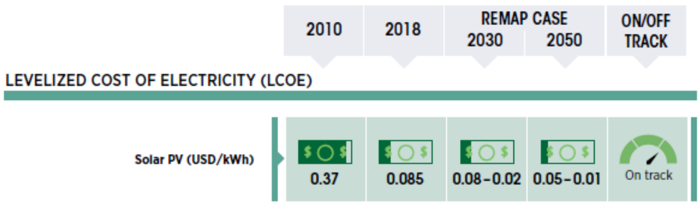
   The **levelised cost of electricity (LCOE) for solar PV** is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. Globally, the LCOE for solar PV will continue to fall from an average of USD 0.085 per kilowatt-hour (kWh) in 2018 to between USD 0.02 to 0.08/kWh by 2030 and between USD 0.014 to 0.05/kWh by 2050 (figure 6.11).

Figure 6.10: Solar total installation cost



Source: IRENA (2019a)

Figure 6.11: Solar levelised cost of electricity (LCOE)



Source: IRENA (2019a)

8. The solar PV industry is a fast-evolving industry, changing rapidly thanks to **innovations along the entire value chain** and further rapids reductions in costs are foreseen.

9. Taking advantage of the fast-growing solar PV capacity across the globe, several research projects and prototypes are ongoing to stimulate future market growth by exploring **innovative solar technologies at the application level**.

10. **Technological solutions** as well as enabling **market conditions** are essential to prepare future power grids to integrate rising shares of solar PV. To effectively manage large-scale variable renewable energy sources:

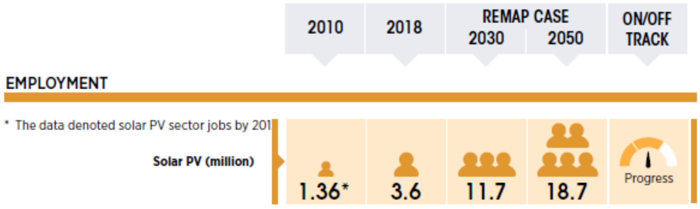
    - **Flexibility** must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems.
    - **Storage** (both electrical and thermal)
    - Increasingly, **flexible demand** (demand-side management and sector coupling).

11. **Innovative business models** and cost competitiveness of solar PV are driving the reductions in system prices. The deployment of **rooftop solar PV systems** has increased significantly in recent years, in great measure thanks to supporting policies, such as net metering and fiscal incentives which in some markets make PV more attractive from an economic point of view than buying electricity from the **grid-PV-hybrid minigrid**, **virtual power plants** and **utility Power Purchase Agreement (PPA)**.

A **virtual power plant (VPP)** is a cloud-based distributed power plant that aggregates the capacities of heterogeneous distributed energy resources (DER) for the purposes of enhancing power generation, as well as trading or selling power on the electricity market.

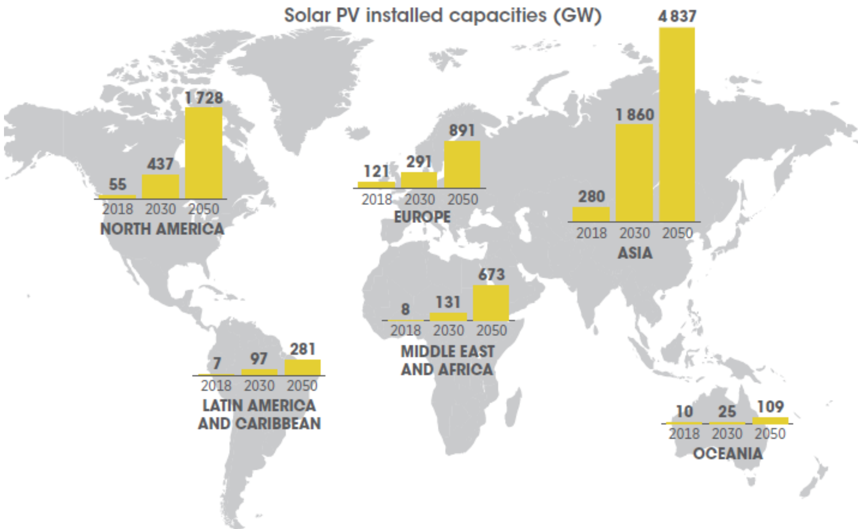
For more information about virtual power plants visit **(virtual power plant (wikipedia))**.

Figure 6.12: Solar employment



Source: IRENA (2019a)

Figure 6.13: Solar installed capacities by region



Source: IRENA (2019a)

12. If accompanied by sound policies, the transformation can bring **socio-economic benefits**. The solar PV industry would employ more than 18 million people by 2050, five times more than the 2018 jobs total of 3.6 million (figure 6.12).

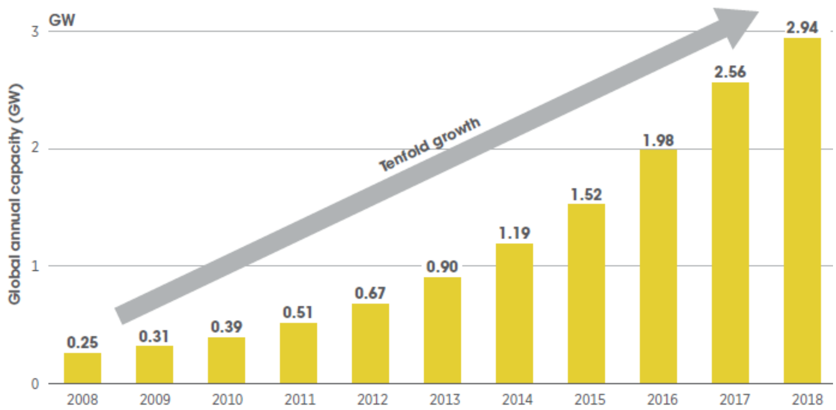
6.5.2 The evolution and future of solar PV markets

The global installed capacity of solar PV would rise six-fold by 2030 (2 840 GW) and reach 8 519 GW by 2050 compared to installations in 2018 (480 GW) (figure 6.7). To achieve the global installed capacity objectives, the global average annual solar PV investment needs to scale up by 68% until 2050 (USD 192billion/year) compared to 2018 investment (USD 114 billion/year) (figure 6.9).

Solar energy by region

The global solar market in 2018 was dominated by Asia, accounting for over half of the world's addition of solar capacity. The region's installed solar capacity reached 280 GW by the end of 2018, dominated by China with 175 GW. The European Union represented the world's second-largest solar PV market, mainly driven by Germany with 45 GW cumulative installed capacity by the end of 2018, followed by North America with 55 GW (figure 6.13), of which the United States accounted for 90%.

Figure 6.14: Solar global power capacity, off-grid solar PV, 2008–18



Source: IRENA (2019a)

Under the REmap scenario Asia would continue to lead global solar PV installations, with 65% of the total capacity installed by 2030 (figure 6.13). Within Asia significant deployment would be seen in China, where installed capacity is projected to reach around 1 412 GW by 2030. North America would have the second-highest installed solar PV capacity, reaching 437 GW by 2030, with more than 90% of these installations in the United States.

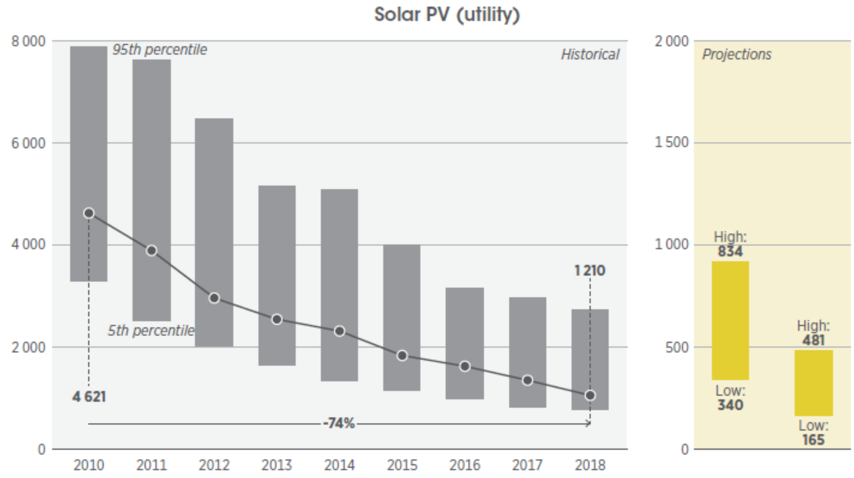
Europe would represent the third-highest region by 2030, with 291 GW of solar PV capacity installed. A similar picture is expected on a 2050 horizon, when Asia would still dominate the scene at almost half of the cumulative global capacity installed (4 837 GW). Within Asia, China would dominate the scene, with a compound annual growth rate (CAGR) of 9% after 2018 leading to projected capacity of around 2 803 GW by 2050. North America would still have the second-largest installed capacity, reaching 1 728 GW by 2050, with the United States still dominating the region. Europe could still hold the third place among regions in 2050, with 891 GW of total solar PV capacity installed. More than 22% of these installations would be in Germany, where the installed capacity is projected to reach around 200 GW by 2050. Even though installed capacity may remain highest in Asia, North America and Europe, market growth seems likely to shift to other regions, with large markets also expected to emerge in South America and Africa.

Solar PV for off-grid solutions

Off-grid (or stand-alone) applications are typically used where there is no electric grid or when the cost of connecting to the grid is high. Applications are normally smaller than other system types and are often used for small-scale projects in rural areas, as a solution in developing countries, as well as for residential households willing to disconnect from the grid (typically not the most economic or efficient option) (IRENA, 2017).

Thanks to its modular and distributed nature, solar PV can be adapted to a wide range of off-grid applications and to local conditions, ranging from lanterns to household systems to village-powering mini-grids. In the last decade (2008–18), the global installed capacity of off-grid solar PV has grown more than ten times, from roughly 0.25 GW in 2008, to 2.94 GW in 2018 (figure 6.14). Currently, off-grid solar solutions constitute about 85% of all off-grid energy installations, comprising of solar home systems (about 50%) and solar lanterns/solar lighting systems (about 35%). This is followed by rechargeable batteries (10%) and mini-grids (2%) (World Bank, 2020a).

Figure 6.15: Solar PV cost evolution



Source: IRENA (2019a)

Strong business case for a significant future solar PV market

The breakthrough in renewables capacity additions over past few years has largely been achieved due to significant cost reductions driven by enabling government policies, including deployment policies, research and development funding, and other policies that have supported the development of the industry in leading countries.

Solar PV is emerging as one of the most competitive sources of new power generation capacity after a decade of dramatic cost declines. A decline of 74% in total installed costs was observed between 2010 and 2018 (figures 6.10 and 6.15).

The levelized cost of electricity for solar PV is already competitive now compared to all generation sources (including fossil fuels) and is expected to decline further in the coming decades, falling within the range of USD 0.02 and 0.08/kWh by 2030 and USD 0.014 0.05/kWh (figure 6.11).

6.5.3 Technological solutions and innovations to integrate rising shares of solar PV power generation

The variable nature of the solar and wind resources will require significant changes to the way the power system operates as the share of variable renewable energy (VRE) reaches high levels in different markets. We have studied those changes in sections 5.6.4 and 5.6.5.

6.5.4 Future solar PV trends

Overview

The main **components** of a solar plant that decision makers may consider manufacturing domestically are the solar cells, solar modules, inverters, trackers, mounting structures and general electrical components (IRENA, 2017).

<u>Solar modules.</u>

The global market for solar module production is highly diversified, although some consolidation among manufacturers is taking place. The majority of the market is held by **crystalline**

Figure 6.16: Solar value chain

Source: IRENA (2019a)

silicon (c-Si) module manufacturers, thanks to the maturity of the technology and the lower investment costs due to the fall in the price of polysilicon – its raw material. The **thin-film market**, by comparison, has fewer manufacturers and relatively few players have been able to consistently commercialise these products.

<u>Solar inverters.</u>

The market for solar inverters is currently in a growth phase, the rising demand for power together and various global initiatives to encourage the implementation of renewable smart grids being the main drivers behind this development.

In 2018 the Asia-Pacific region dominated the market for solar inverters, accounting for 71% of new installations globally. At a country level, China, the United States and India were the top countries, collectively accounting for approximately 70% of global PV inverter installations in 2018.

The next subsections explore the innovation progress in the solar PV industry in materials, module manufacturing, applications, operation and maintenance, and in ways of decommissioning panels and managing their end of- life stage (figure 6.16).

Materials and module manufacturing

<u>Materials.</u>

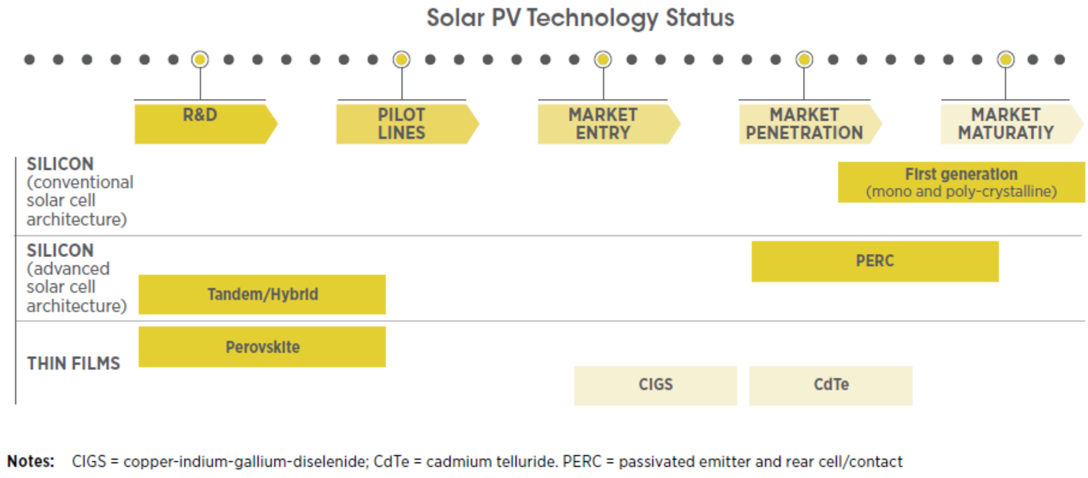
First-generation technologies, which have been evolving along the whole PV value chain, still account for the majority of global annual production (Fraunhofer ISE, 2019). **Tandem and perovskite technologies** also offer interesting perspectives, but in the longer term due to barriers that still need to be addressed and overcome (durability, price).

The figure 6.17 gives an overview of the PV technologies and concepts under development.

1. **Silicon – conventional solar architecture**. Crystalline silicon (c-Si) panels belong to the first generation solar PV panels and they hold 95% share of worldwide PV production (Fraunhofer ISE, 2019). The economies of scale of its main material, silicon, make c-Si more affordable and highly efficient compared to other materials.

   The average module efficiency in 2006 was 13.2% for multi crystalline PV panels and 14.7% for mono crystalline PV panels and since then has increased steadily, reaching 17% and 18% respectively.

Figure 6.17: Solar PV technology status



Source: IRENA (2019a)

However, despite the high-efficiency level of this first-generation PV technology, there remains a lot of **scope for improvement**, including:

- Lowering the cost of c-Si modules for better profit margins.
- Reducing metallic impurities, grain boundaries, and dislocations.
- Mitigating environmental effects by reducing waste.
- Yielding thinner wafers through improved material properties.

2. **Silicon - advanced solar architecture.**

   (a) **PERC.** A PERC cell uses advanced silicon cell architecture. PERC cells are not much different in construction from a typical monocrystalline PV cell; however, the **key improvement is the integration of a back-surface passivation layer**, which is a layer of material on the back of the cells that is able to improve the cell's efficiency. In fact, the passivation layer **increases the overall cell efficiency** in three key ways:

   - It reduces electron recombination.
   - It increases absorption of light.
   - It enables higher internal reflectivity.

   The efficiency gain of implementing PERC architecture for monocrystalline cells is about 0.8% to 1% absolute, while the boost for multicrystalline cells is a little lower, at 0.4% to 0.8%.

   (b) **Tandem/hybrid cells. Tandem solar cells are stacks of individual cells, one on top of the other**, that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. Emerging PV technologies comprise several types of tandem cells that can be grouped mainly depending on materials used (e.g. organic, inorganic, hybrid) as well as on the kind of connection used. The tandem cell approach has been used to fabricate the world's most efficient solar cells that can convert 46% of sunlight into electricity.

3. **Thin-film.** Thin film technologies are often referred to as second-generation solar PV. The semiconducting materials used to produce thin-film cells are only a few micrometres

thick (IRENA, 2016).

These technologies generally include **two main families**:

- **Silicon-based thin film** (amorphous [a-Si] and micromorph silicon [a-Si/c-Si].
- **Non-silicon based** (perovskites, cadmium telluride [CdTe] and copper-indium-gallium diselenide [CIGS]).

These technologies can be cheaper to produce, as such they are being deployed on a commercial scale, but they have historically had lower efficiency levels.

(a) **Perovskites.** Currently most solar cells are made from silicon; however, an area to watch is the development of new materials for solar cells. In particular, one of the most promising material is perovskites, a type of mineral very good at absorbing light. The first perovskite PV devices in 2009 converted just 3.8% of the energy contained in sunlight into electricity. However, because crystals are very easy to make in the lab, their performance was quickly improved and by 2018 their efficiency had soared to 24.2%, set by researchers in the United States and the Republic of Korea — close to silicon's lab record of 26.7%. However, perovskite efficiency records have only been set on tiny samples.

    Perovskites still face some significant **challenges** before achieving market maturity.

    - One of the main ones is **durability**. Because the crystals dissolve easily, they are not able to handle humid conditions and need to be protected by moisture through encapsulation, for instance through an aluminium oxide layer or sealed glass plates.
    - Another challenge for scientists is that, whist they have been able to achieve high **efficiency** levels with small perovskites, they have not been able to replicate such effect with **larger cell areas**.

(b) **Copper indium gallium selenide cells (CIGS).** CIGS cells have achieved high efficiency levels (22.9%) comparable to commercial crystalline silicon (Fraunhofer ISE, 2019). However, **manufacturing** CIGS cells can be difficult due to the rarity of indium, as well as to the complex stoichiometry and multiple phases to produce them, restricting large-scale production in the near term.

(c) **Cadmium telluride (CdTe).** Cadmium telluride cells have achieved an efficiency of 21%, very similar to CIGS, and are characterised by good absorption and low energy losses (Fraunhofer ISE, 2019). CdTe solar cells are made through low temperature processes, which makes their production very flexible and affordable. CdTe currently has the largest market share of all thin-film technologies.

<u>Advanced module technologies.</u>

1. **Bifacial solar cells.** Bifacial solar cells have been under development for decades and their manufacturing process can be considered one of the most advanced for solar modules today. **Bifacial cells are capable of generating electricity not only from sunlight received on their front, but also from reflected sunlight received on the reverse side of the cell**.

   Bifacial operation, facilitated by the uptake of PERC (which is driving the bifacial boom), offers a near term effective efficiency increase of $5 - 20\%$ relative by increasing the energy output from a given module area.

2. **Multi-busbars.** Silicon solar cells are metallised with thin strips printed on the front and rear of a solar cell; these are called busbars and have the purpose of conducting the electric direct current (DC) power generated by the cell. Older solar cells typically had two busbars; however, the industry has moved towards **higher efficiencies** and busbars have increased to three (or more) in most solar cells.

   The increased number of busbars has several **advantages**:

   - First is the high potential for cost saving due to a reduction in metal consumption for front facing metallisation (Braun,S., 2013).
   - Second, series resistance losses are reduced by employing thin wires instead of regular ribbon.
   - Third, optimising the width of the busbars leads to an additional rise in efficiency.
   - Finally, multi-busbar design is highly beneficial for bifacial technology, especially for improving the bifaciality for PERC cells of 90%.

3. **Solar shingles.** Solar shingles are a type of solar energy solution where solar panels are designed to look like conventional roofing materials, while also producing electricity.

   Solar shingles have several **advantages**.

   - First, a key advantage is that they eliminate the need for ribbon, connecting cells like roof tiles.
   - Second and related to the removal of the ribbon, module aesthetics are improved, as the panels are homogeneously coloured.
   - Third, unlike a standard cell, cells for shingle modules have busbars at opposite ends and cells are sliced into several strips, which reduces the current and consequently the load on fingers (metallic super-thin grid fingers, perpendicular to the busbar, collecting the generated DC current and delivering it to the busbars).

Applications: Beyond fields and rooftops

Taking advantage of the rapidly growing solar PV capacity across the globe, several research projects or prototypes are underway to stimulate future market growth, exploring innovating solar technologies at the application level. The major developments are as follows.

1. **Floating PV.** Floating PV is an exciting emerging market, with the potential for rapid growth. According to a World Bank report, as of the end of September 2018 the global cumulative installed capacity of floating PV plants was 1.1 GW (World Bank, 2018).

   Demand for floating PV is expanding, especially on islands (and other land-constrained countries), because the cost of water surface is generally lower than the cost of land. Floating solar is particularly well suited to Asia, where land is scarce but there are many hydroelectric dams with existing transmission infrastructure.

2. **Building-integrated PV panels**. Building-integrated PV (BIPV) solar panels are an application also known as solar shingles (see above). BIPV solutions have several **advantages**.

   - First, they are **multifunctional** as they can be adapted to a variety of surfaces (e.g. roofs, windows, walls) as an integrated solution, providing both **passive** and **active** functions. A key passive function is thermal and acoustic insulation, as with any other construction material, which is complemented by a unique active function – the PV component – which generates renewable electricity that can be directly used in the building.

- Other functions, also unique to BIPV systems, include the possibility of **real-time thermal or lighting regulation**.

An EU-funded project, **PVSITES**, is currently developing a new generation of solar panels that can be part of traditional house elements like roofs, windows and glass façades. The project is creating BIPV solar panels alongside building energy management systems and architectural design tools. The aim is to demonstrate the integration of effective energy production with good design to create cost-effective buildings. The project is also developing design software tools for architects to help them better integrate these novel PV products in their designs.

3. **Solar trees.** Solar trees work very much like real ones, as they have leaf-like solar panels connected through metal branches using sunlight to make energy. Solar trees can be seen as complementary to rooftop solar systems.

4. **Solar carports.** Solar carports are ground-mounted solar panels that are installed so that parking lots and home driveways can be laid underneath to form a carport. They have been a very popular alternative or supplement to the classic rooftop systems.

5. **Solar PV-Thermal systems.** Solar PV-T systems combine the production of both kinds of solar energy in one collector. It consists of a solar PV panel combined with a cooling system where cooling agent (water or air) is circulated around the PV panels to cool the solar cells, such that the warm water or air leaving the panels may be used for domestic applications such as domestic heating.

   This cooling system for PV panels has a **twofold benefit**:

   - It significantly increases the efficiency of PV systems in the electricity sector.
   - It also allows for the capture of the heat from the PV system for use in space, water and process heating in a range of industries and applications.

   In fact, PV modules normally use 15˘20% of the incoming solar energy, while the rest is lost in the form of heat. The PV-T technology aims to increase the overall efficiency by using this "lost" energy to heat air or water and at the same time cool the PV cells by taking away the heat from the panel.

6. **Agrophotovoltaic (APV).** Agrophotovoltaic (APV) combines solar PV and agriculture on the same land and consists of growing crops beneath ground-mounted solar panels. Although the concept was proposed long ago, it has received little attention until recently, when several researchers have confirmed the benefits of growing crops beneath the shade provided by the solar panels.

   Cultivating crops underneath reduces the temperature of the panels, as they are cooled down by the fact that the crops below are emitting water through their natural process of transpiration.

Operation and maintenance

<u>Smart PV power plant monitoring.</u>

1. **Drones for intelligent monitoring of solar PV.**

   The exponential growth seen in PV markets has led to the development of large-scale power plants, which has increased demands for better tools for inspection and monitoring. Normally, the process of monitoring is done by conducting manual inspections; however, these can be replaced by intelligent systems, such as drones. Drones are becoming highly suited to the solar industry due to a wide range of surveillance and monitoring capabilities, the possibility of long-range inspection and easy control.

2. **PV plant power output forecasting.**

   Currently simulation models and meteorological forecasting resources for specific PV plants are well proven technologies. Algorithms that are able to match weather forecasts with PV plant characteristics are being used to predict energy production on an hourly basis for at least the next 48 hours.

3. **Smart PV plant monitoring.**

   Innovations in monitoring systems aim to improve the ability to identify the root causes of performance problems that lead to plant underperformance and unavailability.

<u>Retrofit coatings for PV modules.</u>

1. **Solar power coolant.**

   While progress is being made on increasing efficiency and maximising power output of solar PV, difficulties remain in addressing the need to keep solar PV modules cool, because their performance and lifetime are reduced by the heat of the sun.

   PV-Thermal systems are currently one of the most popular methods for cooling PV panels. Other techniques include the use of water.

   Other approaches include applying a **transparent coating of patterned silica** to solar cells to capture and radiate heat from infrared rays back to the atmosphere. This was found to improve absolute cell efficiency by more than 1%.

2. **Anti-soiling solutions.**

   Regular module washing is common practice in PV plants, as soiling can significantly and negatively impact their performance. For instance, in Europe soiling causes an average 2% power loss with significant rain, which can go as high as 11% in non rainy environments. In this context, **several anti-soiling solutions are being implemented**.

   - First, **robotic panel cleaning technology** consists of robots moving along the array of panels.
   - Second, **sprinkler systems** consist of a water filtration system and a soap dispensing system, mainly used in very dry areas to keep the panels clean with the same cleaning effect as rain.

End-of life management of solar PV

Despite the growth of solar PV and its bright future, the sun sets on even the best panels. As the global PV market increases, so will the need to prevent the degradation of panels and manage the volume of decommissioned PV panels. The sections below explore innovative and alternative ways to reduce material use and module degradation, and opportunities to reuse and recycle PV panels at the end of their lifetime.

The framework of a **circular economy** and the classic waste reduction principles (reduce, reuse and recycle) can also be applied to PV panels.

1. **Reduce: Material savings in PV panels.**

   The best option is to increase the efficiency of panels by reducing the amount of material used. Whilst the mix of materials has not changed significantly, efficient mass production, material substitutions and higher-efficiency technologies are already happening thanks to strong market growth, scarcity of raw materials and reduction of PV panel prices.

2. **Reuse: Repairing PV panels.**

   Most PV systems were installed in the last six years. A six-year-old panel today has aged by an equivalent of 20% of its expected average lifetime of 30 years (IRENA, 2016). If flaws and imperfections are discovered during the early phase of a PV panel's life, customers can claim guarantees for repair or replacement and insurance companies may be involved to compensate for some or all of the repair/replacement costs.

3. **Recycle: Decommissioning and treatment of PV panels.**

   The value creation stemming from end-of-life PV management involves:

   - **Unlocking raw materials and their value.** The extraction of secondary raw materials from end of- life PV panels could create important value for the industry. PV panels have an average lifetime of 30 years, and they build up a large stock of embodied raw materials that will not become available for recovery for some time. As such, recovered raw material can be injected back into the economy and serve to produce new PV panels or other products, thus increasing the security of future PV supply. Rapidly growing panel waste volumes over time will stimulate a market for secondary raw materials originating from end-of-life PV panels.
   - Creating new industries and jobs in the PV sector.

6.6 Solar energy and development

Solar empowerment across countries

United Nations Development Programme. Clean energy

6.7 Some questions to summarize the chapter

1. Which are the main **solar energy production technologies**?

1. **Solar thermal collector**.

A solar thermal collector collects heat by absorbing sunlight. The term "solar collector" commonly refers to a device for solar **hot water heating**.

Solar thermal collectors are either **non-concentrating** or **concentrating**

- In **non-concentrating collectors**, the aperture area (i.e., the area that receives the solar radiation) is roughly the same as the absorber area (i.e., the area absorbing the radiation) (right-hand side, figure below)
- **Concentrating collectors** have a much larger aperture than the absorber area. The aperture is typically in the form of a mirror that is focussed on the absorber, which in most cases are the pipes carrying the working fluid (left-hand side, figure below)

2. **Photovoltaics**.

Photovoltaics (PV) is the **conversion of light into electricity** using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry.

A photovoltaic system employs solar modules, each comprising a number of **solar cells**, which generate electrical power.

PV installations may be ground-mounted, rooftop mounted, wall mounted or floating. The mount may be fixed or use a solar tracker to follow the sun across the sky.

PV has become the **cheapest source of electrical power in regions with a high solar potential**, with price bids as low as 0.01567 US/kWh in 2020. **Panel prices have dropped by the factor of 10 within a decade**.

3. **Solar thermal energy**.

Solar thermal energy (STE) is a form of energy and a technology for harnessing **solar energy to generate thermal energy** for use in industry, and in the residential and commercial sectors.

Solar thermal collectors are classified by the United States Energy Information Administration as **low-**, **medium-**, or **high-temperature collectors**.

Low-temperature collectors are generally unglazed and used to heat swimming pools or to heat ventilation air. **Medium-temperature collectors** are also usually flat plates but are used for heating water or air for residential and commercial use.

High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric power production.

2. Can you define the **concepts** of volts, amps and watts?
   How those concepts can help us to understand **electricity production in solar cells and solar panels**?

To answer this question, it is necessary to watch the video in one of the pink boxes in the chapter.

3. How does the **photovoltaic process work** to produce electricity?

Based on the information from the previous question, the **photovoltaic process works** through the following broad steps:

a. The silicon photovoltaic solar cell **absorbs solar radiation**

b. When the sun's rays interact with the silicon cell, **electrons begin to move**, creating a flow of electric current

c. **Wires** capture and feed this direct current (DC) electricity to a solar **inverter** to be converted to alternating current (AC) electricity

4. Can you explain the concept of **solar efficiency**? Which are the **parameters used to measure solar efficiency**?

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.

Several factors affect a cell's conversion efficiency value, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values.

Because these parameters can be difficult to measure directly, other parameters are measured instead, including **quantum efficiency**, **open-circuit voltage (V_{OC}) ratio**, and **fill factor**.

The architecture of an hybrid solar system is represented in the figure below. Above, we have studied the main features of solar panels. Therefore, we study the role of **inverters**, since they play an important role in hybrid solar systems

5. In an **hybrid solar system**? Which is the role of the **inverters**?

Solar inverters perform **two key functions**:

a. **DC to AC conversion:** All solar panels generate Direct Current (DC); a solar inverter is required to convert this into Alternating Current (AC), the form of electricity usable by your home.

b. **MPP tracking:** The operating conditions of solar panels - sunlight intensity and panel temperature - fluctuate throughout the day. This means that the possible solar panel voltage and current are always changing as well. In a process called Maximum Power Point (MPP) tracking, the solar inverter dynamically selects the exact combination of the two that will produce the most power

6. Which should be the **PV trends** to achieve the Paris agreement?

a. **Solar PV and CO2**: Deployment of solar PV alone can lead to **significant emission reductions** of 4.9 gigatonnes of carbon dioxide (Gt CO2) in 2050, representing 21% of the total emission mitigation potential in the energy sector.

b. **PV production**: **Solar PV would generate a quarter** (25%) **of total electricity needs globally**, becoming one of prominent generations source by 2050.

c. **PV capacity**: Solar PV capacity should increase almost sixfold over the next ten years, from a global total of 480 GW in 2018 to 2 840 GW by 2030, and to 8 519 GW by 2050 – an increase of almost eighteen times 2018 levels.

d. **Regional highlights**
Asia (mostly China) would continue to dominate solar PV power in terms of total installed capacity, with a share of more than 50% by 2050, followed by **North America** (20%) and **Europe** (10%).

e. **PV investments**: The **average annual solar PV investment** should increase 68% from now until 2050 (to USD 192 billion/yr). Solar PV investment stood at USD 114 billion/yr in 2018.

f. **Installation cost**: The **total installation cost of solar PV projects** would continue to decline in the next three decades. This would make solar PV highly competitive in many markets, with the average falling in the range of USD 340 to 834 per kilowatt (kW) by 2030 and USD 165 to 481/kW by 2050, compared to the average of USD 1 210/kW in 2018.

g. **Levelised cost**: The **levelised cost of electricity (LCOE) for solar PV** is already competitive compared to all fossil fuel generation sources and is set to decline further as installed costs and performance continue to improve. The LCOE for solar PV will continue to fall from an average of USD 0.085 per kilowatt-hour (kWh) in 2018 to between USD 0.02 to 0.08/kWh by 2030 and between USD 0.014 to 0.05/kWh by 2050.

7. Which are the main innovations in **materials** to manufacture PV?

a. **Silicon – conventional solar architecture**.

b. **Silicon - advanced solar architecture. PERC.**

c. **Silicon - advanced solar architecture. Tandem/hybrid cells.**

d. **Thin-film.**

8. Which are the main innovations in **modules** to manufacture PV?

a. **Bifacial solar cells.**

b. **Multi-busbars.**

c. **Solar shingles.**

6.8 Bibliography

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Chapter 7

Sustainable energy. Hydrogen

In this chapter we study the role that hydrogen will play in the future energy system. The chapter is organized as follows:

1. Watch a video and discuss the **main points** that we will study during the chapter
2. Electrolysis. The chemical process
3. Study the production of hydrogen by analyzing the **types of electrolysers**, and the main components in a **hydrogen production plant**
4. Study the main **cost challenges** faces by the hydrogen industry
5. Study the interaction between **hydrogen and the rest of renewable energy**
6. Analyze the role of hydrogen increasing **flexibility** in the energy system

7.1 Discussion

To motivate the chapter, we start by watching the video What Is Green Hydrogen And Will It Power The Future?

Based on that video, we discuss the next questions:

1. Why are the main **types of hydrogen**?
2. Which is the difference between **green hydrogen** and the other hydrogen types?
3. Which are the **investments** required to boost the adoption of hydrogen? Which **countries** are investing in hydrogen?
4. Which will be the **role of hydrogen** in the future energy system?
   - Transport: cars, trucks, planes, boats.
   - Energy storage: long vs. short term.
   - Industry
   - Heating system
5. Which are the main **challenges** that face the development of hydrogen? Electrolysers, storage of hydrogen, transport of hydrogen, electricity cost?

Other videos that are very useful to know the technical particularities of the production of hydrogen are:

The Truth about Hydrogen

Energy Storage in Hydrogen : Does this beat batteries?

7.2 Motivation

As more countries pursue deep decarbonisation strategies, hydrogen will have a critical role to play. This will be particularly so where direct electrification is challenging and in harder-to-abate sectors, such as steel, chemicals, long-haul transport, shipping and aviation. **In this context, hydrogen needs to be low carbon** from the outset and ultimately green (produced by electrolysis of water using renewable electricity).

7.3 Electrolysis

This section is based on the video: Electrolysis.

The electrolysis is a process where **electricity** is used to make a **chemical change** happen that **wouldn't** happen otherwise.

1. **Electrolysis of water** (H_2O). The **balance equation** can be written as:

$$2H_2O \rightarrow 2H_2 + O_2$$

H_2 and O_2 are **diatomic elements**: always form groups of two. You will never find just one alone. Other diatomic elements: B_2, I_2, N_2, Cl_2, H_2, O_2, F_2.

The balance equation represents an **oxidation reduction process**: Electrons are transferred to form new elements.

2. How do the **electrons move** during the reduction process? To understand that process, it is useful to write the **oxidation numbers**:

$$2H_2^{+1}O^{-2} \rightarrow 2H_2^0 + O_2^0$$

To satisfy the balance equation:

- The **hydrogen** need to be **reduced** (**gains electrons**).
- The **oxygen** need to be **oxidized** (**loses electrons**).

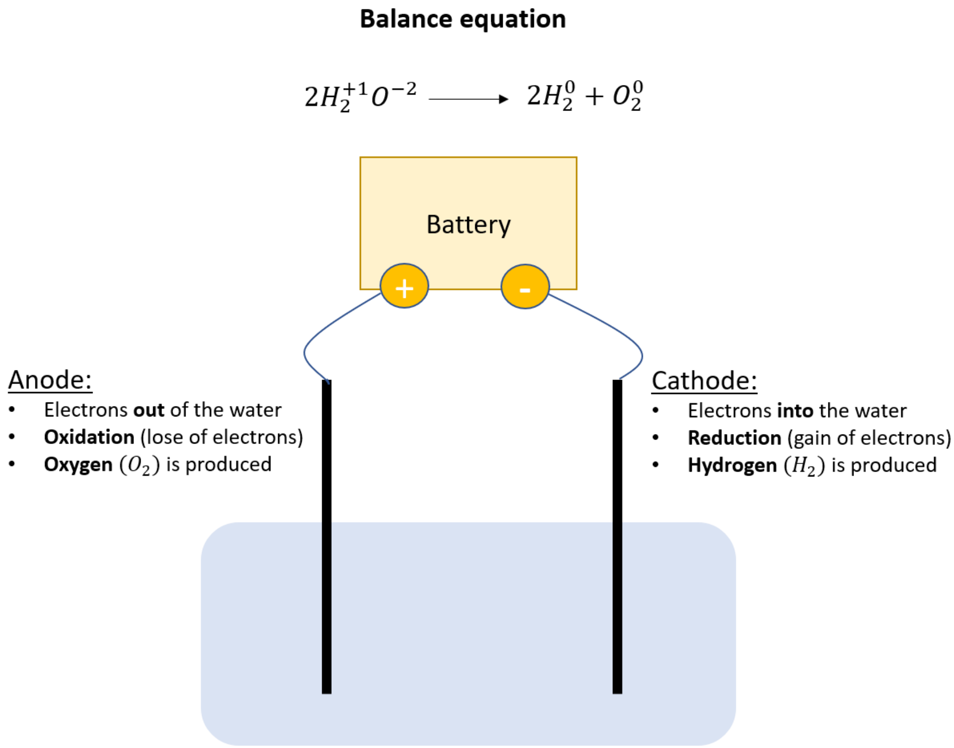
3. This process does not happen on its own. An **electrical current** can force this to happen. The **device** used to facilitate that process is called **electrolyser** (figure 7.1).

An electrolyser consists on a **battery** and **two electrodes**: A cathode, and an anode:

a. **Cathode**: Electrons go **into** the water $\rightarrow$ It will be the place of reduction: H_2 is produced.

b. **Anode**: Electrons go **out** the water $\rightarrow$ It will be the place of oxidation: O_2 is produced.

Figure 7.1: Electrolyser



It will produced twice as much hydrogen gas as oxygen gas (balance equation):

$$2H_2O \rightarrow 2H_2 + O_2$$

4. To fully understand the process, it is necessary to take a look of the **half reactions**:

   a. **Reduction of hydrogen**:

      - In the balance equation, the hydrogen has a positive charge. Therefore, to become neutral, it needs to **gain one electron**.
      - In the electrolysis, that electron comes from the **cathode**. Therefore, the **hydrogen** is formed in the cathode.
      - In equations:

$$2H_2O + 2e^- \rightarrow H_2^0 + 2(OH)^-$$

   b. **Oxidation of oxygen**:

      - In the balance equation, the oxygen has a negative charge. Therefore, to become neutral, it needs to **lose two electrons**.
      - In the electrolysis, that electron goes away at the **anode**. Therefore, the **oxygen** is formed in the anode.
      - In equations:

$$\begin{aligned} 2H_2O - 4e^- &\rightarrow O_2^0 + 4H^+ \\ 2H_2O &\rightarrow O_2^0 + 4H^+ + 4e^- \end{aligned}$$

5. **Combining the two half equations** and making some **algebra**:

a. Multiplying the reduction equation by 2.

$$2\left(2H_2O + 2e^- \rightarrow H_2^0 + 2(OH)^-\right)$$
$$4H_2O + 4e^- \rightarrow 2H_2^0 + 4(OH)^-$$

b. Summing the reduction and the oxidation equations:

$$4H_2O + 4e^- + 2H_2O \rightarrow 2H_2^0 + 4(OH)^- + O_2^0 + 4H^+ + 4e^-$$

c. The electrons can be cancelled out

$$4H_2O + 2H_2O \rightarrow 2H_2^0 + 4(OH)^- + O_2^0 + 4H^+$$

d. By arranging terms:

$$6H_2O \rightarrow 2H_2^0 + 4(H_2O) + O_2^0$$

e. By cancelling terms:

$$2H_2O \rightarrow 2H_2^0 + O_2^0$$

The last equation is the **balance equation**, where for each atom of oxygen two atoms of hydrogen are produced.

Other useful videos to understand the electrolysis process:

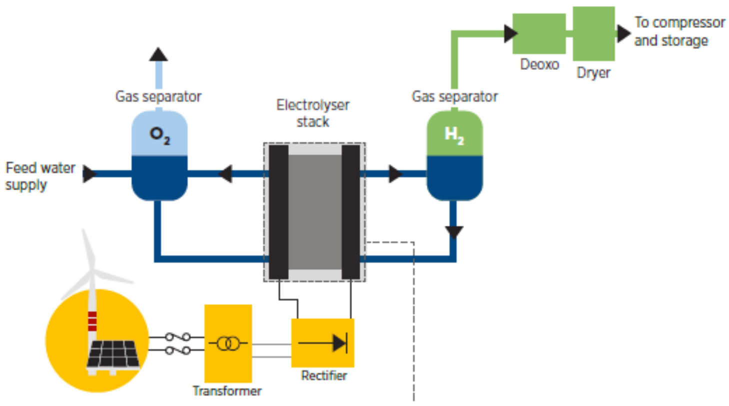
- What Is Electrolysis | Reactions | Chemistry | FuseSchool
- Electrolysis of Water and Hydrochloric Acid | Reactions | Chemistry | FuseSchool

7.4 Electrolyser: Technology characterisation

Water electrolysers are electrochemical devices used to split water molecules into hydrogen and oxygen by passage of an electrical current. They can be fragmented in **three levels** (see figure 7.2:

- The **cell** is the core of the electrolyser and it is where the electrochemical process takes place. It is composed of the two electrodes (anode and cathode) immersed in a liquid electrolyte or adjacent to a solid electrolyte membrane, two porous transport layers (which facilitate the transport of reactants and removal of products), and the bipolar plates that provide mechanical support and distribute the flow.
- The **stack** has a broader scope, which includes multiple cells connected in series, spacers (insulating material between two opposite electrodes), seals, frames (mechanical support) and end plates (to avoid leaks and collect fluids).
- The **system level** (or balance of plant) goes beyond the stack to include equipment for cooling, processing the hydrogen (e.g. for purity and compression), converting the electricity input (e.g. transformer and rectifier), treating the water supply (e.g. deionization) and gas output (e.g. of oxygen).

Figure 7.2: Electrolysers components



Source: IRENA (2020a)

Purified water is fed into the system using circulating pumps, or also by gravity. The water then reaches the electrodes by flowing through the bipolar plates and through the porous transport layers. At the electrode, the water is split into oxygen and hydrogen, with ions (typically H+ or OH-) crossing though a liquid or solid membrane electrolyte. The membrane or diaphragm between both electrodes is also responsible for keeping the produced gases (hydrogen and oxygen) separated and avoiding their mixture. This general principle has remained the same for centuries, but the technology has evolved since William Nicholson and Anthony Carlisle first developed it in 1800.

The principle of water electrolysis is simple, yet it allows the construction of different technological variations based on various physicalchemical and electrochemical aspects. **Electrolysers are typically divided into four main technologies** (figure 7.3). These are distinguished based on the **electrolyte** and **temperature of operation**, which in turn will guide the selection of different materials and components.

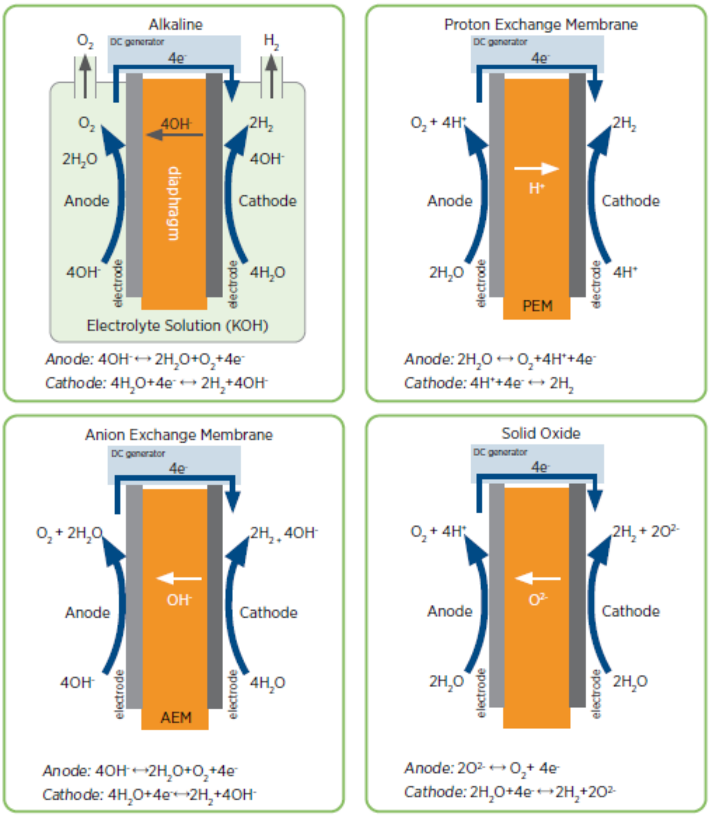
7.4.1 Cell level for each type of electrolyser

1. **Alkaline electrolysers:** These have a simple stack and system design and are relatively easy to manufacture. Currently, they have electrode areas as high as 3 square metres (m^2). They operate with high concentrate KOH (typically 57 moles of solute per litre of solution [mol*L-1]) as electrolyte, robust ZrO2 based diaphragms and nickel (Ni) coated stainless-steel for the electrodes. The ionic charge carrier is the hydroxyl ion OH-, with KOH and water permeating through the porous structure of the diaphragm to provide functionality for the electrochemical reaction. This allows the intermixing of the produced gases (hydrogen and oxygen – H2 and O2) that are dissolved in the electrolyte, limiting lower power-operating range and the ability to operate at higher pressure levels.

Some important considerations:

- To prevent this, thicker (0.252 millimetre [mm]) diaphragms are used, but this creates a higher resistance and lower efficiencies.
- Spacers are sometimes included by some manufacturers between electrodes and diaphragms to further avoid the intermixing of gases.
- These thick diaphragms and added spacers result into high ohmic resistances across the two electrodes, drastically reducing current density at a given voltage.

Figure 7.3: Electrolysers types



Source: IRENA (2020a)

- Today´s advanced designs, using zero gap electrodes, thinner diaphragms and differen electrocatalyst concepts to increase current density, have already reduced their performance gap in comparison to PEM technology.

- On the other hand, classic and sturdy alkaline designs are known to behave very reliably, **reaching lifetimes above 30 years**.

2. **Polymer Electrolyte Membrane (PEM) electrolysers**. These use **a thin (0.2 mm) PFSA membrane** and electrodes with advanced architecture that allows achieving higher efficiencies (i.e. less resistance). The perfluorosulfonic acid (PFSA) membrane is also chemically and mechanically robust, which allows for high pressure differentials. Thus, the PEM cells can operate at up to 70 bar with the oxygen side at atmospheric pressure.

Some important considerations:

- The acidic environment provided by the PFSA membrane, high voltages, and oxygen evolution in the anode creates a harsh oxidative environment, demanding the use of materials that can withstand these conditions.

- **Titanium-based materials**, noble metal catalysts and protective coatings are necessary, not only to provide long-term stability to cell components, but also to provide optimal electron conductivity and cell efficiency.

- These requirements have caused PEM stacks to be more expensive than alkaline electrolysers. PEMs have one of the most compact and simplest system designs, yet they are sensitive to water impurities such as iron, copper, chromium and sodium and can suffer from calcination.

- Today, electrode areas are quickly approaching 2 000 square centimetres (cm^2), yet this is still far from future concepts of large MW stack units using single stack concepts.

- Last but not least, the reliability and **lifetime characteristics of large-scale**, MW PEM stacks still have to be validated.

3. **Solid oxide electrolysers (SOEC)**.

Some important considerations:

- These operate at high (700-850°C) temperatures. This enables: the favourable kinetics that allow the use of relatively cheap nickel electrodes; electricity demand decreases and part of the energy for separation is provided through heat (waste heat can be used and apparent efficiencies based on electricity can be higher than 100%); the potential for reversibility (operating as fuel cell and electrolyser); coelectrolysis of CO2 and water to produce syngas (which is the basic building block for the chemical industry).

- On the downside, thermo-chemical cycling, especially under shutdown/ramping periods, leads to faster degradation and shorter lifetimes. Other issues related to stack degradation include: challenges related to sealing at higher differential pressure; electrode contamination by silica used as sealants; and other additional contaminant sources from piping, interconnects and sealing. SOECs are today only deployed at the kW-scale, although some current demonstration projects have already reached 1 MW.

4. **Anion Exchange Membranes (AEM).**

Some important considerations:

- This is the latest technology with only a few companies commercialising it, with limited deployment.
- AEM's potential lies in the combination of a less harsh environment from alkaline electrolysers with the simplicity and efficiency of a PEM electrolyser.
- It allows the use of non-noble catalysts, titanium-free components, and, as with PEM, operation under differential pressure.
- The reality, however, is that the AEM membrane has chemical and mechanical stability problems, leading to unstable lifetime profiles.
- Moreover, performance is not yet as good as expected, mostly due to low AEM conductivity, poor electrode architectures and slow catalyst kinetics.
- Performance enhancement is typically achieved by tuning membrane conductivity properties, or by adding a supporting electrolyte (e.g. KOH, or sodium bicarbonate [NaHCO3]).
- Such tuning could lead to decreased durability, however. The OH- ion is intrinsically three-fold slower (lower conductivity) than H+ protons within PEM, which forces AEM developers to either make thinner membranes, or ones with higher charge density.

7.4.2 System level for each type of electrolyser

System Components

The system components are in figure 7.2.

Hydrogen processing unit: Compression

Hydrogen from the electrolyser is in gaseous form, conventionally from atmospheric pressure to 30 bar, while higher pressures are possible. To facilitate hydrogen transport, a lower volume is needed. This means either increasing the pressure, liquefying the gas, or converting it for liquid organic hydrogen carriers. Compression can make a large difference. Going from atmospheric to 70 bar (a typical pressure for transmission pipelines) can already reduce the gas volume by a factor of 65. Compressing it to 1 000 bar (a typical pressure for storage in tanks) can reduce the volume by a factor of 625 compared to atmospheric, and liquefaction by a factor of 870.

Compression can be done in mainly **three ways**:

- Using a standard separate compressor.
- By changing the operating pressure of the electrolyser.
- Using a separate electrochemical device.

Power supply system

Power supply system cost can decline through economies of scale, standardised designs and participation of specialised electrical equipment suppliers instead of electrolyser manufacturers.

Water and land use for green hydrogen production

Water use is not barrier to scaling up electrolysis. Even in places with water stress, sea water desalination can be used with limited penalties on cost or efficiency.

For the **land area**, there are no real projects of more than 100 MW in water electrolysis (the largest one, as of November 2020, is 20 MW, in Becancour, Canada). Thus, so far, land area estimates rely on engineering estimates, rather than plot optimisation based on real experience. Yet, there are a couple of estimates available:

- A study funded by the German government in 2014 estimated that a 100 MW electrolyser plant would occupy about 6 300 m2.
- Siemens estimated back in 2017 that a 300 MW electrolyser plant would occupy about 180 metres (m) x 80 m (15 000 m2).
- ITM estimated in 2017 that one 100 MW electrolyser would occupy about 40 m x 87 m (3 500 m2), with the possibility of using multiple layout options to fit different applications and of replicating this easily by having a standardised design.
- In 2018, McPhy proposed a 100 MW facility (composed of five modules of 20 MW each) with a plot size of 4 500 m2.

To put these numbers in perspective, a global capacity of 1 000 GW of electrolysers, which would be enough to replace the entire current pure and mixed hydrogen fossil-based production, would occupy a land area of the size of Manhattan, New York, using the most conservative estimate (i.e. 0.17 km2).

Another reference is that this energy density of almost 7 500 MW/km2 is almost 1 500 times larger than a relatively good onshore wind density of 5 MW/km2, which means the electrolyser would only be a fraction of the space occupied by the renewable electricity input, highlighting the need to use hydrogen only for applications that are hard to electrify and reduce the upstream renewable capacity needed to satisfy the same demand.

7.4.3 Trade-offs to consider in the design of the electrolyser

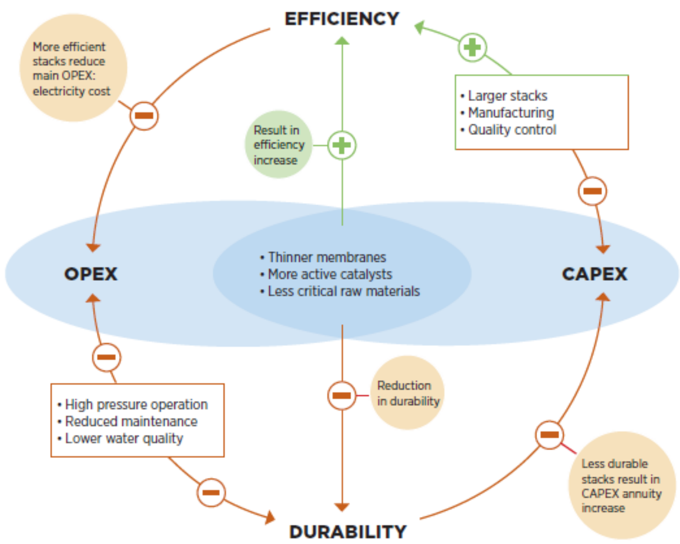
On the supply side, the prospects for green hydrogen depend on the **performance of the electrolyser**. The key dimensions that *R&D* strategies need to address are:

- The **efficiency** increase at the cell, stack, and system level (this reduces operational cost).
- The **current to the stack** is directly related to cell and stack capacity and therefore to hydrogen production.
- A **durability** increase to more than 100 000 hours for any developed system concept.
- An **investment cost** reduction (both stack and system).

These four dimensions are related to each other, however, and improvement in one of them usually leads to a poorer performance in another.

For example, a thicker membrane is mechanically stronger and leads to longer lifetime profiles, but it also increases the resistance to the transport of charges, which in turn decreases the efficiency. While the longer lifetime results in a lower cost contribution of the investment component, the lower efficiency results in a higher operating cost given the higher electricity

Figure 7.4: Trade-offs between efficiency, durability and cost for electrolysers



Source: IRENA (2020a)

consumption. Figure 7.4 shows the positive or negative effect (arrows + colour) some of the independent choices during manufacturing and research (green boxes) can have on each dimension.

Another **two important aspects** are the use of **more active catalysts** and the **specific business case for the electrolyser**.

The use of more **active catalysts** that are able to improve efficiency levels, but could have negative impact on durability. One example is ruthenium catalysts, which are more active than iridium, but suffer from long-term stability. Moreover, any catalyst free of critical raw materials needs to be aimed at higher efficiencies, but this typically result in catalysts that are less robust and more prone to dissolution.

The **specific business case for the electrolyser** will also affect the optimisation of these parameters. For example, an electrolyser that is coupled with PV could only operate typically less than 2 000 hours in a year, making the capital cost a critical parameter to tackle. With such limited operating hours, durability might be less of an issue, since a short operating lifetime still translates into a longer actual lifetime. This could lead to using materials that are cheaper, but degrade faster. This case is different to one where the electrolyser is coupled with a concentrated solar power that has higher operating hours in a year, but that delivers a higher electricity price, making efficiency more important to reduce the operational cost.

Lifetime aspects related to materials and components

The lifetime of electrolyser technologies is a function of the cumulative current passing through the stack, which can be represented by the **number of full load hours** as well as the **number of operating hours** – the number of hours during which the facility is on, regardless of load operating levels.

1. **Alkaline electrolysers** are the most robust, with proven lifetimes of over 30 years.
2. **PEM electrolysers** have reported lifetimes of more than 50 000 hours.

3. **SOEC electrolysers** can achieve lifetimes of 20 000 hours, but under constant power and well-defined operating conditions (i.e. not coupled to variable renewable energy [VRE]).

   The main degradation mechanism is the thermal cycling, due to the high operating temperatures and need to cool down in case of dynamic operation.

   Reversible operation of solid oxide cells (electrolysis + fuel cell) could help increase the hours of operation and thus keep the system at operating temperature.

   Deploying SOEC at large scale would require larger cells than currently used (up from 300 cm2 to more than 1 000 cm2), which renders them more prone to failure.

   Another important aspect is silica contamination and the instabilities of sealing concepts.

4. **AEM electrolysers** suffer from a short lifetime, while limited information about their long-term operation, reliability and robustness is available.

   The stability of the AEM polymer used to fabricate membrane and catalyst layers is well recognised as a major issue, especially when operated with KOH as the supporting electrolyte.

   The main degradation mechanism is hydroxide (OH-) attack on the polymer backbone, which leads to membrane collapse and catalyst layer dissolution within a few days.

   One solution is cross-linking chemical methods, but this comes at a cost of cell efficiency. Another approach is by operating the stack without a supporting electrolyte (i.e. using only pure water), which can lead to a durability beyond 5 000 hours, but this results in much lower efficiencies, or current densities.

Efficiency of a hydrogen production facility

The system efficiency of a green hydrogen production facility, measured in units of kilowatt hours consumed per kilograms of hydrogen produced (kWh/kgH2), is a result of the individual efficiencies of the **cell**, **stack** and **balance of plant**, as follows.

1. **Cell:** The efficiency profile decreases linearly from lower to higher load levels, so the higher the current input, the lower the stack efficiency.

   Naturally, the higher the hours of operation, the lower will be the efficiency due to degradation, though the aforementioned dynamic remains.

   At the operational level, the cell voltage is the element actually measured to infer the system performance, in such a way that, the higher the cell voltage, the lower the stack efficiency.

2. **Balance of plant:** A range of system elements such as cooling, purifiers, thermal management, water treatment and others, consume power in order to operate, which also needs to be considered in the facility's overall efficiency.

   Efficiency losses can be minimised by:

- Designing the electrolyser facility while taking a whole-of-system perspective.
- Using commercially-available components rather than custom made ones.
- Maximising system efficiency including balance of plant, tailored for the specific application.

7.5 Production costs

7.5.1 Cost abatement as key enabler for hydrogen development

In addition to regulations and market design, the cost of production is a major barrier to the uptake of green hydrogen. Costs are falling – largely due to falling renewable power costs – but green hydrogen is still 2-3 times more expensive than blue hydrogen (produced from fossil fuels with carbon capture and storage) and further cost reductions are needed.

The largest single cost component for on-site production of green hydrogen is the cost of the renewable electricity needed to power the electrolyser unit. This renders production of green hydrogen more expensive than blue hydrogen, regardless of the cost of the electrolyser. **A low cost of electricity is therefore a necessary condition for producing competitive green hydrogen**. This creates an opportunity to produce hydrogen at locations around the world that have optimal renewable resources, in order to achieve competitiveness.

Low electricity cost is not enough by itself for competitive green hydrogen production, however, and **reductions in the cost of electrolysis facilities are also needed**. This is the second largest cost component of green hydrogen production and is the focus of this report, which identifies key strategies to **reduce investment costs for electrolysis plants from 40% in the short term to 80% in the long term**. These strategies range from the fundamental design of the electrolyser stack to broader system-wide elements, including:

1. **Electrolyser design and construction**: Increased module size and innovation with increased stack manufacturing have significant impacts on cost. Increasing the plant from 1 MW (typical today) to 20 MW could reduce costs by over a third. Cost, however, is not the only factor influencing plant size, as each technology has its own stack design, which also varies between manufacturers. The optimal system design also depends on the application that drives system performance in aspects such as efficiency and flexibility.
2. **Economies of scale**: Increasing stack production to automated production in GW- scale manufacturing facilities can achieve a step-change cost reduction. At lower manufacture rates, the stack is about 45% of the total cost, yet at higher production rates, it can go down to 30%. For Polymer Electrolyte Membrane (PEM) electrolysers, the tipping point seems to be around 1 000 units (of 1 MW) per year, where this scale-up allows an almost 50% cost reduction in stack manufacturing. The cost of the surrounding plant is as important as the electrolyser stack and savings can be achieved through standardisation of system components and plant design.
3. **Procurement of materials**: Scarce materials can represent a barrier to electrolyser cost and scale-up. Current production of iridium and platinum for PEM electrolysers will only support an estimated 3 GW-7.5 GW annual manufacturing capacity, compared to an estimated annual manufacturing requirement of around 100 GW by 2030. Solutions that avoid the use of such materials are already being implemented by leading alkaline electrolyser manufacturers, and technologies exist to significantly reduce the requirements for such materials in PEM electrolysers. Anion Exchange Membrane (AEM) electrolysers do not need scarce materials in the first place.

4. **Efficiency and flexibility in operations**: Power supply represents large efficiency losses at low load, limiting system flexibility from an economic perspective. A modular plant design with multiple stacks and power supply units can address this problem. Compression could also represent a bottleneck for flexibility, since it might not be able to change its production rate as quickly as the stack.

   One alternative to deal with this is an integrated plant design with enough capacity to deal with variability of production through optimised and integrated electricity and hydrogen storage. Green hydrogen production can provide significant flexibility for the power system, if the value of such services is recognised and remunerated adequately. Where hydrogen will play a key role in terms of flexibility, as it does not have any significant alternative sources to compete with, will be in the **seasonal storage of renewables**. Although this comes at significant efficiency losses, it is a necessary cornerstone for achieving 100% renewable generation in power systems with heavy reliance on variable resources, such as solar and wind.

5. **Industrial applications**: Electrolysis system design and operation can be optimised for specific applications. These can range from:

   - Large industry users requiring a stable supply and with low logistics costs.
   - Large scale, off-grid facilities with access to low-cost renewables, but that incur in significant costs to deliver hydrogen to the end-user.
   - Decentralised production that requires small modules for flexibility, which compensate for higher investment per unit of electrolyser capacity with reduced (or near zero on site) logistic costs.

6. **Learning rates**: Several studies show that potential learning rates for fuel cells and electrolysers are similar to solar PV and can reach values between 16% and 21%. This is significantly lower than the 36% learning rates experienced over the last 10 years for PV (IRENA, 2020b). With such learning rates and a deployment pathway in line with a 1.5°C climate target, a reduction in the cost of electrolysers of over 40% may be achievable by 2030.

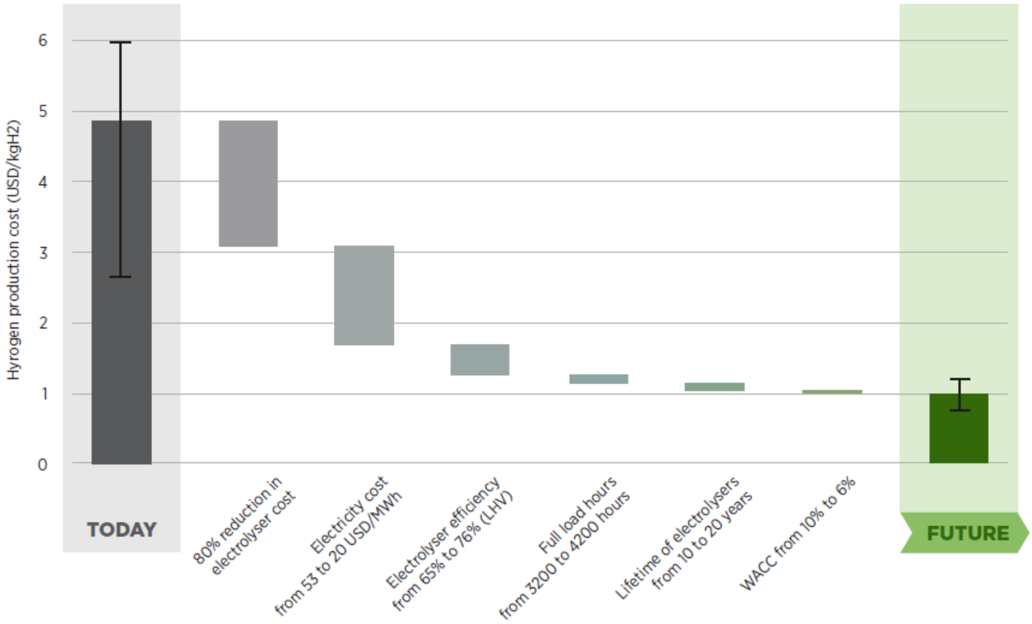
Figure 7.5 shows how up to 85% of green hydrogen production costs can be reduced in the long term by:

1. Access to cheaper electricity.
2. Electrolyser capex investment.
3. Increasing efficiency.
4. Optimising operation of the electrolyser.

Figure 7.6 illustrates the potential green hydrogen production cost reduction between 2020 and 2050 for a range of electrolysers cost and deployment levels. In the best-case scenario, green hydrogen can already be produced at costs competitive with blue hydrogen today, using **low cost renewable electricity**, i.e. around USD 20 per megawatt-hour (MWh).

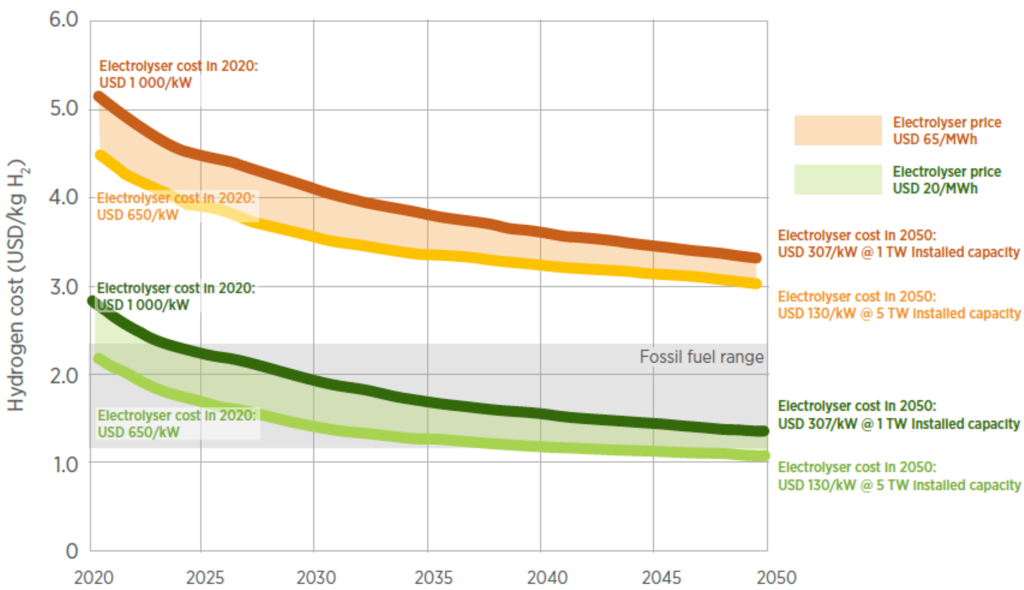
A low electricity price is essential for the production of competitive green hydrogen, and, as illustrated in figure 7.6, cost reductions in electrolysers cannot compensate for high electricity prices. Combined with low electricity cost, an aggressive electrolyser deployment pathway can make green hydrogen cheaper than any low-carbon alternative (i.e. $<$ USD 1/kg), before 2040. If rapid scale-up takes place in the next decade, green hydrogen is

Figure 7.5: Hydrogen cost reduction



Source: IRENA (2020a)

Figure 7.6: Hydrogen cost reduction trends



Source: IRENA (2020a)

expected to start becoming competitive with blue hydrogen by 2030 in a wide range of countries – e.g. those with electricity prices of USD 30/MWh – and in applications.

Today's cost and performance are not the same for all electrolyser technologies (see figure 7.7). Alkaline and PEM electrolysers are the most advanced and already commercial, while each technology has its own competitive advantage. Alkaline electrolysers have the lowest installed cost, while PEM electrolysers have a much smaller footprint, combined with higher current density and output pressure. Meanwhile, solid oxide has the highest electrical efficiency. As the cell stack is only part of the electrolyser facility footprint, a reduced stack footprint of around 60% for PEM compared to alkaline translates into a 20% – 24% reduction in the facility footprint, with an estimated footprint of 8 hectares (ha)-13 ha for a 1 GW facility using PEM, compared to 10 ha-17 ha using alkaline. **Gaps in cost and performance are expected to narrow over time as innovation and mass deployment of different electrolysis technologies drive convergence towards similar costs**.

The wide range in system costs is expected to remain, however, as this is very much dependent on the scale, application and scope of delivery. For instance, a containerised system inside an existing facility with existing power supply is significantly lower cost than a new building in a plot of land to be purchased, with complete water and electricity supply system to be included, high purity hydrogen for fuel cell applications and high output pressure. Normally, numbers for system costs include not only cell stack, but also balance of stacks, power rectifiers, the hydrogen purification system, water supply and purification, cooling and commissioning – yet exclude shipping, civil works and site preparations.

7.5.2 Innovation

Innovation is crucial to reduce cost and improve the performance of the electrolyser. The ultimate goals are to:

1. Reduce cost by standardising and simplifying manufacturing and design to allow for industrialisation and scale-up.

2. Improve efficiency to reduce the amount of electricity required to produce one unit of hydrogen.

3. Increase durability to extend the equipment lifetime and spread the cost of the electrolyser facility over a larger hydrogen production volume.

7.5.3 Government support

Governments can support innovation in electrolysers by issuing clear long-term signals that support policy on:

1. Facilitating investment in production, logistics and utilisation of green hydrogen, including all areas that will help this low-carbon energy carrier to become competitive; technology cost and performance improvements, material supply, business models and trading using common standards and certifications.

2. Establishing regulations and design markets that support investments in innovation and scale-up the production of green hydrogen. This includes approaches such as setting manufacturing or deployment targets, tax incentives, mandatory quotas in hard to decarbonise sectors and other de-risking mechanisms, while enabling new business models that can guarantee predictable revenues for the private sector to invest at scale.

Figure 7.7: Electrolysers cost components (four technologies)

	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/KgH$_2$]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only, > 1 MW) [USD/kW$_{el}$]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW$_{el}$]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

Source: IRENA (2020a)

3. Supporting research, development and demonstration (*RD&D*) to: reduce the use of iridium and platinum in the manufacture of PEM electrolysers; transition all alkaline units to be platinum- and cobalt-free; and, in general, mandate reduced scarce materials utilisation as a condition for manufacturing scale-up.

4. Fostering coordination and common goals along the hydrogen value chain, across borders, across relevant sectors and between stakeholders.

7.6 Hydrogen and renewables

Hydrogen is only one option in **decarbonising hard-to-abate sectors**. Energy efficiency is key to reducing the energy supply and renewable capacity upstream, while bioenergy might be suitable, not only in the form of biofuels for those transport sectors that have limited fuel alternatives (especially aviation), but also as a source of carbon for synthetic fuels. Direct electrification is more efficient from a systems perspective, leading to lower cost, with this already commercially deployed in many areas (e.g. heating or passenger vehicles). Carbon capture and storage (CCS) might be attractive for existing assets that are still in early stages of their lifetime (the case for many assets in Asia) and process emissions (e.g. from cement production). Even for the most ambitious scenarios, these technological choices might not be enough, however, and behavioural changes might be needed to push energy demand even lower. Thus, for energy transition, hydrogen is one solution amongst others and should be tackled in parallel. Hydrogen is part of a wider technology portfolio to be adapted to domestic conditions in each country, with this report further exploring this pathway.

Once produced at scale and competitive cost, green hydrogen can also be further **converted into other energy carriers**, such as ammonia, methanol, methane and liquid hydrocarbons. As a fuel, hydrogen can be used in fuel cells (i.e. an electrochemical device that combines hydrogen with oxygen from the air and produces electricity), but also combusted in engines and turbines. Fuel cells can be used for stationary applications in large-scale power plants, microgrid or backup generation (e.g. in data centres), or for a wide range of transport applications – as is already done in fuel cell electric vehicles (FCEV), trucks, light-duty vehicles, forklifts, buses, ferries and ships. As a chemical, green hydrogen can reduce greenhouse gas (GHG) emissions from sectors where hydrogen from fossil fuel is widely used today, including oil refining, methanol and ammonia production.

Green hydrogen is only one of the production pathways. Hydrogen can also be produced from **bioenergy, methane, coal or even directly from solar energy**. Most of the production today is based on methane and coal (about 95%) (IRENA, 2019) and could be made low carbon with the use of CCS. CCS might be suitable for regions with low-cost natural gas and suitable underground reservoirs. In the short term, CCS might also be a good fit for large-scale applications in industry, given the relatively small scale of deployment for electrolysis.

Low-carbon hydrogen can also be produced from **methane pyrolysis**, where the carbon ends up as solid rather than as CO2, with 4-5 times lower electricity consumption than electrolysis and potentially lower hydrogen production cost. Each pathway has its own limitations. Bioenergy might be best suited for other applications, considering its limited nature and the low inherent hydrogen yield. CCS does not lead to zero emissions, requires significant infrastructure for the CO2, does not enable sector coupling, is still exposed to the price fluctuations characteristic of fossil fuels, and could face social acceptance issues. In addition, methane leakages associated with production and transportation of the gas have been increasingly under scrutiny as significant contributors to the acceleration of climate change. Methane has 86 times higher global warming potential compared to CO2 over a 20-year time horizon. Pyrolysis is still at the pilot scale stage and would require high-temperature renewable or low carbon heat. Hence, considering the sector, green hydrogen is one of the most attractive options, given its nature and renewable character, and as such, it is the focus of this report.

7.6.1 Strategies focused on electrolysers scale-up

A few selected hydrogen strategies are highlighted here, in particular those with a clear focus on electrolysers scale-up.

1. **Australia:** National hydrogen strategy sets a vision for a clean, innovative, safe and competitive hydrogen industry, with the aim of positioning it as a major player by 2030. The strategy outlines an adaptive approach that equips Australia to scale up quickly as the hydrogen market grows. The strategy includes a set of nationally coordinated actions involving governments, industry and the community. Australia has adopted eight international standards to shape its hydrogen future, as it bids to use the fuel to enhance energy security and build a billion dollar export industry. The rules have the potential not only to support the safety of users – with guidance on storage, transport and refuelling – but also to facilitate international trade, as the nation aims to assume a major role in the global hydrogen economy.

   As mentioned above, one of the key targets is "H2 under 2", which targets a production cost of AUD 2/kg (USD 1.4/ kg) for hydrogen to be competitive across various applications. By 2019, when the national strategy was launched, the government had committed over AUD 500 million (USD 355 million) towards hydrogen projects. Additionally, the government has announced an investment package of AUD 1.9 billion (USD 1.35 billion) to support new energy technologies, including hydrogen, with AUD 70.2 million (USD 49.8 million) dedicated specifically to hydrogen export hubs.

2. **European Union:** On July 8, 2020, the European Commission published its hydrogen strategy for a climate neutral Europe. This aims to boost the clean production of hydrogen to be used as a feedstock, fuel, energy carrier, and ultimate storage alternative for European renewables. The drivers for hydrogen are carbon neutrality, job creation, economic growth and technology leadership (especially for electrolysers). the strategy has explicit electrolyser capacity targets of 6 GW by 2024 and 40 GW by 2030, as well as production targets of 1 million and 10 million tonnes of renewable hydrogen per year for those two milestone years. Reaching these production targets would require a larger capacity than the 6 GW and 40 GW specified, which implies additional import from neighbouring countries. Investments in renewable hydrogen are estimated to be in the order EUR 220-340 billion (USD 280- 430 billion) for the electricity production and EUR 24-42 billion (USD 30.5-53 billion) for the electrolysers by 2030.

   Hydrogen is seen by the European Commission as a key vector across energy sectors and this strategy was released together with a strategy called "Energy System Integration", highlighting this function. The Clean Hydrogen Alliance (CHA), a platform that brings together multiple stakeholders from industry, government, civil society and academia, was also launched the same day. Besides bringing actors together, the CHA is also meant to provide a robust pipeline of projects that will support the scale-up process. The commission´s economic recovery plan, "Next Generation EU", highlights hydrogen as an investment priority to boost economic growth and resilience, creating local jobs and consolidating the EU´s global leadership. The total fund is EUR 750 billion (about USD 950 million) and while only a small share of this is expected to be used for hydrogen, it could represent a large step towards the 2024 goal of 6 GW.

3. **Japan:** This was the first country to adopt a "basic hydrogen strategy" and with specific plans to become a "hydrogen society". The Japanese strategy primarily aims to achieve cost parity with competing fuels, such as gasoline in the transportation sector or liquefied natural gas (LNG) in power generation. The strategy also covers the entire supply chain, from production to downstream market applications.

   Given limited natural resources and limited land availability, hydrogen import plays a key role in the Japanese strategy. The approach has been to pursue parallel demonstration projects with multiple sources, hydrogen carriers and enduse sectors to derisk future imports and increase the flexibility of supply. There are projects with Australia (coal with CCS and liquid hydrogen5), Saudi Arabia (oil and ammonia), Brunei (gas and liquid organic carriers) and Norway (hydropower and liquid hydrogen). Japan's strategy could have a positive global impact and contribute to the creation of new synergies regarding international energy trading and business cooperation. These will be crucial in driving development and making technologies more affordable. According to the roadmap of the Japanese Ministry of Economy, Trade and Industry (METI), Japan expects hydrogen technologies to become profitable by 2030. METI has set specific targets6 for green hydrogen in terms of electrolyser cost (USD 475/kW), efficiency (70%, or 4.3 kWh per normal cubic metre [Nm3]) and finally production cost (USD 3.3/kg) by 2030.

7.7 Flexibility of green hydrogen production facilities

To ensure that green hydrogen supply cost is as low as possible, a holistic approach needs to be applied to system design and operations. System design can be optimised to **minimise cost** and **increase flexibility** as necessary, depending on a variety of factors. These can include:

1. The variability of electricity supply (i.e. constant consumption of grid electricity, or direct feed from variable solar or wind farms).

2. The technology used for the stack (e.g. alkaline, PEM and AEM being more flexible than solid oxide).

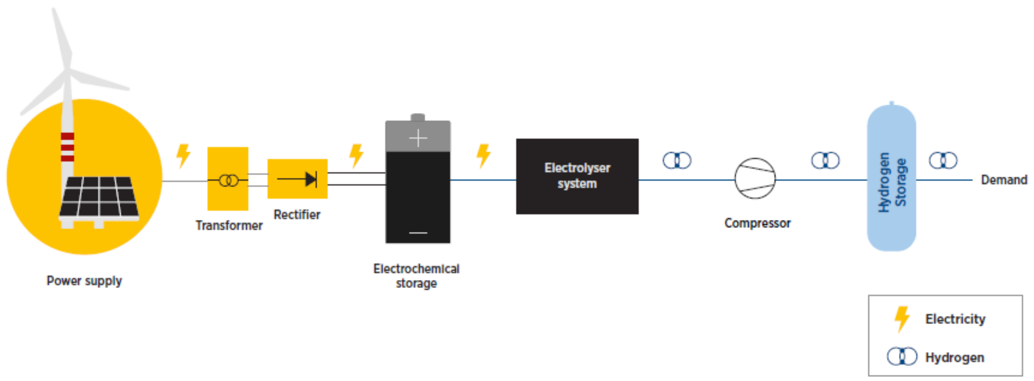
3. The flexibility of hydrogen demand (e.g. constant demand for chemical processes, general annual demand for export without hourly or daily constraints).

4. Storage can significantly help to decouple variable supply from hydrogen demand. This can come in the form of electrochemical storage for short-term fluctuations (before the electrolyser stack), or in the form of hydrogen storage for long-term fluctuations (after the stack, before the downstream off-taker). Similarly, hydrogen storage in tanks, caverns and pipelines can help decouple variable hydrogen production from inflexible hydrogen demand (e.g. to produce ammonia).

The type of electricity supply and hydrogen demand will drive system design, where no single electrolyser technology is better than any other, as the combination with electricity and hydrogen storage can effectively provide any level of flexibility, as illustrated in figure 7.8.

Where hydrogen has a significant role to play in terms of **flexibility provision** in future decarbonised power systems is in long duration storage and system adequacy. The seasonality of solar, wind and hydropower resources can provide challenges in terms of adequacy – if not every year, at least in unusual weather years (e.g. dry years, or years with extended periods of low wind). Hydrogen from renewable power can be stored cost effectively – for example, in salt caverns – and can be used for power generation in these particular periods.

Figure 7.8: Green hydrogen production facility with electricity and hydrogen storage



Source: IRENA (2020a)

Due to the near zero short run marginal cost of solar and wind, when they are reach significant generation share in a market interval (e.g. in a one hour period), they drive down electricity prices. Figure 7.9 shows how hydrogen production follows renewable electricity availability, highlighting an important seasonality in the production of hydrogen.

The key message is that hydrogen production from electrolysers can be uniquely positioned to provide seasonal flexibility to the power system – something that no other resource can effectively provide. This can play a significant role in balancing a power system with high shares of solar and wind, not only instantaneously and intra-day, but also across seasons. To be able to provide such services, electrolysers must be designed not to operate at full capacity the entire year, but rather to purchase electricity when green and affordable. This is only possible if they are sufficiently oversized to avoid purchasing non renewable electricity, or prohibitively expensive electricity, just to be able to meet hydrogen demand.

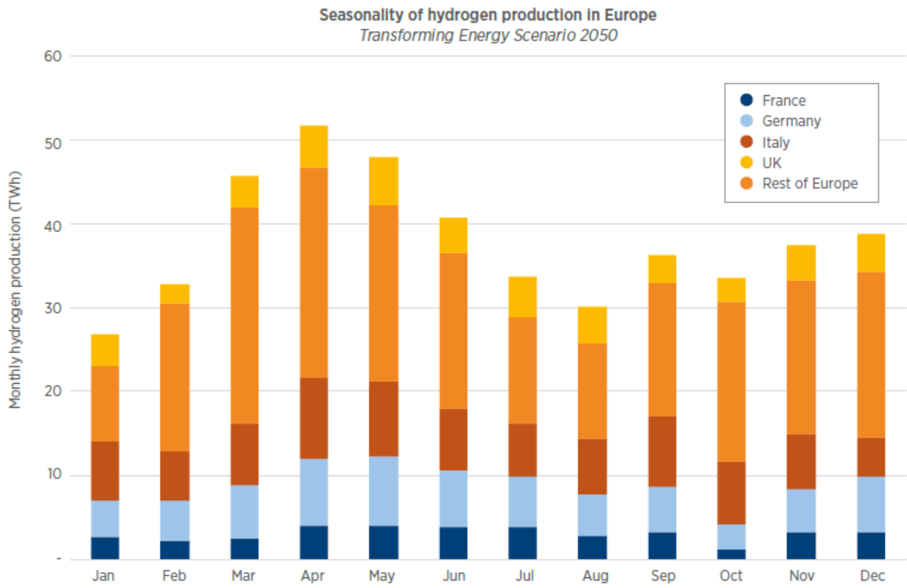
Hydrogen can be **stored** and **transported** in multiple ways. In terms of flexibility services, electrolysers have been evaluated in terms of:

1. The time they take to respond to a change in power set-point.
2. The time they take to settle after a power set-point change.
3. The rate at which they can change power consumption.
4. The lower operation limit, or the minimum turn down level.
5. The time they take to start up and shut down.

A **report** (Eichman, Harrison and Peters, 2014) has found that:

1. Small electrolyser systems (around 40 kW units) begin changing their electricity demand within milliseconds of a set-point change.
2. The settling time after a set-point change is in the order of seconds.
3. Electrolysers can reduce their electrical consumption to zero for an unlimited amount of time.
4. Electrolysers exhibit low part load operation capabilities.

Figure 7.9: Seasonality of hydrogen production in Europe (IRENA simulation)



Source: IRENA (2020a)

5. Electrolysers can start up and shut down in several minutes.

From the point of view of **short-term flexibility** alkaline and PEM water electrolysers still present the most interesting technical capability, as they have proven to provide very fast dynamics among all available electrolysis process.

For **congestion management**, large scale electrolysers can contribute to the reduction of critical peak loads by reducing their electricity demand, or even by completely interrupting operation. This service should be remunerated adequately, however, to compensate for the economic incentive to operate the electrolyser as many hours as possible to reduce the contribution of the investment cost to the total cost. Moreover, such an application can also have its limitations, since several industrial processes cannot be stopped when integrated with the electrolyser facility, therefore limiting flexibility of operations based on the size of the hydrogen storage.

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Chapter 8

Sustainable energy. Bioenergy

In this chapter, we study the role that bioenergy will play in energy mix in a context of decarbonization. We will focus mainly in the role of bioenergy in the industry sector, the transport sector, the building sector and the power sector. First, we motivate the chapter by watching a video and discussing the main points that we will address in the chapter. Then, we study the current status of bioenergy in the energy mix. We conclude by studying the technology outlook and the future trends of bioenergy. We complement the chapter by studying important topics as types of bioenergy, biogas or bioethanol.

This chapter is based in the document IRENA (2020a).

8.1 Discussion

To motivate the chapter, we start by watching the video How Gasification Turns Waste Into Energy

Based on that video, we discuss the next questions:

1. The video claims that bioenergy could have several **advantages for the environment**. Could you enumerate some of those advantage?
   - The waste produces **methane** that cause a lot of pollution.
   - The final use of the energy produced from waste generates pollution, but the environmental net effect is positive
2. The video proposes different ways to obtain **energy from waste**. Could you enumerate them?
   - **Direct way**: Incineration.
   - **Indirect way**: Gasification to obtain biodiesel, hydrogen, ethanol, methanol, ammonia, fertilizers.
3. Can you explain briefly the **gasification process**? Steam and oxygen is mixed with the waste to produce gas that will be transformed in biodiesel, hydrogen, ethanol, methanol, ammonia, fertilizers.
4. Do you know **other ways** to generate biodiesel, biogas or methanol? Those products could be also obtained through a fermentation process from organic residuals from forest or farms (see next box for some videos with extra information).

5. Can you explain the **business model** used during the gasification process?
    - **Downstream**: The companies are paid to take the waste.
    - **Upstream**: The companies are paid for producing high-valuable products.
6. Can you enumerate some of the **main challenges** that could face the implementation of gasification by using waste? Scaling the business could be difficult; uncertainty on regulation could limit investments; the risk of being a first mover in the business.

Other videos that are very useful to know more bout bioenergy:

How does a biogas plant work?

Bio-Energy with Carbon Capture and Storage (BECCS)

8.2 Bioenergy. Process

The **green house gas emissions** derived from agriculture, forestry, land use and waste suppose the 21.6% of the total green house gas emissions (figure 8.1). Moreover, The agricultural sector is responsible for more than 40% **of anthropogenic methane (**CH_4**) emissions** and more than 50% **of nitrous oxide (**N_2O**) emissions**. The waste sector also contributes to methane and nitrous oxide emissions. Both methane and nitrous oxide are potent greenhouse gases with global warming potentials (for a 100-year time horizon) that are, respectively, **21 and 310 times greater than that of** CO_2. Significant reductions in green house gas emissions are therefore possible if methane and nitrous oxide emissions can be reduced via improved management practices.

To avoid methane and nitrous oxide emissions, the residuals from agriculture and waste can be transformed into **bioenergy**. There are two processes to produce bioenergy: **Gasification**, and **anaerobic fermentation**. We explain the fundamentals of each of those two processes.

8.2.1 Gasification

This section is based on the National Energy Lab webpage (link)

An useful video that summarize the chemical reactions within the gasification process is in this (link).

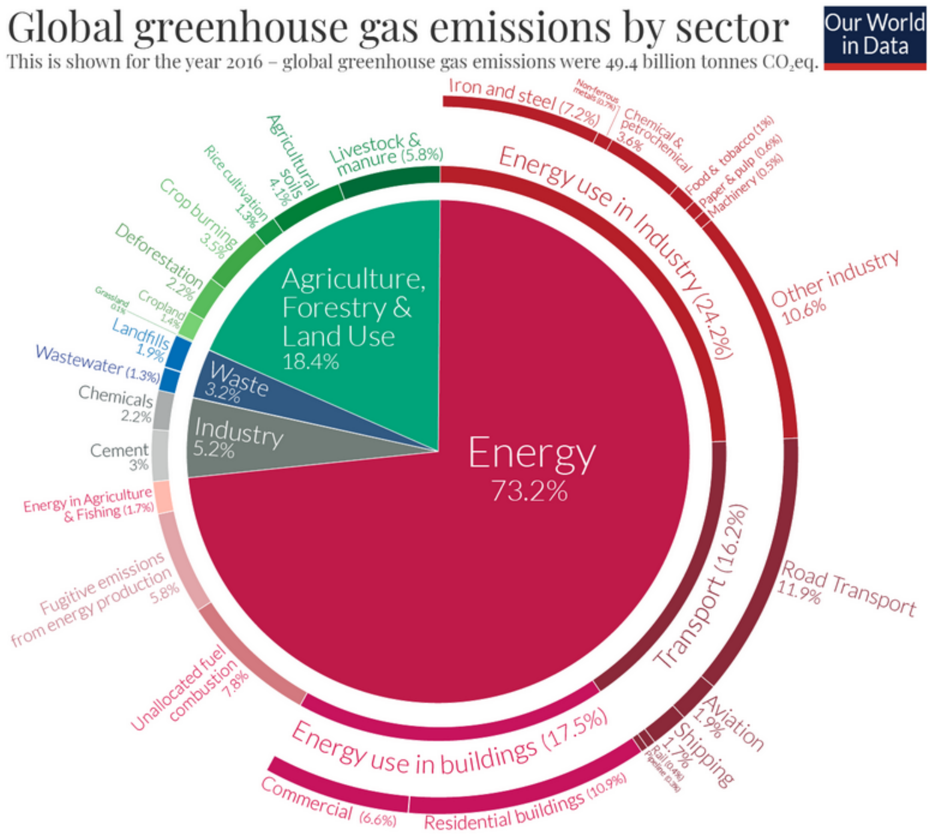
1. Introduction

Gasification is a technological process that can convert any carbonaceous (carbon-based) raw material such as coal into fuel gas, also known as synthesis gas (syngas for short).

Gasification occurs in a gasifier, generally a high temperature/pressure vessel where oxygen (or air) and steam are directly contacted with the coal or other feed material causing a series of chemical reactions to occur that convert the **feed** to **syngas** and **ash/slag (mineral residues)**.

Syngas is so called because of its history as an intermediate in the production of synthetic natural gas. Composed primarily of the colorless, odorless, highly flammable gases **carbon monoxide** (CO) and **hydrogen** (H_2), syngas has a variety of uses. The syngas can be further

Figure 8.1: Green House Gas emissions



converted (or shifted) to nothing but **hydrogen** and **carbon dioxide** (CO_2) by adding **steam** and reacting over a **catalyst** in a **water-gas-shift** reactor.

When hydrogen is burned, it creates nothing but **heat and water**, resulting in the ability to create electricity with no carbon dioxide in the exhaust gases. Furthermore, hydrogen made from coal or other solid fuels can be used to **refine oil**, or to make products such as **ammonia** and **fertilizer**. More importantly, hydrogen enriched syngas can be used to make **gasoline** and **diesel fuel**. Polygeneration plants that produce multiple products are uniquely possible with gasification technologies. Carbon dioxide can be efficiently captured from syngas, preventing its greenhouse gas emission to the atmosphere and enabling its utilization (such as for Enhanced Oil Recovery) or safe storage.

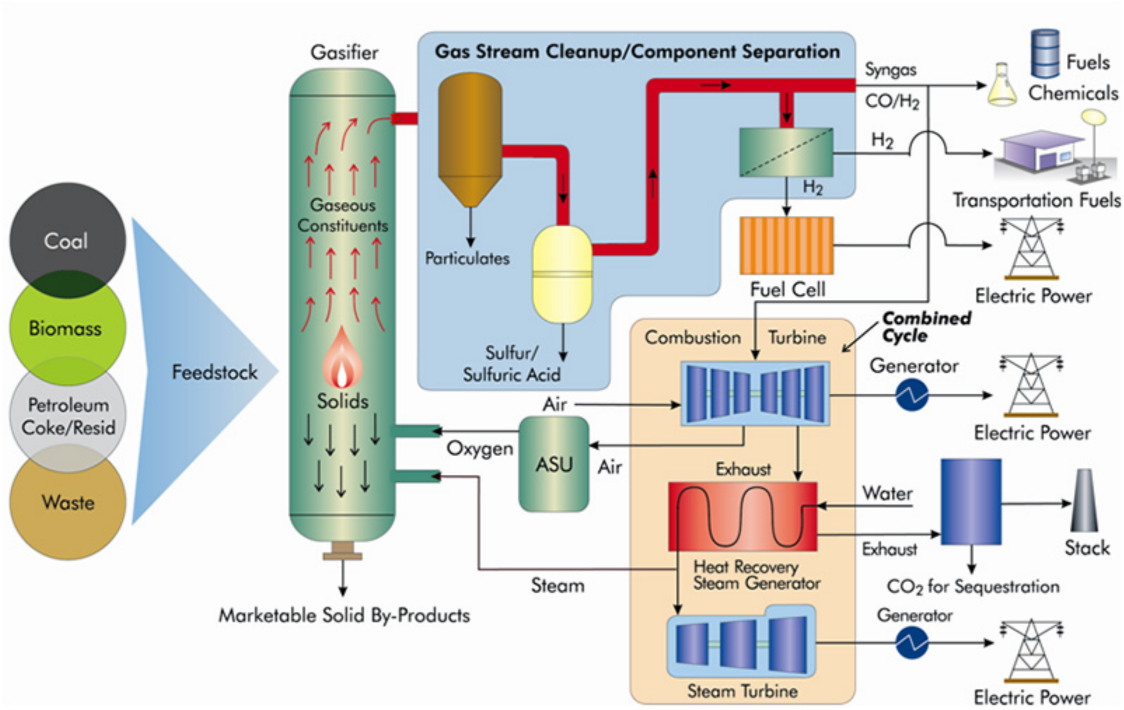
Figure 8.2 is a representation of a gasification process for coal, depicting both the feedstock flexibility inherent in gasification, as well as the wide range of products and usefulness of gasification technology.

2. Fundamentals

Gasification is a **partial oxidation process**. The term partial oxidation is a relative term which simply means that less oxygen is used in gasification than would be required for combustion (i.e., burning or complete oxidation) of the same amount of fuel. Gasification typically uses only 25 to 40 percent of the theoretical oxidant (either pure oxygen or air) to generate enough heat to gasify the remaining unoxidized fuel, producing syngas.

The major combustible products of gasification are **carbon monoxide** (CO) **(30-60%)**

Figure 8.2: Gasification plant



Source: National Energy Technology Laboratory

and **hydrogen** (H_2) **(25-30%)**, with only a minor amount of the carbon completely oxidized to **carbon dioxide** (CO_2) **(5-15%)** and **water** (H_2O) **(2-30%)**.

The heat released by partial oxidation provides most of the energy needed to break up the chemical bonds in the feedstock, to drive the other endothermic gasification reactions, and to increase the temperature of the final gasification products.

3. Detailed gasification chemistry

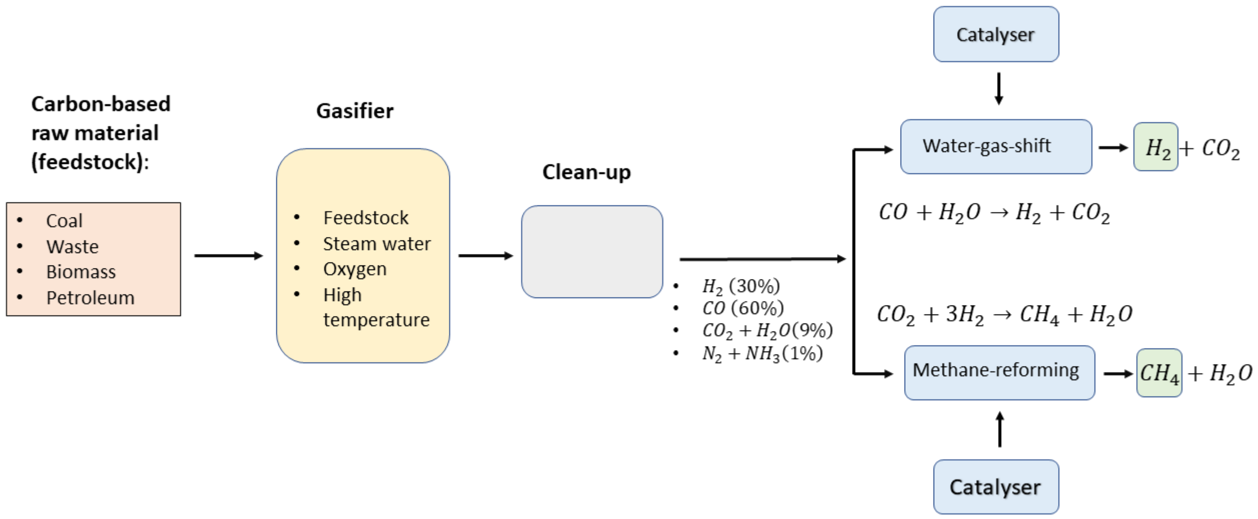
Within a gasification process, the major chemical reactions are those involving carbon, CO, CO_2, hydrogen (H_2), water (steam) and methane (CH_4), as follows:

The **combustion reactions**:

$$\begin{aligned} C + \frac{1}{2}O_2 &\rightarrow CO \\ CO + \frac{1}{2}O_2 &\rightarrow CO_2 \\ H_2 + \frac{1}{2}O_2 &\rightarrow H_2O \end{aligned}$$

Other important **gasification reactions** include:

Figure 8.3: Gasifier. Chemical reactions



$$
\begin{aligned}
C + H_2O &\leftrightarrow CO + H_2 \\
C + CO_2 &\leftrightarrow 2CO \\
C + 2H_2 &\leftrightarrow CH_4
\end{aligned}
$$

The combustion reactions are essentially carried out to completion under normal gasification operating conditions. And, under the condition of high carbon conversion, the three gasification reactions can be reduced to two homogeneous gas phase reactions of **water-gas-shift** and **steam methane-reforming**, which collectively play a key role in determining the final equilibrium synthesis gas (syngas) composition.

1. The **water-gas-shift** process transform the elements from the combustion and the gasification reactions into hydrogen (H_2) and carbon dioxide (CO_2) through the next equation (figure 8.3):

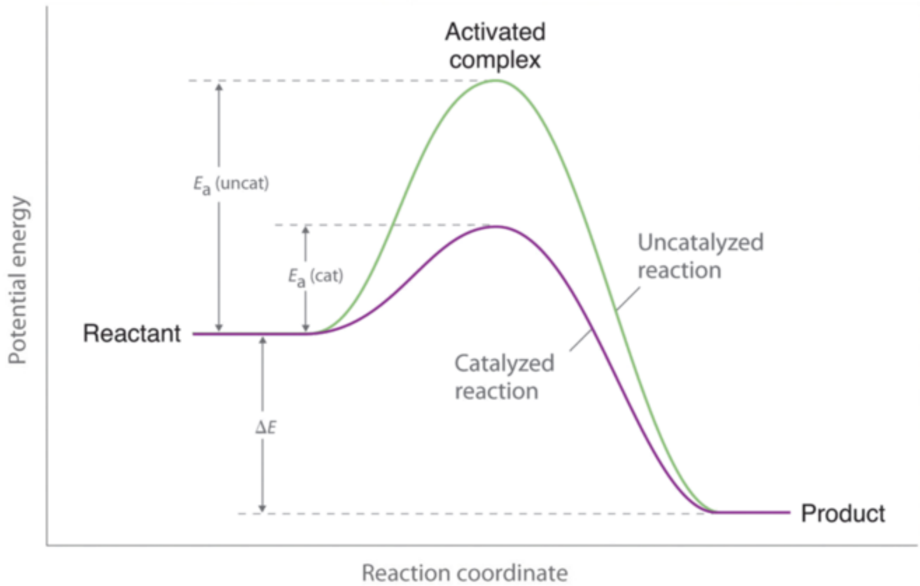
$$CO + H_2O \leftrightarrow CO_2 + H_2$$

2. The **methane-reforming** process transform the elements from the combustion and the gasification reactions into methane (CH_4) and water (H_2O) through the next equation (figure 8.3):

$$CO_2 + 3H_2 \leftrightarrow CH_4 + H_2O$$

3. On top of the products from obtained from the combustion and the gasification reactions and the subsequence water-gas-shift or methane-reforming processes, some **other elements** as gaseous nitrogen (N_2) and ammonia (NH_3)are produced (figure 8.3).

Figure 8.4: Catalysis: Energy profile diagram



Source: Chemistry. Libretexts

To accelerate the **water-gas-shift** and **methane-reforming** processes, **catalysts** can be employed.

Catalysis is the process of increasing the rate of a chemical reaction by adding a substance known as a **catalyst**. Catalysts are not consumed in the catalyzed reaction but can act repeatedly. Often only very small amounts of catalyst are required.

Catalysts work by providing an (alternative) mechanism involving a different transition state and lower **activation energy**. Consequently, more molecular collisions have the energy needed to reach the transition state. Hence, catalysts can enable reactions that would otherwise be blocked or slowed by a kinetic barrier. The catalyst may increase reaction rate or selectivity, or enable the reaction at lower temperatures. This effect can be illustrated in the energy profile diagram in figure 8.4.

Some videos that illustrate the **catalysis process** are:

- What Are Catalysts? | Reactions | Chemistry | FuseSchool
- Energy Diagrams, Catalysts, and Reaction Mechanisms

8.2.2 Anaerobic digestion

This section is based on the next two links: link 1, link 2.

An useful video to understand the anaerobic digestions is in this (link).

1. Introduction

Anaerobic digestion is a sequence of processes by which **microorganisms break down biodegradable material in the absence of oxygen**. The process is used for industrial or domestic purposes to manage waste or to produce fuels.

Anaerobic digestion is used as part of the process to treat **biodegradable waste**. As part of an integrated waste management system, anaerobic digestion **reduces the emission of landfill gas** into the atmosphere. Anaerobic digesters can also be fed with purpose-grown energy crops, such as maize.

Anaerobic digestion is widely used as a source of **renewable energy**. The process produces a biogas, consisting of methane, carbon dioxide, and traces of other 'contaminant' gases. This biogas can be used directly as **fuel**, in combined heat and power gas engines or upgraded to natural gas-quality **biomethane**. The nutrient-rich digestate also produced can be used as **fertilizer**.

2. The process

1. The photosynthesis process (figure 8.5) uses light transform carbon dioxide (CO_2) and water (H_2O) into sugar ($C_6H_2O_6$) and oxygen (O_2) according with the equation:

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_2O_6 + 6O_2$$

2. By following **four different steps** (figure 8.5), the anaerobic digestion transforms the sugar ($C_6H_2O_6$) into methane (CH_4) and carbon dioxide (CO_2).

1. **Hydrolysis**: Through hydrolysis the complex organic molecules are **broken down** into simple sugars, amino acids, and fatty acids.
2. **Acidogenesis**: The biological process of acidogenesis results in **further breakdown of the remaining components** by acidogenic (fermentative) bacteria. Here, volatile fatty acids (VFAs) are created, along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other byproducts.
3. **Acetogenesis**: The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are **further digested** by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen.
4. **Methanogenesis**: Methanogens use the intermediate products of the preceding stages and **convert them** into methane, carbon dioxide, and water.

The **formula** that summarizes the process is defined by:

$$C_6H_2O_6 \rightarrow 3CH_4 + 3CO_2$$

3. **Clean and upgrade process** (figure 8.5): Usually, the produced biogas must be **dried** and drained for condense water and biological or chemical **cleaned** for hydrogen sulphur H_2S, NH_3 and trace elements. **Further upgrading steps** to increase the CH_4 content, membrane separation of CO_2 and pressurising the biogas can be taken depending on the utilisation purpose.

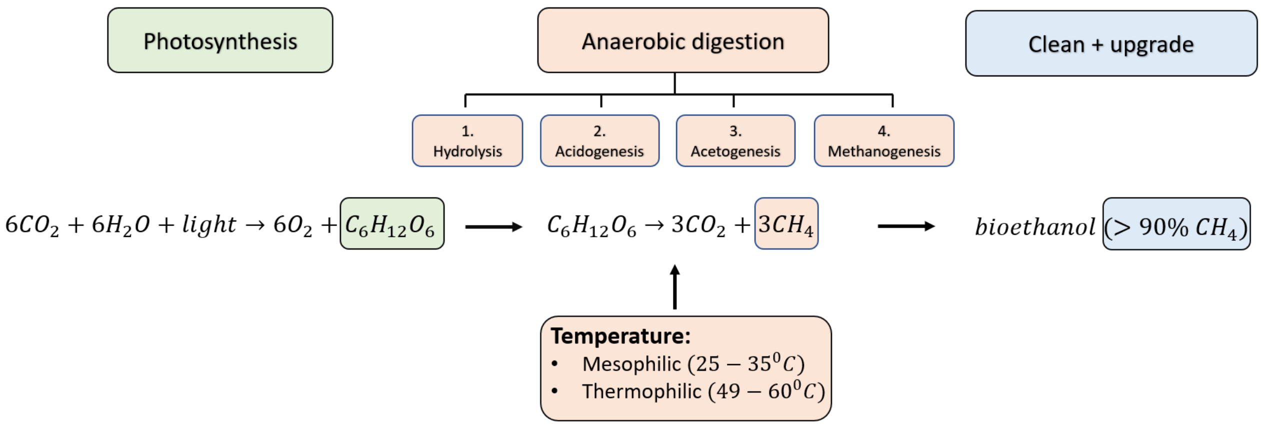
The upgrade to bioethanol implies the removal of contaminants such as hydrogen sulphide or siloxanes, as well as the carbon dioxide. Bioethanol contains at least 90% of methanol CH_4.

Depending on the **temperature**, the anaerobic digestion can be classified as:

- **Mesophilic** temperature from $25 - 35°C$.
- **Thermophilic** temperature from $49 - 60°C$.

The majority of the agricultural biogas plants are operated at **mesophilic temperatures**. Thermophilic temperatures are applied mainly in large-scale centralised biogas plants with co-digestion, where more stringent sanitation requirements are required.

Figure 8.5: Anaerobic digestion process



3. The plant

The **digester** is an airtight container in which the waste is dumped and decomposed, and the **gas holder** is a tank that harnesses the gases emitted by the slurry. Bacteria within the digester tank breaks down the waste and, as it decomposes, gases such as carbon monoxide, methane, hydrogen, and nitrogen, are released. Through a pressurized system, the gas holder conducts the flow of these gases upward into a hole in its drum. The hole is specially designed to allow gases to pass freely into the holder while prohibiting any gases from escaping back into the digester. In a controlled environment, the gases are later combusted, or reacted, with oxygen to create an energy source for such processes as heating and vehicle propulsion.

Construction of a biogas plant may vary depending on the amount of gas needed, the amount of waste at hand, and whether the digester is designed for **batch feeding** or **continuous feeding**. Batch feeding systems use mostly solid wastes that are added to the tank in installments, and continuous feeding models feed mostly liquids to the digester.

A biogas plant may be constructed either **above** or **below ground**, with advantages and disadvantages to both models. An above ground biogas plant is easier to maintain and benefits from solar heating, but takes more care in construction because it must be built to handle the internal pressure of the digester. A below ground biogas plant is cheaper to construct and easier to feed, but is more difficult to maintain.

8.3 Current status

Bioenergy makes up a large share of renewable energy use today and plays a key role as a source of energy and as a fuel in the end-use sectors (**industry**, **transport** and **buildings**), as well as in the power sector.

Bioenergy today accounts for 70% of the global renewable energy supply and 10% of the total primary energy supply.

In terms of end **uses**, the largest share of total bioenergy use (modern and traditional) is in the buildings sector, which includes cooking and space heating (26%). The second largest share is in the industry sector (at 7%), followed by the transport sector (3%), mostly in the form of liquid biofuels from crops such as sugar cane and corn, and the power sector (2%) (IRENA, 2020b).

Figure 8.6: Anaerobic digestion plant

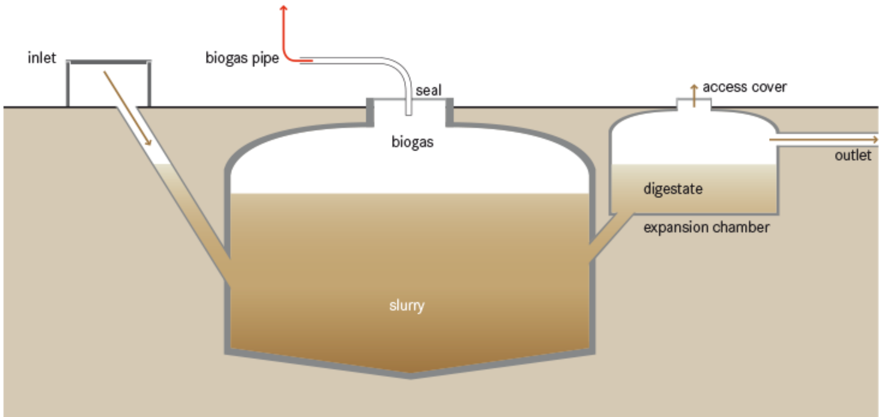
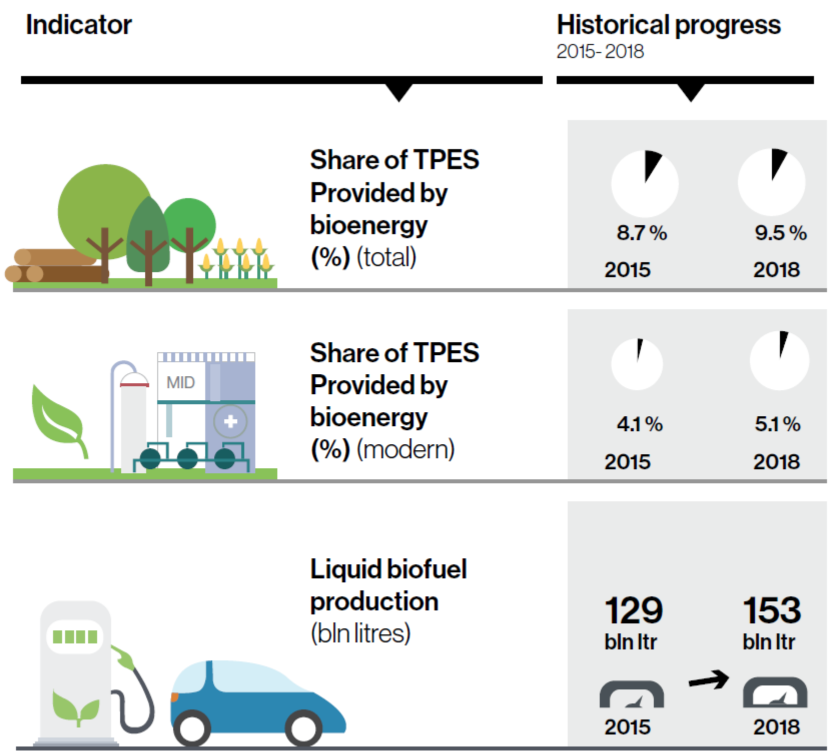


Figure 8.7: Bioenergy. Total Primary Energy Supply (TPES)



Source: IRENA (2020a)

Traditional vs. Modern biomass.

Biomass is any organic material derived from plants or animals. It includes wood, agricultural crops, herbaceous and woody energy crops, algae, animal fats, livestock manure and municipal organic wastes.

- **Traditional use** refers to the use of wood, charcoal, agricultural residues and animal dung locally collected or from unsustainably produced sources with basic techniques for cooking and heating at very low conversion efficiency (10% to 20%) in open stoves or fires with no chimney or hood. These uses often release flue gases indoors or cause high concentrations of air pollutants.
- **Modern use** refers to the direct combustion of commercially produced primary biomass and the indirect use of pre-treated solid biomass with heightened energy density for electricity and/or heat generation. It includes liquid forms of biomass produced via conventional or advanced conversion routes for transport fuels, cooking and industrial applications; biogas produced through anaerobic digestion of residues and waste; and syngas produced through biomass gasification. Biomass use in improved cookstoves can be categorised as modern use if sustainably sourced.

Primary energy (PE).

Primary energy (PE) is an energy form found in nature that has not been subjected to any human engineered conversion process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be non-renewable or renewable.

Where primary energy is used to describe fossil fuels, the embodied energy of the fuel is available as thermal energy and around 70% is typically lost in conversion to electrical or mechanical energy. There is a similar $60-80\%$ conversion loss when solar and wind energy is converted to electricity, but today's UN conventions on energy statistics counts the electricity made from wind and solar as the primary energy itself for these sources. One consequence of this counting method is that the contribution of wind and solar energy is under reported compared to fossil energy sources, and there is hence an international debate on how to count primary energy from wind and solar.

Total primary energy supply (TPES).

Total primary energy supply (TPES) is the sum of production and imports subtracting exports and storage changes.

The concept of primary energy is used in energy statistics in the compilation of energy balances, as well as in the field of energetics. In energetics, a primary energy source (PES) refers to the energy forms required by the energy sector to generate the supply of energy carriers used by human society.

Secondary energy.

Secondary energy is a carrier of energy, such as electricity. These are produced by conversion from a primary energy source.

8.3.1 Industry sector

- The industry sector uses energy for a **wide range of purposes**, such as for processing and assembly, steam generation, cogeneration, process heating and cooling, lighting, heating, and air conditioning.
- **Most of the energy consumed in industry** is in the form of heat, especially in the most energy-intensive industrial sectors – iron and steel, chemical and petrochemical, nonmetallic minerals, pulp and paper, and the food industry.
- Current direct renewable energy use in industry is predominantly in the form of **biofuels** and **energy from waste**.

At a regional level, the largest share of biomass in industry's final energy consumption in 2017 was in Latin America and the Caribbean at 32%, followed by Asia and Sub- Saharan Africa, both at 29%.

Biomass is also used for carbon emissions reductions in the industry sector through the production of **natural synthetic fibres** based on cellulose, and **biomaterials to produce bioplastic**. Biomass used for **bioplastic production** mainly comes from corn, sugarcane or cellulose (European Bioplastic, 2020).

8.3.2 Transport sector

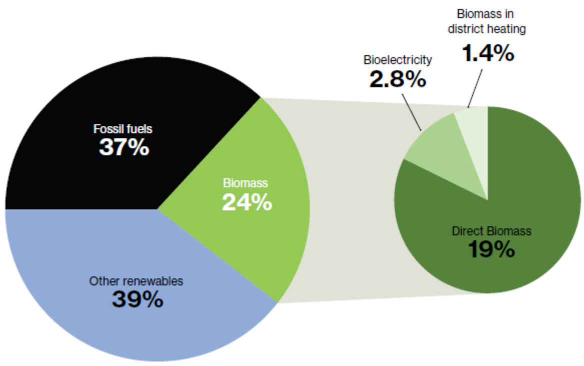
- Globally, the share of renewable energy in this sector is very small at just 3% in 2017.
- In **road** transport, the use of renewables is dominated by liquid biofuels, mostly **bioethanol** and **biodiesel**, which offer an alternative fuel for all types of internal combustion engines in both passenger vehicles and trucks.
- **North America** had the largest production of liquid biofuels in 2017, with 64 billion litres, followed by Latin America and the Caribbean with 31 billion litres and the European Union with 25 billion litres.
- Liquid biofuels could also help decarbonise the **shipping** and **aviation** sectors, which currently are entirely fueled by fossil sources.
- Advanced biofuels offer significant **emissions reductions** compared to petrol and diesel.
- They can be made from **non-food** and **non-feed biomass**, including waste materials (such as vegetable oils or animal fats) and energy-specific crops grown on marginal or degraded land.

8.3.3 Buildings sector

There are two different ways of using biomass in the buildings sector: **space heating** and **cooking**.

1. **Buildings** can currently be heated using biomass through town-scale district heating systems or building-scale furnaces, both of which use feedstocks such as wood chips and pellets very efficiently.
2. **Cooking** with biomass is typically one of the traditional uses of biomass in developing countries.

Figure 8.8: Renewables in industry



Source: IRENA (2020a)

- Inefficient traditional cookstoves paired with solid fuels and kerosene emit indoor smoke that imperils the **health of mainly women and children** and causes nearly 4 million premature deaths every year.
- Unsurprisingly, the largest share of biomass consumption in the buildings sector in 2017 was in **Sub- Saharan Africa** at 91% (entirely in the form of traditional uses).

8.3.4 Power sector

- Biomass and waste fuels in solid, liquid and gaseous forms are currently used to **generate electricity**.
- The feedstocks and technologies range from mature, **low-cost options**, like the combustion of agricultural and forestry residues, to less mature and/or **expensive options**, like biomass gasification or municipal solid waste generators with stringent emissions controls (IRENA, 2019).
- Electricity generation from biomass is most often provided through **combined heat and power (CHP) systems**.

8.4 Future projections

8.4.1 Industry Sector

Biomass, due to its versatility, could play significant roles in the industry sector. Biomass can be used as a feedstock to replace fossil fuels, it can be used to produce low-, medium- and high-temperature heat, and it can be used as a fuel for localised electricity production.

The versatility of biomass and its finite supply, however, also result in competition for its use within and between industry sectors, and other sectors of the economy.

Renewable energy (including renewable electricity and district heating) could contribute 63% of industry's total final energy consumption by 2050 (89 EJ in absolute terms). Of that total energy, 24% would be sourced from biomass (direct, bioelectricity and biomass in district heating) and the remaining 39% from other renewable sources (figure 8.8).

Other potential industrial applications include the use of biomass residues generated in biomass based industries such as pulp and paper, lumber and timber, food and biofuels.

In addition, biorefinery systems offer attractive routes for energy generation, in the form of **combined heat and power (CHP)** and biofuels, alongside chemical production, with great promise for reduced environmental impacts.

Application of bioenergy in some industrial sectors that are hard to decarbonise.

1. **Iron and Steel**. A significant share (about 78%) of the **total energy consumed for iron and steel production** comes from the use of coal and coke as chemical reducing agents for iron production. The substitution of biomass products for coal and coke can provide carbon and at the same time could be upgraded to have similar characteristics to fossil fuels. Using biomass instead of coal and coke more widely could **cut emissions** by almost 50%, but it remains costly and its use on a larger scale is only at the research stage.

2. **Cement**. The manufacture of clinker is responsible for the bulk of the CO2 emissions associated with cement production. **Biomass could be considered as a clinker substitute** (however, its role and potential are still quite limited). In addition to this role, biomass can also be used as an alternative material to cement in the construction industry, where wood materials contribute to reaching zero carbon if produced sustainably.

3. **Aluminium**. Most energy consumed in the aluminium industry is in the form of electricity used for smelting. The use of **biofuels and solar heat** are among several new technologies emerging in this industry to reduce the electricity needed for smelting, as they can readily replace fossil fuels and low- and medium-temperature alumina production.

4. **Chemicals and Petrochemicals**. Biomass is one of the prime alternatives to fossil fuel use in the sector, either through **biomaterials** or using biomass building blocks. Key **bio-based feedstocks**, which can be used to produce conventional products such as plastics, are bio-ethylene and biomethanol; others include also biogas or bio-naphtha.

8.4.2 Transport Sector

Biofuels and **biogas consumption would grow** to nearly five times 2017 levels by 2050 and provide 20% of total transport final energy demand.

Biofuels would play a particularly important role for the **decarbonisation of long-haul transport** (aviation, marine and long-haul road freight).

Transport will become much more electrified, **but not everywhere**, **not in all sectors** and **not all at once**. While EVs powered by renewable electricity will dominate light vehicle fleets, they can only enter markets with well-developed power grids. Long-haul transport is unlikely to be fully electrified due to the higher energy density it requires. Hence, a mix of oil-based, and carbohydrate-based biofuels has to be developed and used.

Applications of bioenergy in some transport sectors that are hard to decarbonise

1. **Aviation**. Aviation, and in particular jet fuel use, is one of the fastest-growing sources of greenhouse gas emissions. Biofuel for jet aircraft, known as bio-jet, is the **only currently available option** for achieving significant reductions in aviation emissions. Despite the large potential, the **current market for bio-jet is quite limited**, due to high costs and lack of supportive regulatory framework and/or carbon pricing.

2. **Shipping**. Liquid biofuels are an option for decarbonising the shipping sector. From a **technological perspective**, liquid biofuels are mature, require few adjustments to existing ship engines or port infrastructure, and can significantly reduce emissions. However, there are **three main barriers** to wider use: economics, availability and sustainability concerns.

3. **Heavy-duty trucks**. Biomethane, biodiesel and renewable diesel can be used in **heavy-duty natural-gas-powered or diesel-powered vehicles** (as well as in light-duty vehicles) without any specific adaptation. Some truck manufacturers are trying to develop biogas-fueled trucks for heavy and long-haul transport, while biodiesels are already being blended with conventional diesel and used in existing vehicles without any modification.

8.4.3 Buildings Sector

Heating and cooking in open fireplaces or stoves.

- Traditionally, biomass has been used for heating and cooking in open fireplaces or stoves, and today modern biomass is being used in **efficient boiler**s and furnaces and improved cookstoves.

- However, more than 3 billion people still rely on **inefficient traditional use of biomass**, such as fuelwood and charcoal, for cooking.

- The hazardous emissions released during inefficient cooking cause **one of the world's major public health challenges**, leading to over 4 million deaths per year (World Bioenergy Association, 2016).

- The problem is most severe in developing countries, where access to modern forms of energy is limited, and where cooking is typically done with solid fuel like wood logs and twigs, or with agricultural residues such as straw, especially in rural areas.

- The solution is a systems approach that uses **innovative cookstove designs** to vastly improve the efficiency of solid biomass combustion, while also replacing traditional charcoal or wood with modern biomass use like pellets, biogas and ethanol.

Bioenergy in the district heating.

- Modern bioenergy use also is expected to play an increasing role in the decarbonisation of the buildings sector, particularly in areas with high demand for space heating.

- Buildings can be heated through **town-scale district heating systems** or building-scale furnaces, both of which use feedstocks like wood chips and pellets very efficiently.

- It is important, therefore, to **replace existing low-efficiency heating systems** by high efficiency district heating and cooling (DHC) or buildingscale furnaces fueled by renewable sources as much as possible.

Combined-heat and power (CHP) plants.

- Using **biomass solely for electricity generation** is not seen as a good choice because of its low efficiency, at about 30%.
- The **overall efficiency of biomass-based CHP plants** for industry or district heating can be 70% – 90%.
- As a result, sustainable bioenergy used to provide heat and power can **reduce emissions considerably** compared to coal, oil and natural gas-generated heat and power.

8.4.4 Power Sector

The **share of electricity in total final energy** use would increase from just 20% today to 49% by 2050, and 86% of that electricity would be generated by renewable sources, mostly wind (35% of renewable electricity), solar PV (25%) and some hydro (14%). Biomass would be the fourth largest renewable power source, generating 7% of electricity (figure 8.9).

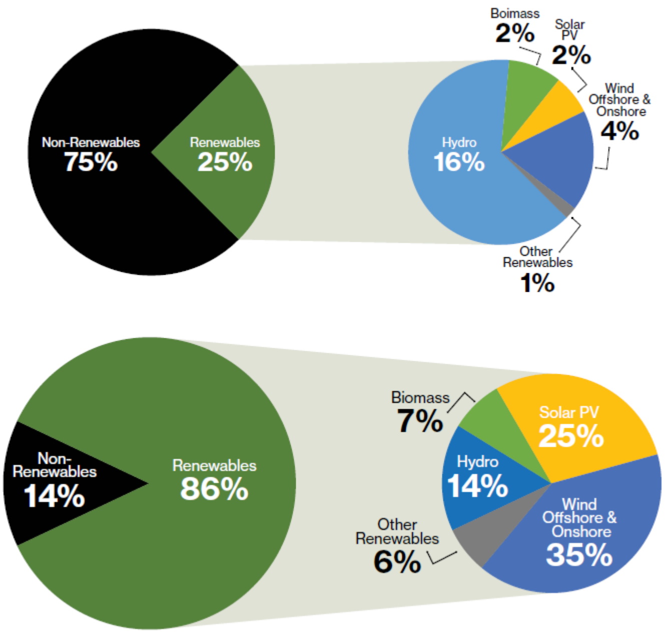
To produce that much power, bioenergy **installed capacity** would increase six-fold from 108 GW in 2017 to 685 GW in 2050.

Asia would lead in bioenergy installed capacity, with 318 GW, followed by the **European Union** with 107 GW and **Latin America** and the **Caribbean** with 94 GW. In addition, biomass can be used for co-firing coal power plants as an intermediate measure to reduce CO2 emissions.

Bioenergy-based electricity can play a particularly important role when:

1. Its **generation costs** are lower than other sources (i.e. where biomass feedstock costs are low or where heat can be used in co-generation systems).
2. It helps to **balance output** over time on electricity grids with high shares of variable wind and solar power.
3. It is possible to use **Bioenergy with carbon Capture and Storage** (BECCS).

Figure 8.9: Energy mix 2017-2050



Source: IRENA (2020a)

Biogas applications.

- Biogas can be burned directly for **cooking and lighting** or indirectly in **combustion engines** to generate electricity or motive power.
- Biogas for cooking is particularly relevant for many developing countries, where it can reduce traditional use of solid biomass, offering a sustainable way to meet community energy needs, especially in areas without good grid access or where heat requirements cannot be met only by electricity.

Biomethane applications.

- Biomethane is a **versatile energy carrier** produced from biomass via gasification or upgraded from biogas.
- It is sometimes also known as **renewable natural gas**, as it possesses compatible properties to natural gas.
- In the **transport sector**, biomethane can be used as a drop-in substitute for natural gas in existing light- and heavy-duty natural-gas-powered vehicles, such as commercial vehicles, city buses and urban service fleets for delivery and refuse collection.
- Biogas and biomethane can also be used for **greening the gas system**.
- Biomethane production via anaerobic digestion (AD, biogas), thermal gasification of biomass, or power-to-gas from hydrogen and carbon dioxide represents a clean and feasible solution for **cleaning the gas system**.

In 2019, the **World Biomass Association** estimated that there were about 700 biogas upgrading plants, with more than 75% of them in Europe. Germany is the world's largest producer of biomethane with 220 plants, nearly half of the global installations. As of 2019, Denmark injects 10% biogas into its natural gas network, and the Danish gas industry has set a goal of reaching 100% by 2035.

8.5 Bibliography

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Chapter 9

Sustainable energy. Batteries and electric vehicles

In this chapter we study the relation between batteries, electric vehicles and the electric system.

1. We start the chapter by watching a video and **discussing** key aspects of the chapter.
2. We study the fundamentals of **voltaic cells** and **lithium-ion batteries**.
3. We study the **EV market evolution**, and the **flexibility potential** in the EV market today, in 2030, and in 2050.
4. We study the **impact of smart charging** on demand and grid structure. We also study the services provided by smart charging EV, and the types of smart charging.
5. We study the **business models** and the **profitability and competitiveness of EV flexibility**.
6. We enumerate the main factors that determine the **cost evolution** and the **implementation of EV**.
7. We compare the advantages and disadvantages of **EV** and **hydrogen vehicles**.
8. We conclude the chapter with a set of **questions** that summarize the main points studied in the chapter.

9.1 Discussion

Based on the CNBC video How Tesla, GM And Others Will Fix Electric Vehicle Range Anxiety, discuss the next questions:

1. The video present some of the main trends in EV: sales, number of brands in the market, and number of charge stations? **What do you know about this market**? Evolution of sales, penetration, e-buses, e-tracks?

2. The video explain that the two main challenges for the adoption of EV are infrastructure (charges), and durability of the battery. Can you enumerate **other factors** that could affect the adoption of EV? Batteries costs, variety of models, transport as a service, regulation (ban the sell of non-EV).

3. The video present that there are three main types of chargers level 1 and level 2 (120-240 volts), level 3 (480 volts). Could you explain how the type of chargers could affect the **contribution of EV to the flexibility** of the electricity system?

4. Do you have **any other point** that you consider that it could be relevant for the discussion?

9.2 How do batteries work?

We study first how do galvanic cells (voltaic cells) work, and based on that the lessons learned in that section, we study how do lithium-ion batteries work.

9.2.1 How do galvanic cells (voltaic cells) work?

This section is based on the video Galvanic Cells (Voltaic Cells).

Galvanic cells also called voltaic cells are devices that use a **chemical reaction to produce electricity**. As in the chapter where we study hydrogen, the chemical reaction used to produce electricity is the **oxidation-reduction reaction**.

Galvanic cells (voltaic cells) are very popular, since **batteries** work by using the same principle. The batteries have chemicals that react together in an oxidation-reduction reaction to produce electricity.

Before to explain the chemical reaction that generates electricity, we introduce the **parts of a voltaic cell** (figure 9.1).

1. There are two containers with **water**.

2. One of the containers has a **zinc-sulfate solution** ($ZnSO_4$). The other container has a **copper-sulfate solution** ($CuSO_4$).

3. We have a **piece of zinc metal** in the zinc-sulfate solution ($ZnSO_4$), and a **piece of copper metal** in the copper-sulfate solution ($CuSO_4$).

   In the electrochemical series, there are metals that have a **high tendency to lose electrons** (Li(3.04V), Mg(2.37V), Al(1.66V), Zn(0.76V), Fe(0.44V)); and others metals that have a **high tendency to gain electrons** (Hg(-0,24V), Cu(-0.34V), Ag(-1.69V)).

   The idea behind a battery is to connect metals with tendency to lose electrons with metals with tendency to gain electrons to generate an electric current.

4. A **metal wire** connects the metallic pieces of zinc and copper.
5. Finally, a **salt bridge** connects the two containers with water.

We explain how voltaic cells work. We divide the entire process in two steps. First, we explain the **oxidation-reduction process**. Second, we explain the role of **salt bridge** in the entire process. By splitting the process in two parts, we will make easier to understand the entire process. Moreover, this will also help us to know how do lithium-ion batteries work (next section).

Oxidation-reduction reaction (figure 9.1).

1. **Anode (oxidation process)**. The zinc metal has a high tendency to lose electrons. Therefore, the oxidation process (lose of electrons) will take place in the container where the zinc metal is located.
2. **Cathode (reduction process)**. The copper has a high tendency to gain electrons. Therefore, the reduction process (gain of electrons) will take place in the container where the copper metal is located.
3. **During the oxidation process**, the atoms of zinc (Zn) in the metal lose two electrons. When a metal loses electrons tends to become liquid. Therefore, during the oxidation process **the zinc metal stick becomes more and more thinner**.

   The **half-equation in the anode**:

$$Zn(s) \rightarrow Zn^{+2}(aq) + 2e^- \tag{9.1}$$

4. **During the reduction process**, the atoms of copper (Co^{+2}) dissolved in the copper-sulfate solution ($CuSO_4$) gains two electrons. When a metal becomes neutral, it has a tendency to become solid. Therefore, during the reduction process, **the copper metal stick becomes more and more thick**.

   The **half-equation in the cathode**:

$$Cu^{+2}(aq) + 2e^- \rightarrow Cu(s) \tag{9.2}$$

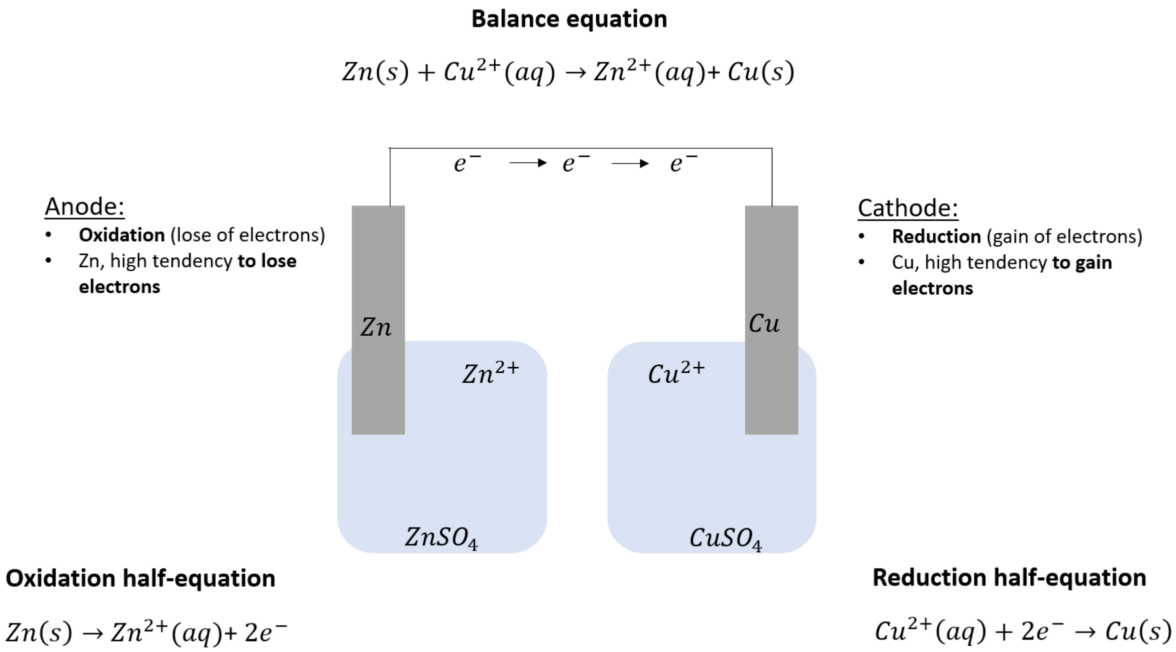
5. The **balance equation**. By placing together equations 9.1 and 9.2, we obtain the balance equation:

$$Zn(s) + Cu^{+2}(aq) \rightarrow Zn^{+2}(aq) + Cu(s) \tag{9.3}$$

Salt bride (figure 9.2).

1. Due to the loss of electrons, **during the oxidation process**, the zinc-sulfate solution ($ZnSO_4$) becomes more and more positively charged.
2. Due to the gain of electrons, **during the reduction process**, the copper-sulfate solution ($CuSO_4$) becomes more and more negatively charged.
3. Due to the oxidation-reduction reaction, the charge in the containers changes, and that **could stop the flow of electrons**, since the electrons do not want to move to the container full of electrons (electrons repeal each other).

Figure 9.1: Voltaic cell (oxidation-reduction process)



4. To avoid that the flow of electrons stops, a **salt bridge** is used to maintain the charge of the zinc-sulfate ($ZnSO_4$) and the copper-sulfate ($CuSO_4$) solutions neutral. The salt bridge contains chlorine Cl^- and sodium Na^+.

   The Chlorine Cl^- move to the container where the oxidation takes place (anode), and the sodium Na^+ moves to the container where the reduction takes place (cathode). By doing that, the zinc-sulfate ($ZnSO_4$) and the copper-sulfate ($CuSO_4$) solutions are balanced and the flow of electrons can continue.

9.2.2 How do lithium-ion batteries work?

This section is based on the next links:

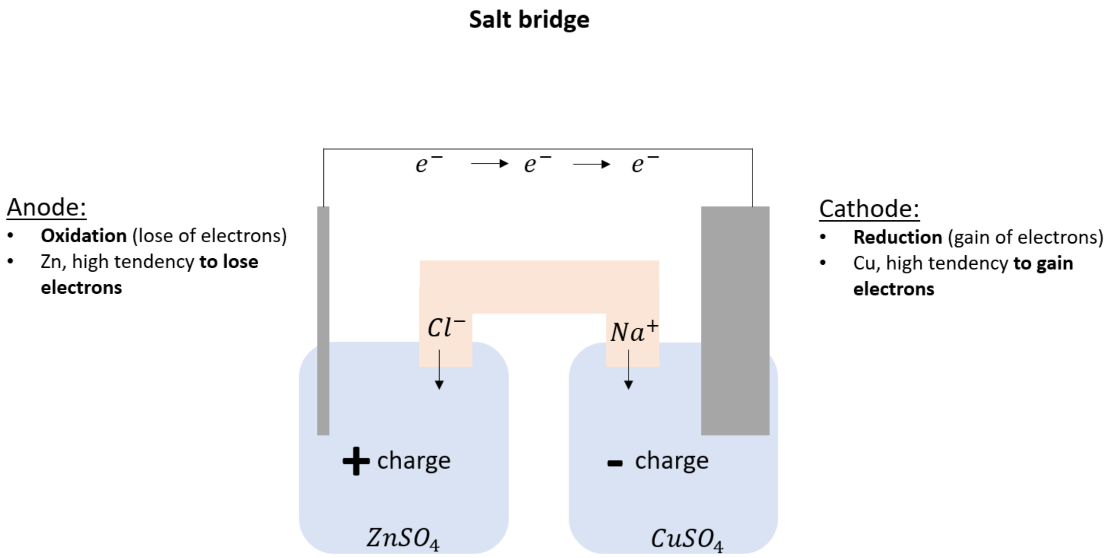
- Lithium-ion battery, How does it work?
- How do Lithium-ion Batteries Work?
- How batteries work - Adam Jacobson
- Lithium-ion battery

As voltaic cells, lithium-ion batteries use a **chemical reaction to produce electricity**.

Before to explain the chemical reaction that generates electricity, we introduce the **parts of a voltaic cell** (figure 9.3).

1. There are **two electrodes**. The **anode** is a structure that combines carbon and lithium (LiC_6) (lithium-graphite structure). The **cathode** is a structure that combines cobalt and Oxygen (CoO_2) (oxido(oxo)-cobalt).

Figure 9.2: Voltaic cell. Salt bridge



The lithium has a high tendency to lose electrons. The cobalt combined with the oxygen has a high tendency to gain electrons.

An electric current is generated by connecting the structure that contains (LiC_6) (anode), and the structure that contains (CoO_2) (cathode).

2. A **metal wire** connects the structures (LiC_6) and (CoO_2).

3. Finally, a **electrolyte** connects the two structures. The electrolyte plays a similar role to the salt bridge in the voltaic cells, since it leaves to pass lithium-ions (Li^+) to balance the charge in the anode and the cathode to facilitate the flow of electrons.

We explain how voltaic cells work. We divide the entire process in two steps. First, we explain the **oxidation-reduction process**. Second, we explain the role of **electrolyte** in the entire process.

Oxidation-reduction reaction (figure 9.1).

1. **Anode (oxidation process)**. The lithium has a high tendency to lose electrons. Therefore, the oxidation process (lose of electrons) will take place in the anode where the lithium-graphite structure (LiC_6) is located.

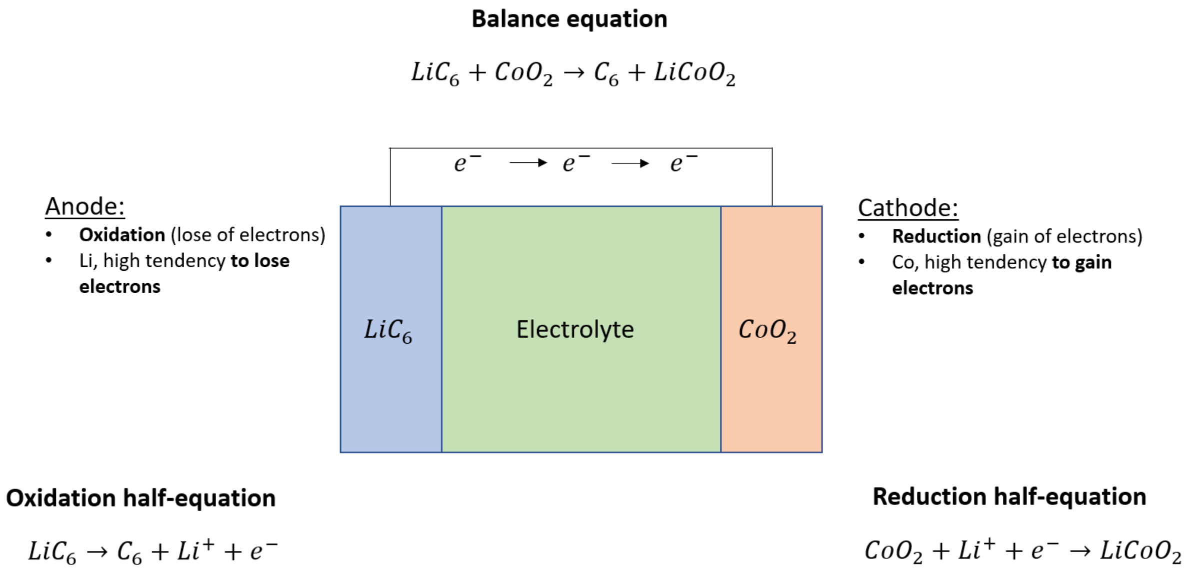
2. **Cathode (reduction process)**. The cobalt has a high tendency to gain electrons. Therefore, the reduction process (gain of electrons) will take place in the cathode where the oxido(oxo)-cobalt (CoO_2) structure is located.

3. **During the oxidation process**, the atoms of lithium (Li) in the lithium-graphite structure (LiC_6) lose one electron. When the lithium loses one electron it does not form part any more of the lithium-graphite structure.

The **half-equation in the anode**:

$$LiC_6 \rightarrow C_6 + Li^+ + e^- \tag{9.4}$$

Figure 9.3: Lithium-ion battery (oxidation-reduction process)



4. **During the reduction process**, the oxido(oxo)-cobalt (CoO_2) structure gains one electron.

   The **half-equation in the cathode**:

$$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2 \tag{9.5}$$

5. The **balance equation**. By placing together equations 9.4 and 9.5, we obtain the balance equation:

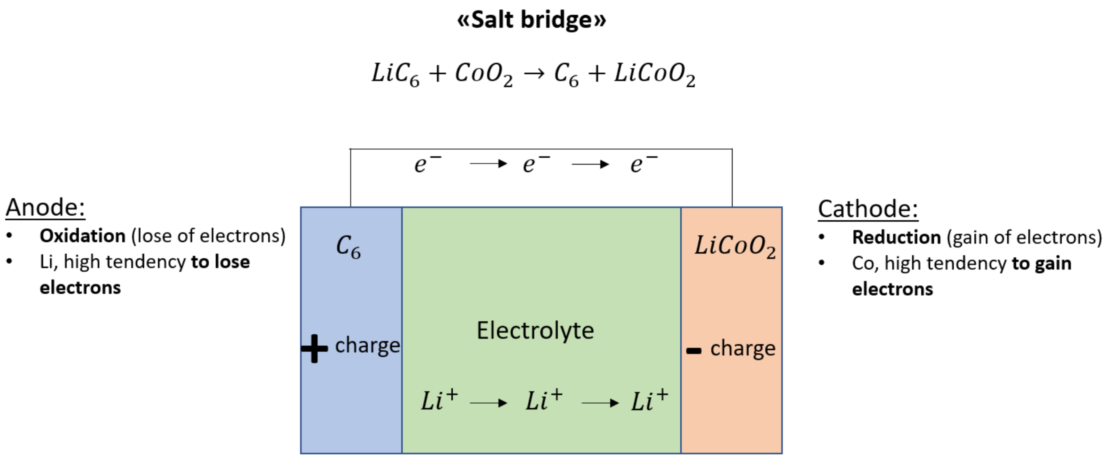
$$LiC_6 + CoO_2 \rightarrow C_6 + LiCoO_2 \tag{9.6}$$

Electrolyte ("Salt bride") (figure 9.2).

1. Due to the loss of electrons, **during the oxidation process**, lithium-graphite structure (LiC_6) becomes more and more positively charged.
2. Due to the gain of electrons, **during the reduction process**, the oxido(oxo)-cobalt (CoO_2) structure becomes more and more negatively charged.
3. Due to the oxidation-reduction reaction, the charge in the electrodes changes, and that **could stop the flow of electrons**, since the electrons do not want to move to the electrode full of electrons (electrons repeal each other).
4. To avoid that the flow of electrons stops, a **electrolyte ("salt bridge")** is used to maintain the charge of the lithium-graphite (LiC_6) and the oxido(oxo)-cobalt (CoO_2) structures neutral.

   The electrolyte membrane gives the free Lithium-ions (Li^+) to pass through it and move to the oxido(oxo)-cobalt (CoO_2) structure forming a lithium oxido(oxo)-cobalt ($LiCoO_2$) structure.

Figure 9.4: Lithium-ion battery. Electrolyte ("Salt bridge")



When an electric current is connected to the battery, the process is reversed, and the lithium passed through the electrolyte membrane to form again the lithium-graphite structure (LiC_6) in the anode. During the charging-discharging process some permanent crystals are formed and that makes more difficult the flow of electrons. In the long-term those permanent crystals the battery stop working.

9.3 State of play

9.3.1 Market evolution

EV sales evolution.

According to the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), 5.6 million EVs were on the world's roads at the beginning of 2019. **China and the United States (US)** are the largest markets, with 2.6 million and 1.1 million EVs, respectively. On average, EV sales grew rapidly during the period 2012 to 2017, with a **compound annual growth rate (CAGR) of** 57%. However, the market is still in an incipient phase, with EVs representing only 1.3% of all light-duty vehicles sold in 2017.

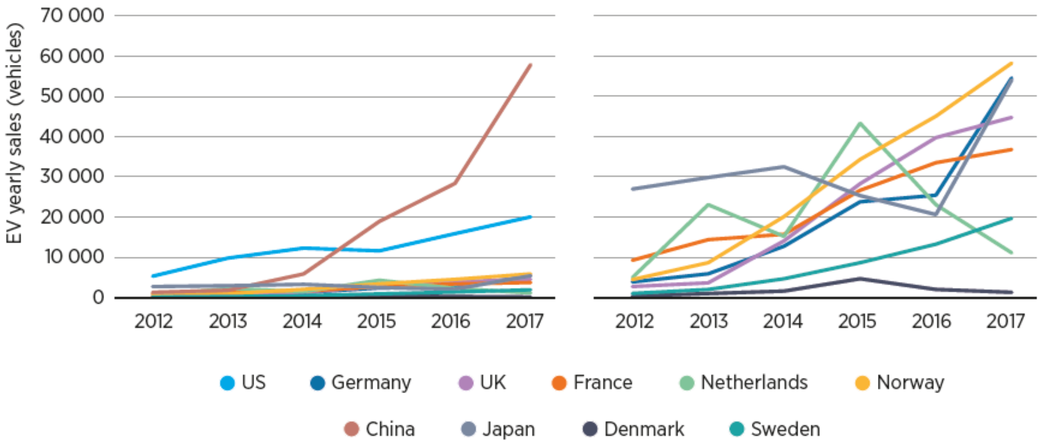
The **Chinese** EV market has experienced the largest increase in sales, with a CAGR of 114% between 2012 and 2017. In 2015 China surpassed the US in total EV sales, and in 2017 it was responsible for 48% of worldwide electric light-duty vehicle sales. The Chinese government has offered direct monetary incentives to support the purchase of EVs, including one-time subsidies and purchase tax exemptions, as well as non-monetary incentives, such as restrictions on registrations for ICE vehicles.

After China and the US, the next largest markets are in **Europe**, with considerable growth in EV sales from 2012 to 2017 in Germany (CAGR of 75%), Norway (70%) and the UK (68%). Figure 9.5 shows the evolution of EV sales in the 10 countries that represented 88% of worldwide electric light-duty vehicle sales in 2017.

EV penetration.

Although the Chinese and US markets are the largest for EV sales, other countries have had greater success in integrating EVs into their overall vehicle fleets. Figure 9.6 shows the evolu-

Figure 9.5: Evolution EV sales (2012-2017)



Source: IRENA (2019a)

tion of market **penetration of EVs** in light-duty vehicle sales. **Norway** has made remarkable progress since 2012, becoming a global leader with an almost 40% share of EVs in 2017. This was the result of a favourable policy environment in recent years comprising a large range of incentives, from tax breaks and exemptions to waivers on road tolls and ferry fees.

After Norway, the markets with the highest progress in EV integration between 2012 and 2017 were **Sweden**, the **US** and the **Netherlands**, with EV shares representing 5.1%, 3.3% and 2.7%, respectively, of the light-duty vehicle market in 2017. The remaining six largest markets did not exceed ratios of 2.5% of EV penetration and rank similarly to the global average.

EV in big companies.

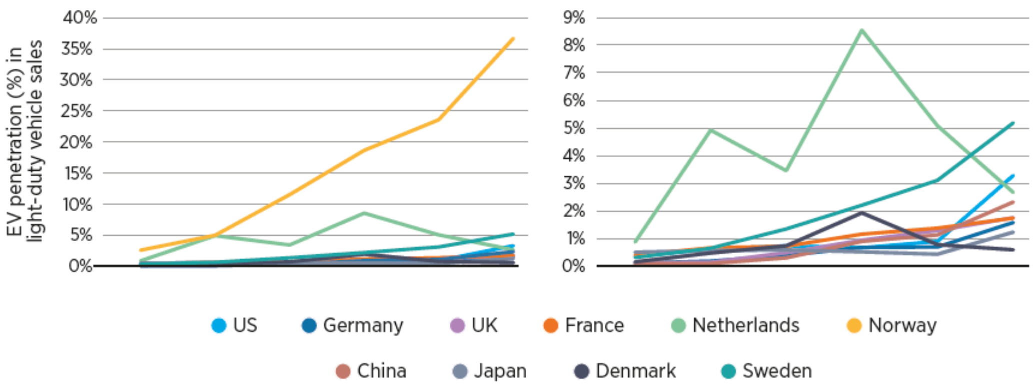
The **EV100 initiative**, launched by The Climate Group in 2017, encourages companies to commit to moving towards 100% electric corporate fleets and to install charging infrastructure. In its first several months, the initiative had already signed on **10 multinationals**, among them the Swedish power company Vattenfall, IKEA Group and the Chinese Internet giant Baidu (The Climate Group, 2017). **Vattenfall** has the most timeambitious goal of the initiative so far, with the company setting targets to shift its fleets (3 500 light-duty vehicles) to 100% electric by 2022 as part of its goal to be climate neutral by 2050. The replacement will take five years and will include fleets in Germany, the Netherlands and Sweden.

The **French postal service** La Poste is also a pioneer in the field, owning 35 000 EVs out of a total fleet of 75 000 vehicles. In 2017 **Germany's Deutsche Post DHL Group** also set a target to achieve zero-emission logistics by 2050, in part through the use of EVs.

E-buses.

The market for e-buses is concentrated mainly in **Asia Pacific**, where a market penetration of 27.6% was reached in 2016. Since 2014 there has been a large uptake of e-buses in **China**, which is now responsible for 99% of the worldwide sales and fleet. Market penetration in **North America and Western Europe** is around 0.6%. Whereas China reached 340 000 e-buses in 2017, the largest fleet of e-buses in Europe is in the UK and accounts for only 344 units.

Figure 9.6: Penetration EV sales (2012-2017)



Source: IRENA (2019a)

China is at the leading edge of the electrification of public transport buses because of the air pollution problems in its cities and industrial zones. The strategy of electrifying public transport comes from city administrations that want to reduce air pollution. The rapid and strong uptake of e-buses in Shenzen, for example, has helped to dramatically reduce the city's greenhouse gas emissions. The shift to e-buses is also supported by the national government, which has huge ambitions in mass transit. Apart from electrification, China has invested in a national high-speed railway network, subways and bus rapid transit.

In **Europe**, the number of e-buses is expected to grow considerably in the coming years. At least 19 public transport operators and municipalities in 25 European cities have outlined e-bus strategies for 2020.

E-tracks.

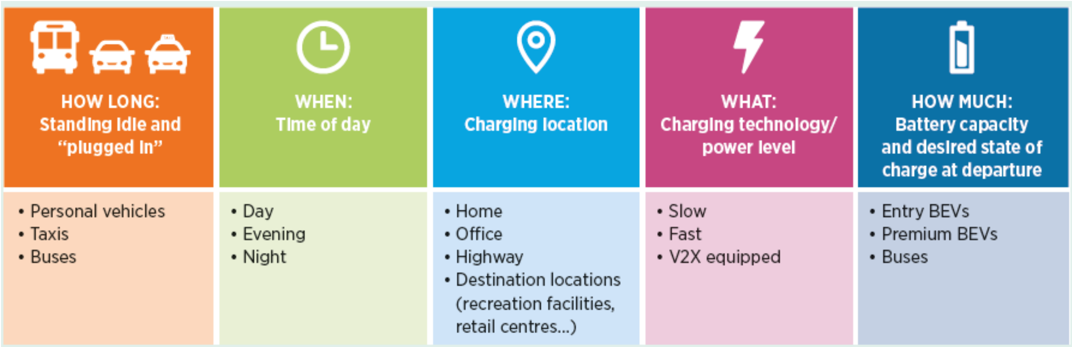
The largest market for electric drive trucks is in **Asia Pacific**, responsible for around half of worldwide sales in 2016. However, electric trucks reached the highest market penetration in **Western Europe**. Although this is still a small market, with less than 10 000 units sold in 2016, the use of electric trucks is expected to rise rapidly in certain sectors such as smaller service and delivery trucks (IRENA, 2017a).

9.3.2 EV flexibility potential

The uptake of smart charging for electric mobility is expected to establish a positive feedback loop with the integration of renewables, given that e-mobility is a power-dense, mobile and controllable load. Studies have shown that **cars in general, including EVs, are parked for about** 95% **of their lifetime**. This, combined with their storage capacity, could make **EVs an attractive flexibility solution to support system operation**. They can become grid-connected storage units with a potential to provide a broad range of services to the system. In 2050, around 14 TWh of EV batteries would be available to provide grid services, compared to 9 TWh of stationary batteries (IRENA, 2019b).

The typical electricity consumption of an EV driving 15 000 km/year is about 3 000 kWh/year. Even with slow charging (i.e., charging with low power, say 3.7 kW), the total time needed to charge the yearly energy is about 10% of the time the car stands idle. Supposing that an EV is connected to charging infrastructure 100% of its parking time, this means that the yearly

Figure 9.7: Factors determining the amount of available flexibility from a single EV



Source: IRENA (2019a)

"flexibility window" for charging represents about 85% of the time. Theoretically, this would translate into a flexible energy output of about 3 000 kWh/year per car. In other words, EVs can be charged in a fraction of their parking time. Incentivising charging at times when electricity is the cheapest represents a significant opportunity for the power system and for EV owners.

In practice, flexibility can be lower due to drivers' time constraints, with fast charging, or when the vehicle is parked but not plugged in. The different factors that determine the amount of available flexible (dis-) charging energy from EVs available in the system are summarised in figure 9.7.

EVs providing power system flexibility today

Today, the EV fleet is very limited and the cars still have relatively small batteries. EVs can already help maximise self-consumption of on-site renewable production. However, the flexibility that EVs provide to the grid is limited. Their aggregated storage capacity today is marginal from a power system perspective.

How long the car can be connected to the grid depends on the immobilisation time, which is determined by the type of vehicle and its use. Taxis or buses that travel a high daily distance will have less immobilisation time and therefore less flexibility than single cars used by individuals. While an **electric bus or truck** may use 100% or more of battery capacity every day, **passenger cars and two-wheelers** may use 40% to 50% of it.

<u>When and where.</u>

When and where the vehicle is charged also depends on the car type, its use, the **geography** and the **availability of the infrastructure**:

1. **Individual electric cars** have predictable charging patterns:
    - **Long-duration ($>$ 4 hours)** charging provides the highest flexibility for the system: most of the charging takes place at home during the evening, and at night and at the workplace during the day. EV drivers without home charging need assigned workplace charging.
    - **Medium-duration (30 minutes to 2 hours)** charging at shopping or leisure centres (movie theatre, gym, etc.) or short-duration (15 minutes to 1 hour) charging provide

minimum flexibility for the system and are ill-suited for grid services: fast charging on highways is rather exceptional today as EVs are mostly not yet used for long trips (due mainly to the limited range issue and the lack of appropriate charging infrastructure).

2. **Charging patterns of shared and commercial cars** (e.g., taxi and other car fleets) may be less predictable, depending on the business models. Nevertheless, the transport service revenue is critical and the time of standing still should be reduced to a minimum, leading to smaller time with grid connection and higher charging power, compared to individual cars.

3. **Electric bus** charging patterns depend on the place of charging:

   - Long duration ($>$ 4 hours) at the bus depot.
   - Medium duration (10 minutes) at the bus end-ofline.
   - Very short duration (flash charging) (30 seconds) at the bus stop.

Depending on the **geography** and specifically the access to a **private parking space at the residential level**, the proportions among the charging locations might differ. In less densely populated areas, most of the charging cycles are performed at home or at work. In densely populated cities with no charging points at home or at work, a larger proportion of the charging could be done in public places in the city. Large parking spaces or bus depots have more technical opportunities and incentives to contribute to energy flexibility than do disperse charging locations.

EVs providing power system flexibility by 2030

By 2030 individual ownership of vehicles will most likely still prevail over car sharing. As a result, an **increase in flexibility** can be expected:

- **More EVs available to the grid due to falling cost**: EVs get cheaper due to falling battery cost and government policies, as outlined in the previous section.

- **Bigger batteries helping to overcome range anxiety**: there will be more EVs with larger batteries connected to the grid. Battery packs will be bigger – increasing from 20-30 kWh currently to 40-60 kWh, with ranges of around 300 km becoming widespread in the next two years and growing even further.

- **Cars, charging stations and smart charging and discharging functionalities**: as standardisation progresses and as the requirements for better control of the charging power increase, the vehicles and charging points will have smart charging options including discharging as a common feature (provided by auto manufacturers), and technically enabling provision of ancillary services to the grid.

- More opportunities for EV drivers to **charge at workplaces**.

- **Fast charging** will remain limited as drivers will use it mainly for long-distance trips and for necessary top-ups given that enough range is available and as long as charging at home remains cheaper. While higher nominal charging capacity generally increases the challenge of uncontrolled charging, daytime fast charging could be aligned with grid needs in areas with high solar production during the day.

EVs providing power system flexibility by 2050

Between 2030 and 2050, this picture could **change substantially**. Mobility business models such as **mobilityas- a-service (MaaS)** – i.e., seamless multimodal transport – and technologies such as **autonomous vehicles** may emerge and be broadly implemented, leading to a shift from individual ownership of vehicles to fleet management.

Studies have shown that "ride-sharing" could lead to an **increase in the number of kilometres** driven as the shift from public transport towards shared private transport occurs at a larger scale. However, it also should lead to lower use of private cars with low passenger occupancy, which could in turn imply a reduction in the net emissions of the transport system.

Nevertheless, downwards pressure on available flexibility is likely to occur under this scenario, as:

- **Distance travelled by individual cars would increase**, reducing the amount of time that they are idle, connected to the grid.
- MaaS will also eventually impact the number of EVs in the system. The increase in **EV sales would slow down**: under the assumption that the EV revolution will precede the advent of an advanced MaaS ecosystem, new business models in MaaS will translate to downwards pressure on car sales for individuals after approximately 2030, following years of increasing market growth.
- **Zones of strain on the local power grid can be created once charging is focused in hubs**. These hubs may be relevant for centralised flexibility management in the night but still probably lower than with individual car ownership, as transport service optimisation will aim at maximum usage. Vehicle fleets will have to be steered towards an optimised fleet charging and routing, contributing to the goals of EV grid integration and optimised renewable energy use.

9.4 Smart charging

9.4.1 Impact on electricity capacity and demand

If EVs were charged simultaneously in an uncontrolled way they could increase the peak demand on the grid, contributing to overloading and the need for upgrades at the distribution level. The extra load may even result in the need for upgrades in the generation capacity (or at least in an altered production cost profile). The extent of possible impacts would depend on the power system's electricity mix, grid typology and penetration of EVs, as demonstrated by various trials and studies conducted globally.

The studies converge on **three main conclusions** about the **impacts of EVs on the power system** and how these impacts can be mitigated:

1. **Impact on electricity demand** will be limited:
    - In a 100% electric mobility scenario for Europe, the energy needs of EVs might represent no more than 10% to 15% of total electricity production. However, EV grid integration might lead to local power issues with increasing EV volumes (Eurelectric, 2015).
    - If all 2.7 million cars in Norway were EVs, they would only use $5-6\%$ of the country's annual hydropower output.

- In a 25% electric mobility scenario for Germany, 10 million EVs by 2035 would translate to an overall consumption increase of only $2.5 - 3\%$.
- If all light-duty vehicles in the US were electric, they would have represented about 24% of the total electricity demand in the country in 2016.

2. The **impact on peak demand**, however, can be much greater if the additional demand is not distributed smartly. For this, smart charging is key:

   - In a 10 million EV scenario for the UK by 2035, evening peak demand increases by 3 GW if charging is uncontrolled, but increases by only 0.5 GW if charging is smart. With smart EV charging, the lowest price periods could see demand increase by 7 GW.
   - Modelling of EVs in New England showed that a 25% share of EVs in the system charged in an uncontrolled fashion would increase peak demand by 19%, requiring significant investment in grid and generation capacities. However, by spreading the load over the evening hours, the increase in peak demand could be cut to between 0% and 6%. And charging only at off-peak hours could avoid any increase at all in peak demand.

3. The **impact on local distribution grids** might also be significant if not managed with smart charging:

   - Xcel Energy, Colorado in the US demonstrated that 4% of distribution transformers could be overloaded at EV market penetration of 5% if charging is aligned with peak load times.
   - The My Electric Avenue Project in the UK identified a need for 32% of distribution circuit upgrades with a $40 - 70\%$ share of electrified cars.

9.4.2 Impact on grid infrastructure

EV charging will have an impact on **distribution grid investments**. The scope of grid investments (in terms of cables and transformers) that will need to be made in a given location will depend at least on the following parameters:

1. **Congestion:** such as in the local distribution network prior to any EV deployment.

2. **Simultaneity factor:** as applied based on the size of each distribution grid. The simultaneity factor/coefficient measures the probability that a particular piece of equipment will need to be switched on at the same time as another piece of equipment. Every distribution system operator considers a different simultaneity factor.

3. **Load characteristics:** for example, the impact of uncontrolled EV charging will be higher in locations with high shares of electric heating (thus leading to higher grid reinforcement). But if smart charging is used in such locations, it may be included with lower grid reinforcements than in locations where no electric heating is used, as the local grids are dimensioned for higher peaks.

4. **Generation assets connected at low voltage level:** for example, integration of high shares of solar PV connected at low voltage level (e.g., in Germany) could be facilitated with smart charging, whereas in locations with no or very low shares of solar PV, EVs could increase the strain on local grids.

5. **Grid code limits and other regulations:** for example, national grid codes define physical constraints in terms of both voltage and frequency variations that distribution system operators have to respect, and investment in grid reinforcement if these country-specific limits are exceeded due to EV charging.

Fast charging represents a challenge for grid infrastructure development. The higher the power, the more capacity you need from the distribution grid. In addition, the locally deployed charging station/cables and vehicle must support this power. Both of those are technologically feasible but come at a price:

1. Vehicles require **more expensive electronics** and protection devices.
2. Grid connection of fast-charging stations requires **bigger cables and transformers**.
3. Such charging stations require more expensive electronics and cooling as well as protecting devices.
4. **Active cooling of the charging cable is needed if very heavy cables are to be avoided**. Increasing voltage from today's level will mitigate the need for heavier cable and/or active cooling, but this is not an optimal solution considering the interoperability with the existing infrastructure (and with the existing EVs).

EV charging impact on Hamburg's distribution grid.

Hamburg is currently the city with the highest number of charging points in Germany (several hundred charging points in households and 810 public charging points as of November 2018). The city expected to install 1 000 public charging points by the beginning of 2019. Electrification of public buses and EV growth are the most critical drivers of load development in the city. The majority of EVs will be in the suburbs where, in Hamburg's case, the grid is weaker.

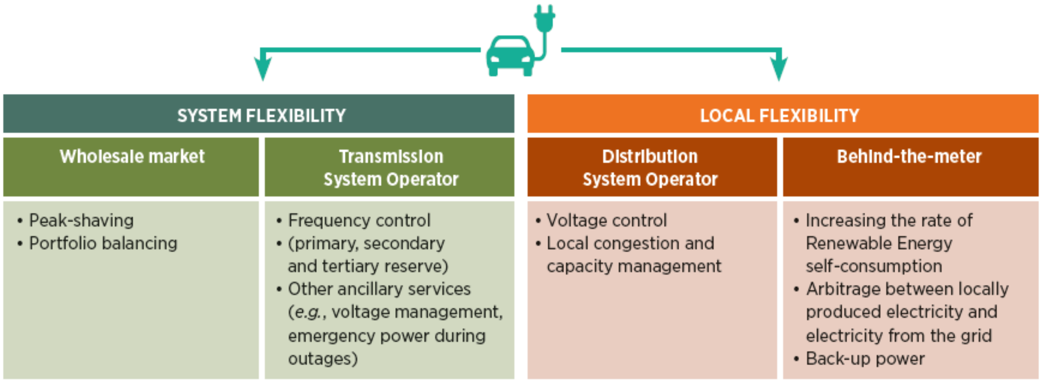
The local distribution system operator, Stromnetz Hamburg, ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point loads of 11 kW and 22 kW. **A 9% EV share, corresponding to 60 000 EVs loading in private infrastructure, will cause bottlenecks in 15% of the feeders in the city's distribution network**.

To avoid these critical situations, Stromnetz Hamburg assessed that investment needs for reinforcing the local grids would reach at least EUR 20 million. Stromnetz Hamburg is also exploring alternative solutions to address the problem. The key is to decrease the simultaneity, meaning decreasing the number of EVs that are charged at the same time on the same local grid. For that, a smart solution using digital technologies is being tested, which includes a real-time communication system that enables the distribution system operator to reduce the load of the charging points needed to address the problem. The 11 kW charging points, for example, can reduce their load from 16 amperes (A) to 8 A, allowing EVs to be charged but in a longer period of time.

9.4.3 Services provided by smartly charged EVs

Smart charging using vehicle-grid integration (VGI) technologies is a means of managing EV loads. This is done either by customers responding to price signals, by the Electric vehicle supply equipment (EVSE) automated response to control signals that react to the grid and market situations, or by a combination of the two while respecting customers' needs for vehicle availability. It consists of shifting some charging cycles in time or modulating the power in function of constraints (e.g., connection capacity, user needs, real-time local energy production). Smart charging therefore is a way of optimising the charging process according to distribution grid constraints and local renewable energy availability, as well as the preferences of drivers and EVSE site hosts.

Figure 9.8: Potential range of flexibility services by EVs



Source: IRENA (2019a)

If charged smartly, EVs can not only avoid adding stress to the local grid but also provide services to fill flexibility gaps both on the local level and on the system level (figure 9.8).

The EVs can operate as grid-connected storage units with a potential to provide a broad range of services to the system. They could alternate their charging patterns to flatten peak demand, fill load valleys and support real-time balancing of grids by adjusting their charging levels.

Smart charging not only mitigates EV-caused demand peaks but also flattens the load curve to better integrate VRE, both at the system level and locally, at the shorter term time scales. More specifically, adjusting charging patterns that today stand idle in parking for most of the time ($90-95\%$ of the time for most cars) could **contribute to**:

1. **Peak shaving (system level/wholesale)**: flattening the peak demand and filling the "valley" of demand by incentivising late morning/ afternoon charging in systems with large penetration of solar and nighttime charging that could be adjusted following nighttime wind production as cars are parked for longer time than they need to fully charge. Early-evening charging that may otherwise increase peak demand would be deferred in this way.

2. **Ancillary services (system and local levels / transmission and distribution system operators)**: supporting real-time balancing of grids by adjusting the EV charging levels to maintain steady voltage and frequency.

3. **Behind-the-meter optimisation and "back-up power" (local level / consumers and prosumers)**: this includes increasing self-consumption of locally produced renewable electricity as well as lowering dependence on the electricity grid and reducing the energy bill by buying cheap electricity from the grid at off-peak hours and using it to supply home when the electricity tariff is higher (during evenings).

Key technical terms for classifying battery technologies:

- **End of life (EoL)**: moment when the battery retains only a fraction (typically 70initial capacity. It is expressed as a percentage of initial capacity.
- **Depth of discharge (DoD)**: the percentage (compared to full capacity) to which the battery can be discharged.
- **State of charge (SoC)**: the capacity of the battery expressed as a percentage of the full capacity at which the battery is during usage charge.
- **Cycling rate (C-rate)**: the rate of charge or discharge. 1C refers to a charge or discharge in 1 hour, 2C refers to 2 hours, and 0.5C refers to 30 minutes.

9.4.4 Types of smart charging and their implementation

Smart charging includes different pricing and technical charging options. The basic technical options are summarised in figure 9.9.

Direct control mechanisms enabled by the EV and the charging point will be necessary as a long-term solution at higher penetration levels and for delivery of close-to-real-time balancing and ancillary services. Such mechanisms range from basic switching on and off of the charging or unidirectional control of vehicles or EVSE (**also called V1G**) that allows for an increase or decrease in the rate of charging, to more challenging bidirectional **vehicle-to-everything (V2X)**.

For **V2X**, two specific configurations are particularly relevant:

- **Vehicle-to-home (V2H)** or **vehicle-to-building (V2B)** do not typically directly affect grid performance. The EV is used as a residential back-up power supply during periods of power outage or for increasing self consumption of energy produced on-site (demand charge avoidance).
- **Vehicle-to-grid (V2G)** refers to providing services to the grid in the discharge mode. The utility / transmission system operator may be willing to purchase energy from customers during periods of peak demand, and/or to use the EV battery capacity for providing ancillary services, such as balancing and frequency control, including primary frequency regulation and secondary reserve.

In the **V1G**, the driver, the EV charging site host or the aggregator can be rewarded only for adjusting their rate of charging up and down compared to the initial charging power (3 kW is assumed for illustration). In **V2G**, EVs can charge and discharge electricity from and to the grid, respectively. The size of the "bids" for grid services corresponds to the capabilities of the EV and the requirements in the given market.

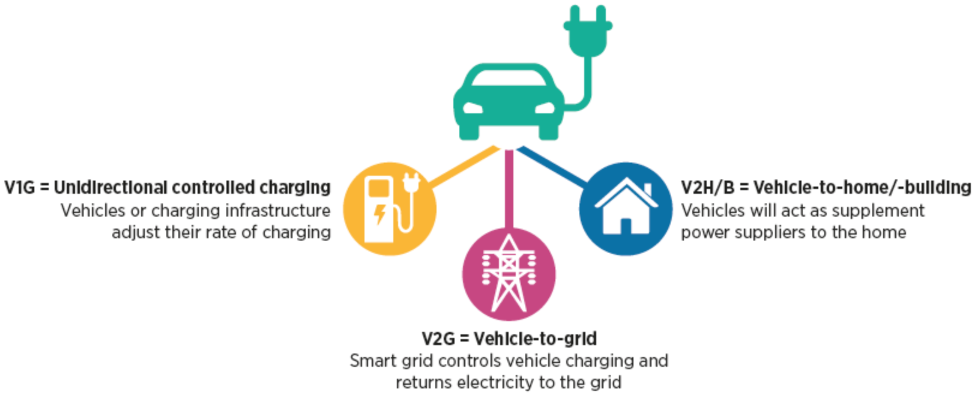
9.5 Business models

9.5.1 E-mobility market actors

The e-mobility market includes the **following segments**:

- **EV sales**: while most light-duty vehicles are sold via leasing, public procurement needs to be considered for public transport means such as buses.
- **Mobility services**: these services include e-car sharing, intermodal transport, fleet management, electromobility service provision and, increasingly, collection and analytics of data from drivers, fleet managers and charging stations.

Figure 9.9: Forms of smart charging



Source: IRENA (2019a)

- **Electricity sales to power EVs**: this includes electricity retail sales as well as re-selling by charging infrastructure providers.
- Installation and maintenance of charging infrastructure.
- **Charging station operations** (smart charging / data management / billing).
- E-roaming: this is key for interoperability of charging services as well as regional/national charging independence.
- **Advanced grid services** such as aggregation and V2G (emerging).

Many traditional as well as new actors from both the mobility and energy sectors are active in this emerging market. In addition to Tesla – with its vision of an integrated mobility company stirring change in the sector – new independent providers include **e-car-sharing service providers** (e.g., Zen Car and BlueIndy by Bolloré), dedicated charging **station developers**, **operators**, **data managers**, **e-roaming platform providers**, as well as providers and aggregators of advanced grid services.

9.5.2 Smart energy services provider and aggregator

The business model of monitoring and controlling large number of resources together by aggregating them and selling their energy and/or capacity in the wholesale or ancillary services markets has been maturing for larger loads and distributed generation. However, **aggregation of batteries from EVs** and offering services that EVs can provide to the market have not yet been fully commercialised.

Profitability and competitiveness of EV flexibility with other flexibility sources at the system level remains a key issue:

1. **Price spreads** in the system may be lowered – for example, by daytime solar PV generation – and may not rise again if there is sufficient flexibility in the system (low price spreads are expected in the German and Spanish day-ahead markets, but high ones are expected in the UK market).
2. **Revenues from ancillary services** may not provide sufficient flexibility in all markets. For instance, the calculation for Germany was based on a market volume of primary and

secondary control of EUR 265 million for 2015, assuming 10 million EVs with 90% availability, representing a value of EUR 29 per EV per year.

Notably, the demand for these services is currently limited to 660 MW, and these 10 million EVs would represent an approximate volume of 30 000 MW, thus pushing the prices even lower.

3. **EVs will compete with other types of decentralised flexibility such as demand-response resources**, and with the used EV batteries themselves. Second-life EV batteries will be inexpensive and are already being deployed by automakers today.

<u>Types of EV flexibility.</u>

1. **Unidirectional V1G** could be handled by a charging point manager. If it were performed remotely, this could be done via a **software-as-a-service (SaaS) structure**, which could manage numerous charging points and other loads on a site. Alternatively, it can be implemented locally as within the charging infrastructure (e.g., local EV-PV synchronisation).

2. **V2G and second-life batteries** operation **require an aggregator**. The original "niche" energy services provider and aggregator model will develop into an energy services platform provider, combining multiple VGI revenue streams and other energy products and services. Tailor-made combining of smart energy services / home and building energy management (smart charging, V2X) with V2G as part of a larger portfolio of aggregated distributed energy resources as well as second-life batteries will be commonplace, rather than a focus on a specific application as occurs today.

3. **Virtual Power Plant** operator Next Kraftwerke, and Jedlix, an electric vehicle (EV) aggregator and smart charging platform provider, have launched an international pilot project which uses EV batteries to deliver secondary control reserve to TennET, the transmission system operator in Netherlands. By connecting the EV to the Jedlix platform, Jedlix can coordinate user charging preferences and establish a live connection with the EV, making sure they are charged smartly. Depending on the charging preference, each EV can provide either positive or negative control reserves. Jedlix will be able to combine user preferences, car data, and charging station information to provide a continuous forecast of the available capacity. This is then used by Next Kraftwerke in the bidding process of TenneT for procuring grid services (NextKraftwerke, 2018).

4. The current **Vehicle-grid integration (VGI)** is based largely on the provision of charging management software from developers of proprietary solutions (like AutoGrid or Nuvve) to utilities and fleets, sometimes operated by Original equipment manufacturer (OEMs). The energy services platform provider model is no longer B2B but integrates the software and provides a spectrum of B2C services. The case studies of Enel and Nissan (green box below) illustrate this emerging business strategy from the utility and the OEM perspectives, respectively.

5. But energy services platforms also may be integrated into other platforms and by other actors from other sub-sectors. For example, **smart building "as-a-service"** integrating energy management is gaining traction, and collecting data from occupants, aggregation and Vehicle-grid integration (VGI) back to the grid could be the next step, even if not the current focus. This space is currently dominated by electronics giants (Schneider Electric, Siemens, Panasonic). Siemens is using its building automation system Desigo in a research project integrating EVs into the energy management of the building (Siemens, 2017).

Future energy services platform providers: Enel and Nissan strategies

In addition to developing charging infrastructure and bundled offers for home and public charging, Enel has invested in the development of an accessible DC V2X home charging station that charges and discharges at 10 kW. Enel has participated in various pilot projects – for example, in the pilot with Nissan in the UK they have played the role of electricity supplier at the charging point, charging software provider as well as aggregator.

In this pilot, **EV clients received compensation** in the form of a reduction in their electricity bill in exchange for provision of grid services, and, thanks to smart energy service, they locally optimise their consumption by increasing self-consumption of their locally generated solar energy and saving on the network charges. Enel integrated the purchased V2G power into its **larger aggregated ancillary services portfolio**, thus creating a "buffer" for uncertainties due to possible deviations in the schedules of individual vehicles, without directly controlling them. Enel is paid by the transmission and distribution system operators and shares the value with the client.

The automaker **Nissan** also eyes valorisation of aggregated flexibility as an additional revenue stream. In January 2018 Nissan launched a new solar generation and energy storage system for domestic use in the UK (Nissan, 2018). The automaker claims that its solution will allow UK homeowners to **increase the rate of self-consumption** from on-site PV and cut energy bills by up to 66%. Over 880 000 UK homes already have solar panels and the market is growing. This new product is a further extension of **xStorage Home** that Nissan developed in partnership with Eaton with second-life EV batteries.

In October 2017 Nissan announced a partnership with OVO Energy to launch a new offering combining the VNet capability of OVO with Nissan's xStorage Home system to develop an OVO SolarStore and a V2G offering for private customers buying the latest Nissan LEAF (OVO Energy, 2017).

9.6 E-mobility outlook

9.6.1 Cost and competitiveness of EVs

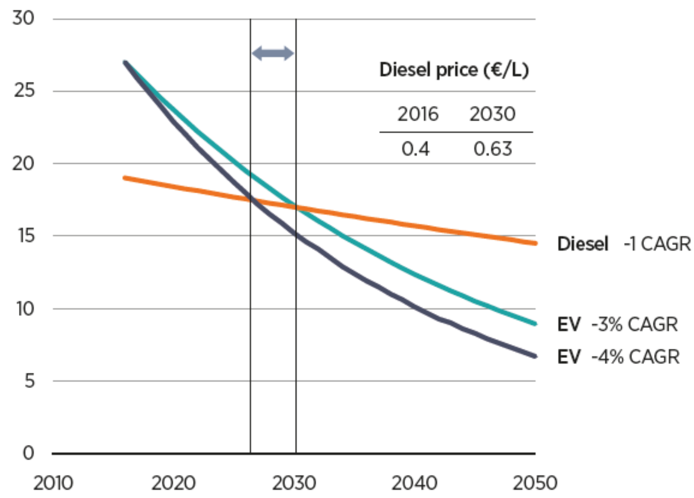
Until now, the most crucial factor that has led to a substantial cost decrease for EVs in the last few years is the **decline in battery pack costs**. Improvements in battery technologies have reduced the average price of battery packs from USD 1 000/kWh in 2010 to around USD 200/kWh in 2017 (UCS, 2017). Analysts expect a further decrease in price to levels of USD 100/kWh in 2025 (McKinsey, 2014), which in turn would result in EVs being competitive with ICE vehicles. As a rule of thumb, this total cost of ownership parity between EVs and conventional gasoline vehicles will be reached at battery prices of around EUR 175/kWh (UCS, 2017).

Another notable factor that has helped to reduce EV prices over the years is the increasing **variety of models** being offered in the market. Whereas in 2010 early customers interested in EVs could choose among only a few limited options – such as the Nissan LEAF, the Citroën C-Zero, etc. – today the range of models is more extensive.

Total cost of ownership (TCO) comparison.

Figure 9.10 shows how the total cost of ownership (TCO) of diesel and EVs could evolve until

Figure 9.10: Total cost of ownership (TCO) for electricity and diesel-powered cars until 2050



Source: IRENA (2019a)

2050. The graph, although illustrative, aims to emphasise that in the medium term (the second half of the 2020s) EVs will eventually be more competitive than diesel vehicles even without subsidies and taxes. If that is the case, EVs could reach a global flee penetration of 7% (IEA, 2018a).

The continued decrease in TCO is supported by the same trends described earlier and can be strengthened by **two more observations**. On the one hand, because of **new mobility business models** oriented to car-sharing practices that are expected by 2050, there will be a shift from privately owned cars to shared vehicles. This will inevitably increase the EV utilisation rate to ranges from 40 000 to 55 000 km per year, and will in turn increase the EV's fuel cost savings in comparison with a diesel car driving the same yearly mileage.

On the other hand, an **unknown variable is how quickly the TCO of EVs will go down in comparison with diesel vehicles**. This point could be influenced by the recent and upcoming wave of countries setting **bans on fossil fuel vehicle sales** by as early as 2025 (in the Netherlands) or by 2030 to 2040 (in France and the UK).

9.6.2 Outlook of batteries

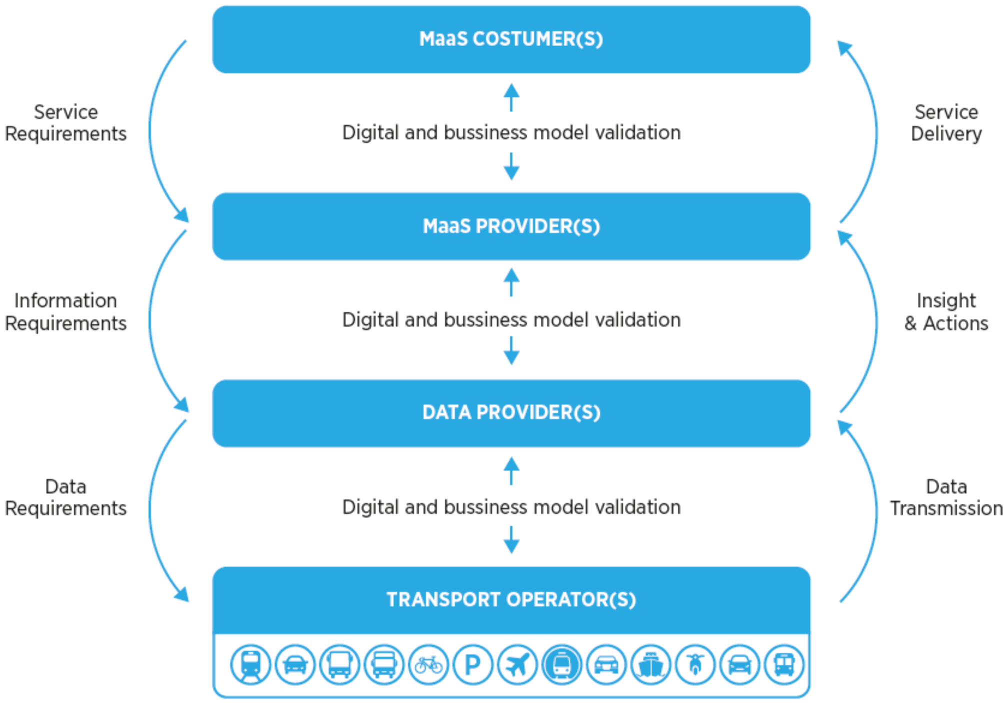
While **Li-on will probably remain the prevalent technology until 2030**, potential breakthroughs in other technologies may lead to its replacement in the long-term horizon.

Two technologies that have already been commercialised – for example, as minor technologies in e-buses for around 10 years – are **Zeolite Battery Research Africa (ZEBRA)** and **lithium-metal-polymer (LMP)** battery technologies.

Other technologies with lower maturity levels are currently under development (only cells are sold, not systems) and could be potentially disruptive if their issues are solved, including:

- Li-ion systems with silicon (Si) as a negative electrode
- Lithium-sulphur system (Li-S)
- Sodium-ion batteries (Na-ion), which are raising interest due to the potential low cost and environmental friendliness

Figure 9.11: Simplified mobility-as-a-service value chain



Source: IRENA (2019a)

- Metal-air batteries including aluminium-air (Al-air) and zinc-air (Zn-air)
- Redox flow batteries for mobility applications.

9.6.3 Shared e-mobility: Mobility-as-a-service

Changing mobility needs will lead to the rise of business models that could transform mobility systems over the coming decades. Removing the pain points that travellers face during their journeys could prove to be a crucial opportunity for new businesses to appeal to customers. A new concept is already paving the way for these business opportunities to emerge, via a shift from an ownership-centred approach of transport to mobility options that are consumed as a service. This service-centred mobility is called **mobility as-a-service (MaaS)**.

Mobility-as-a-service is a way to seamlessly combine transport alternatives from various providers (including shared mobility providers but beyond). MaaS goes beyond calculating the fastest path from one place to another and instead offers a one-stop shop for everything from optimised travel itineraries to payments. A MaaS offering thus consists of **four complementary functionalities**: **trip planning**, **booking**, **payment** and **ticketing/billing**.

At the centre of the MaaS design are **four main actors**, each of them having a key role in providing the MaaS offering. These actors are the **customers**, the **MaaS providers**, the **data providers** and the **transport operators** (figure 9.11).

Although customers have progressively adopted new mobility possibilities over the last decade, and while transport operators are already in place in many countries, MaaS providers and data providers remain almost non-existent. The following section and Figure 28 clarify the value that each step of the value chain offers to the customer.

9.7 Hydrogen versus Electric vehicles

The Truth about Hydrogen

9.8 Questions to summarize the chapter

1. Can you describe briefly the **state of the play in the EV sector**? Market evolution, market penetration, EV in big companies, e-buses, e-tracks?
2. Can you identify the main sources of **EV flexibility potential** today, in 2030, in 2050?
3. Which will be the **impact of smart charging** on electricity demand, electricity peak demand, grid infrastructure?
4. Which will be the **services provided by introducing smart charging EV**? Peak shading, ancillary services, back-up power.
5. Can you describe the **main smart charging methods**? V1G (grid), V2B (building), V2G (grid).
6. Can you explain the **main challenges for the profitability** of EV flexibility?
7. Can you enumerate the main factors that determine the **cost evolution** and the **implementation of EV**? Battery cost, variety of models, business models (mobility as a service), regulation.
8. Can you explain the main actors that determine the **e-mobility business model**? **customers**, the **MaaS providers**, the **data providers** and the **transport operators**

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Chapter 10

Sustainable energy. Carbon Capture Storage (CSS)

This chapter studies the main characteristics of Carbon Capture Storage technologies, and its potentiality to decarbonize the economic system.

10.1 Introduction

Two good videos to frame the discussion:

Money Is Pouring Into Carbon Capture Tech, But Challenges Remain

Carbon Capture - Humanity's Last Hope?

10.2 The role of Carbon Capture

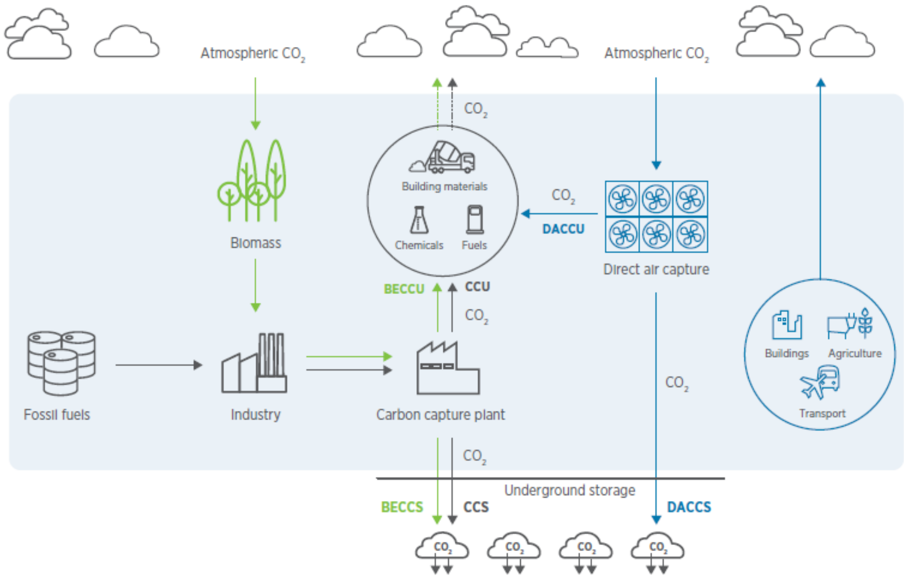
As he have studied in the previous chapters, the **use of renewables** alongside **efficiency improvements** can deliver most of what is needed, providing 80% of the required CO2 emissions reductions. **Renewable sources**, including renewable power generation sources and the direct use of renewable heat and biomass, would contribute to 25% of CO2 emissions reductions, an additional 25% of CO2 reductions would come from the **reduced demand compared to the baseline scenario, efficiency improvements and circular economy**. The **electrification of transport and heat applications** would account for 20% of CO2 emissions reductions, while the use of **hydrogen and synthetic fuels and feedstocks** would enable 10% of CO2 emissions reductions.

However, the scale of the challenge, the relatively limited time available, the legacy of systems built around fossil fuel use, and the complexities of some industrial processes mean that even a very aggressive ramping up of renewables will not be sufficient to address all emissions. Some fossil fuel use will remain in 2050 and some industrial processes will produce CO2 emissions irrespective of the energy source.

There is a targeted role, therefore, for a combination of **carbon capture and storage (CCS)** processes that reduce emissions released into the atmosphere, for **carbon capture and utilisation (CCU)** processes that might reduce emissions, and for **carbon dioxide removal (CDR)** processes which, combined with long-term storage, can remove CO2 from the atmosphere, resulting in negative emissions.

There are different types of carbon capture technologies (figure 10.1):

Figure 10.1: Carbon cycle



Source: IRENA (2021)

- **Carbon Capture and Storage (CCS)** refers to processes that directly capture CO2 emissions from “point sources” – i.e. from fossil-fuel use or industrial processes with the CO2 subsequently stored in ways that lock it away for long periods. If effectively implemented, the process reduces most of the CO2 emissions being released into the atmosphere, although usually not all.
- **Carbon Capture and Utilisation (CCU)** refers to processes that directly capture CO2 emissions from “point sources” – i.e. from fossil-fuel use or industrial processes – but then utilise that CO2 in secondary processes such as producing synthetic fuels, chemicals and materials. As with CCS, if effectively implemented, CCU reduces some CO2 emissions being immediately released into the atmosphere but, depending on the life-cycle of the products produced, some or all of the utilised CO2 may be subsequently released into the atmosphere. The impact of CCU on emissions is complex therefore and must be carefully managed.
- **Carbon Dioxide Removal (CDR)** refers to processes that actually “remove” CO2 from the atmosphere rather than simply reduce what is added. If combined with long-term storage, these can result in negative emissions. These technologies and practices are sometimes therefore called negative emissions technologies (NETs) and include natural approaches such as afforestation or reforestation and technological or engineered approaches such as the use of bioenergy coupled with CCS (BECCS) or direct air capture and storage (DACCS).

CDR Technologies Remove CO2 from the atmosphere.

- **BECCS (bioenergy with carbon capture and storage)** When growing, biomass captures CO2 from the atmosphere. In power or industrial processes, the biomass (or fuels derived from the biomass) is combusted, releasing CO2. In BECCS the majority of that CO2 is captured and then stored. BECCS applies the same technology as CCS with the difference that it uses biogenic feedstock/fuels.
- **DACCS (direct air carbon capture and storage)** Instead of capturing CO2 from point sources such as relatively high concentration flue gas streams, the CO2 is separated from ambient air. The low concentration of CO2 in ambient air requires a higher surface area of solvents or sorbents in their liquid or solid form in contact with the input air stream, as well as a large amount of energy.

10.3 The current status of carbon capture, transportation, utilisation and storage

As of early 2021, **24 commercial fossil fuel-based CCS and CCU facilities** were in operation globally with an installed capacity to capture around 0.04 Gtpa of energy- and process-related CO2 emissions.

Of these **CCS and CCU facilities**, 11 are **natural gas processing plants** (where CO2 needs to be removed anyway to produce natural gas that meets specific standards) and one is a **coal-fired power plant**. **Chemical plants** (mostly for ethanol production), **hydrogen production in refineries**, and **iron and steel plants** account for the remainder. Three plants were operational but are now closed or suspended. An additional 30 plants are at various stages of development. A further 16 small scale pilot and demonstration plants are operating, 19 are at various stages of development, and 24 have been completed and closed (figure: 10.2).

If all 30 commercial plants under development are completed, the capture capacity would rise to approximately 0.1 Gtpa.

There are currently three operational commercial facilities that use **bioenergy with CCS (BECCS)** and seven commercial plants are in development. The current capture capacity of operational commercial BECCS plants is very small at 1.13 Mtpa, which would rise to 9.7 Mtpa if all plants under development reach operation. A further nine smaller scale BECCS pilot and demonstration plants are operational – six completed and four in different stages of development.

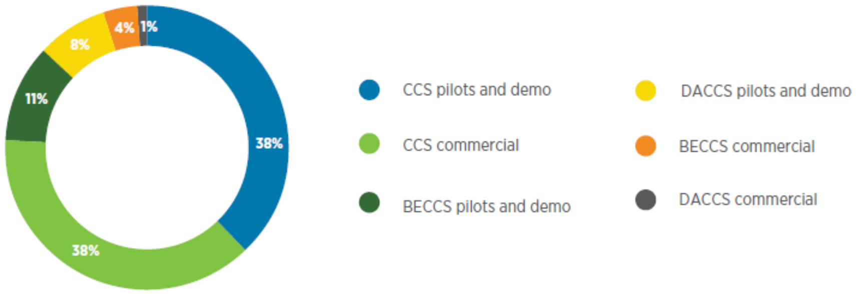
There are currently **two facilities that use DACCS**, with one in development, plus 15 pilot and demonstration plants in operation or development; however, collectively their capture capacities are quite small.

10.3.1 Costs are uncertain and vary by application

The costs of CCS, CCU and CDR will be a crucial factor in decisions on their future roles; however, **cost estimates vary widely**, with **future projections having a high degree of uncertainty**.

CCS is capital intensive and, in some cases, has significant operating costs. In general, **capture costs** dominate but in some cases **CO2 transportation costs** can be significant. Actual costs are site specific and differ significantly depending on the technology used. Capture costs are mainly dependent on CO2 concentration and pressure, and transport cost on volume and

Figure 10.2: Share of commercial CCS, DACCS and BECCS



Source: IRENA (2021)

distance.

While the costs of capture in CCU are fairly well understood, the **costs of converting CO2 into products** such as fuel, fertilisers, building materials, etc. are less clear and require further research and analysis. The **costs of CDR**, and particularly BECCS, depend on biomass feedstock, while the costs of DACCS as a novel technology are currently very high with an uncertain cost reduction trajectory.

Many cost estimates focus only on capture costs and either do not include costs for compression/liquefaction, transportation and storage (including assessment and monitoring costs) or treat transport and storage as lump sums.

Cost estimates tend to focus on large-scale CCS facilities with large CO2 volumes (such as gas plants) that can justify dedicated transport and storage infrastructure, rather than smaller industrial plants that emit lower CO2 volumes per year (such as cement plants) and will therefore have to rely on clusters, hubs and transportation networks to benefit from economies of scale. The same applies to CDR facilities. The calculated costs in feasibility studies also tend to be much lower than the costs of actual projects that have been implemented.

When discussing and comparing costs, therefore, the project specifics and the full end-to-end project costs need to be considered.

As CCS applied to fossil fuel processes results in additional energy use, it can in turn lead to additional CO2 emissions and the difference can range from 10 to 25%. To account for that, cost per tonne of CO2 avoided (and not cost per tonne of CO2 captured) is the best measure to compare CCS with renewable options.

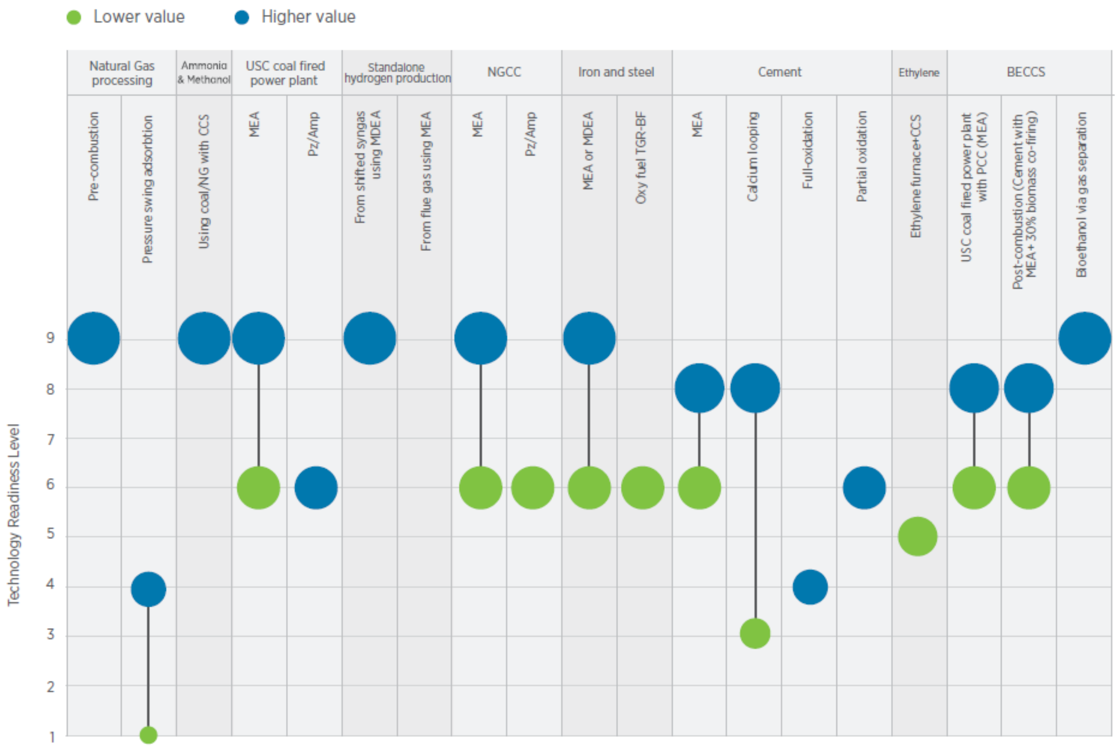
10.3.2 Transportation costs

Transporting relatively small quantities of CO2 is an established process and there are a few larger projects, mostly located in the US, which involve the pipeline transportation of CO2 for enhanced oil recovery (CO2- EOR) or EU regional transport by ships.

With experience of transporting other more volatile gasses, the safe transportation of CO2 is not likely to be barrier to CCS uptake, although public acceptance may remain a concern, particularly for onshore transportation options.

There is a lack of detailed data on costs. Transport and storage costs are often modelled in

Figure 10.3: Technology readiness levels of CO2 capture technologies



Source: IRENA (2021)

the integrated assessment models as lump sums at USD 10/tCO2 and disregard the flowrate, distance to storage and utilisation sites, transport mode and storage type, as well as the variability in geographical, geological and institutional settings. The models also focus mostly on large-scale plants with high volumes of CO2. There are a few more detailed studies that focus on a handful of countries with established infrastructures.

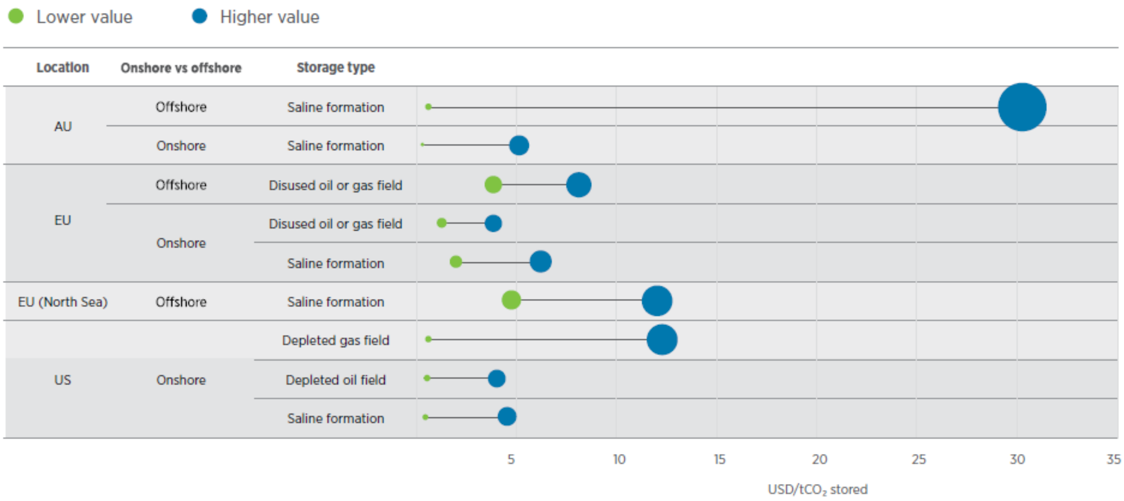
Based on current estimates, for pipelines the **capital expenditure** (CAPEX) is the major component amounting up to 90% of total transport costs. For transporting CO2 by ship, the situation reverses and the major component is **operating costs** (OPEX) for liquefaction, fuels, loading/unloading and temporary storage.

Based on current estimated costs for capacities of 2.5 to 20 Mtpa CO2 for distances between 180 km and 500 km, **onshore pipeline** has the lowest costs at USD 1.7–6.1/tCO2, followed by **offshore pipelines** at USD 3.5-32.4/tCO2. Transport via **offshore pipelines** up to 1 500 km entails costs of up to USD 58.4/tCO2. **Shipping ranges** from USD 12.5-22.4/tCO2 for distances between 180 km to 1 500 km.

10.3.3 Geological storage of CO2

Permanent geological storage options include saline formations and depleted oil and gas fields. Other storage options relate to enhanced hydrocarbons – **particularly enhanced oil recovery (EOR)**. Geological storage in saline formations and in EOR has been carried out at Mtpa scale in past decades, but there is not yet experience in storing CO2 at Gtpa scale, as the CO2 captured has not yet reached Gtpa scale.

Figure 10.4: Cost estimates for onshore and offshore storage



Source: IRENA (2021)

The largest experience in storing CO2 is in EOR, which has a very low risk of CO2 leakage. For CO2 pumped underground into geological formations, researchers expect less than 0.0008% of stored CO2 to be leaked over 10 000 years. While the risks of leakage are small, public perceptions towards this approach may still become an issue. Monitoring and verification processes will be important, and must be a mandated and –ideally – a regulated part of any storage project.

There is more than **12 000 Gt of potential**, albeit mostly unverified, of CO2 storage resources in saline formations globally, out of which 400 Gt of storage is currently well documented; but there are only a small number of large-scale commercial projects. There are currently six projects storing almost 0.009 Gtpa of CO2 in the United States, Canada, Algeria and Norway.

Depending on the continent, **onshore saline formation cost** estimates range from USD 0.2–6.2/tCO2, with the cheapest storage in Australia and the most expensive in the EU. **Offshore saline formation costs** range from USD 0.5-30.2 /tCO2, with a lower range in Europe (figure 10.4). Costs estimates for depleted oil onshore fields in the US range from USD 0.5-4.0/tCO2, and gas onshore fields in the United States range from USD 0.5-12.2/tCO2. Cost estimates for **depleted onshore oil and gas fields** in the EU range from USD 1.2-3.8/tCO2, with offshore at USD 3.8–8.1/tCO2. These cost ranges come with many caveats; in particular, lower ranges look optimistic and it is unclear how much they include the costs of monitoring, verification or pressurisation.

10.3.4 Total end-to-end process costs

Cost estimates of avoided CO2 for carbon capture, transport and storage range from USD 22-225/tCO2 depending on the sector, capture technologies, distance from storage and storage location.

The lowest range is for the production of **ammonia and methanol** (USD 22–62/tCO2), followed by **natural gas processing plants** (USD 31–49/tCO2) and production of **hydrogen** (USD 73–88/tCO2). The highest range is in the **iron and steel industry**, with costs of USD 75–131/tCO2, followed by the **cement industry** (USD 62–102/tCO2), with the most expensive price put on the production of **ethylene** (USD 212–225/tCO2).

Cost estimates for **bioenergy** with carbon capture, transport and storage also vary significantly depending upon the sector of application (USD 69–105/tCO2).

10.4 The future role of CCS, CCU and CDR

Low-cost renewables make carbon capture combined with fossil fuel use unnecessary in many sectors and contexts, but it will be needed in some applications (figure 10.5).

Renewables and CCS (applied to fossil fuel use and/or process emissions) are often perceived as competitors in the energy transition but in some applications they can be partners and, in a few cases, CCS is the only option.

The respective roles of renewables versus CCS vary by country, sector and the specific contexts of each deployment. **Factors of importance include:** relative costs; practicality of deployment; availability of supporting transport and storage infrastructure; actual emission abatement potential; deployment time scales; skills and knowledge; social impacts; and societal attitudes.

In most contexts in the **power sector, renewables outcompete CCS** on cost per tonne of CO2 and sustainability grounds.

10.4.1 Carbon capture in industry

Carbon capture for fossil fuel and process **emissions in industry** must be aggressively scaled to reach c. 3.4 Gtpa by 2050 (figure 10.5).

In IRENA's 1.5°C Scenario, the use of CCS and CCU for fossil fuel or process emissions is limited to the most essential applications – in particular to capturing process emissions in hydrogen, cement, iron and steel and chemical production with a limited deployment for industry/waste incinerators, etc. CCS is not deployed for fossil-fuel based power production.

In the 1.5°C Scenario, CCS and CCU for fossil fuel or process emissions from power, fuel production and industrial process rises from 0.04 Gtpa today to 2.8 Gtpa of CO2 in 2040 and 3.4 Gtpa of CO2 in 2050, cumulatively capturing 58 Gt globally over that period.

These figures include 2.4 Gtpa in 2050 from CCS applied in the **cement, chemical and steel sectors**, and 1.1 Gtpa in 2050 captured in the production of **blue hydrogen from natural gas with CCS**, which accounts for 30% of total hydrogen supply.

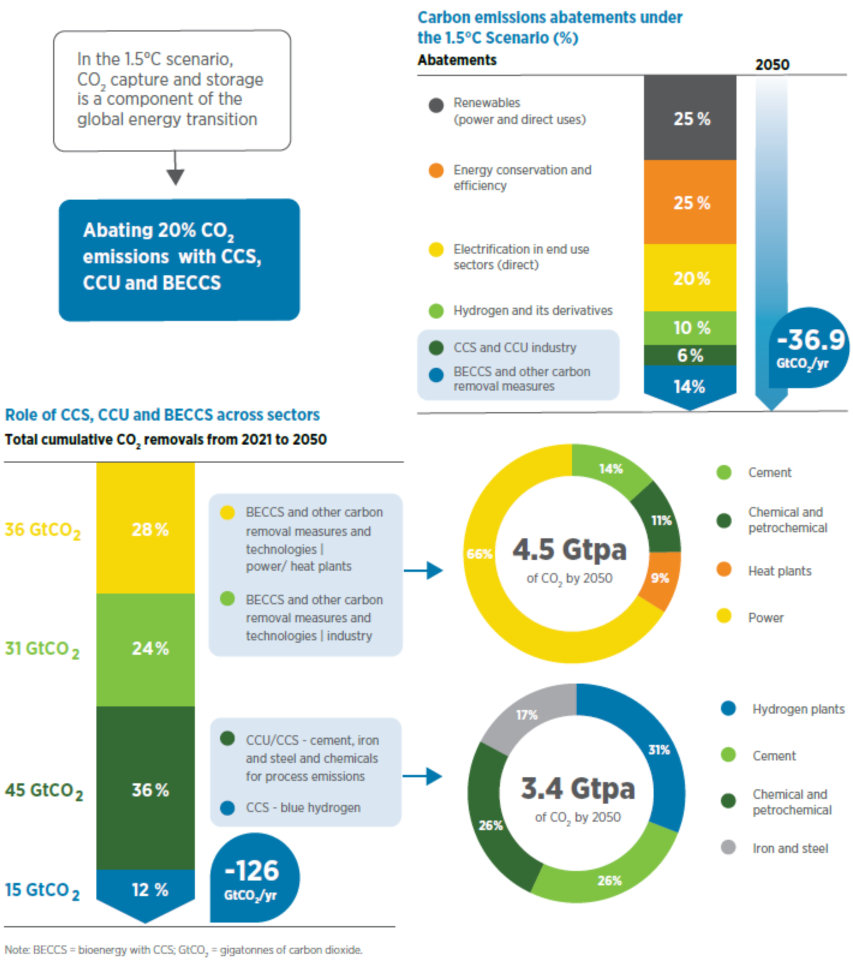
10.4.2 Bioenergy with CCS (BECCS)

Bioenergy with CCS (BECCS) is essential for the net-zero goal but needs to reach **4.5 Gtpa by 2050** and faces multiple challenges (figure 10.5).

CDR processes, combined with long-term storage, can in principle remove CO2 from the atmosphere, resulting in negative emissions. CDR technologies are therefore a critical component of net-zero pathways.

CDR measures and technologies can include nature-based processes such as reforestation, as well as technology or engineered approaches such as BECCS, DACCS and some other experimental approaches.

Figure 10.5: The role of CCS, CCU and BECCS across sectors



Source: IRENA (2021)

The most developed example of CDR technology is BECCS. Biomass absorbs CO2 from the atmosphere as it grows, and the use of CCS prevents most of that CO2 from going back to the atmosphere during biomass final use. The overall result is that CO2 is effectively removed from the atmosphere through biomass growth and storage elsewhere.

Net-zero pathways rely on BECCS but it is currently unproven in most contexts and there are complexities to be addressed. The extensive use of BECCS requires both a scaling up of CCS deployment and strategies to ensure sufficient suitable and sustainable biomass feedstock supplies.

There are a range of potential applications of BECCS, including: power and heat generation with biomass providing some or all of the fuel (e.g. wood pellets, sugarcane or municipal solid waste); cement kilns with biomass providing the fuel; blast furnaces for iron production, where charcoal can be used as a fuel and reducing agent; chemical plants where the chemical feedstock is biomass (e.g. bio-methanol or in bioethanol production); and biogas upgrading where the CO2 fraction of biogas is separated for the production of biomethane.

Depending on the plant design, biomass can be the only fuel, or it can be co-fired with coal or natural gas. In the past decade, a small number of coal power plants have been converted into 100% biomass power plants or are in the process of doing so. However, the number of such conversions to date is small and only one fully converted power plant has a clear publicly announced plan to add CCS; as yet, no co-firing coal or natural gas power plants have announced plans to add CCS.

In IRENA's 1.5°C Scenario, BECCS use results in 2.7 Gtpa of CO2 captured and stored in 2040, and 4.5 Gtpa of CO2 in 2050 (figure 10.5). This includes the carbon balance in the chemical and petrochemical industry through carbon stocks in chemical products, recycling and carbon capture in waste incineration. As a result, towards 2050 the power and industry sectors become net negative; i.e. the CO2 captured more than compensates for remaining CO2 emissions in those sectors. To capture 4.5 Gtpa of CO2 by 2050 would require investments of more than USD 1.1 trillion between 2021 and 2050.

BECCS can, in principle, be utilised in a range of processes but the optimum application of BECCS requires more detailed investigation of costs, logistics and sustainable biomass supply chains, and will be highly country and context specific. IRENA's 1.5°C Scenario includes biomass-based processes from which 10.12 Gtpa could be captured and stored by 2050 (see figure 10.6). Of that potential, the scenario assumes 44% (4.5Gtpa) is actually captured and stored but is not specific about where BECCS would be applied. The most significant opportunities are in power, heat, chemicals and biorefineries but BECCS could also be significant in cement, pulp and paper, and food production. The potential in iron and steel production is low in the 1.5°C Scenario by 2050, since the scenario assumes a nearly complete transition away from blast furnaces by then, but the BECCS potential could be larger there during the transition or if more blast furnaces utilising biomass and CCS are retained.

To illustrate the scale of BECCS required, the Drax power plant in the UK has converted four coal-fired units (each rated at c. 660 MW) to biomass and is planning to retrofit CCS to at least two units. Each individual unit would capture circa 4 Mtpa. Capturing 4.5 Gtpa would require over 1 100 such units around the world, or an equivalent, and most BECCS applications will be much smaller than this.

Figure 10.6: Potential for biogenic carbon capture in 2050 in IRENA's 1.5°C Scenario

Process group	Biogenic carbon capture potential in 2050
	$GtCO_2$
Power	4.43
Heat	1.29
Cement	0.37
Iron and steel	0.03
Chemicals	1.18
Pulp and paper	0.35
Food sector	0.30
Biorefinery	2.15
Total	**10.12**

Source: IRENA (2021)

10.4.3 Other CDR technologies

Other CDR technologies include DACCS and some other approaches that are mostly at an early experimental stage, which makes their future potential hard to quantify. According to this early experience, projects face high energy and land requirements, but offer flexibility in terms of their location.

DACCS is another CDR technology that is in the early stages of development and a long way from reaching the gigatonne-scales needed to be impactful. There are two commercial plants currently operating and capturing a negligible amount of CO2 (0.0009 Mtpa, 0.9 ktpa), and one other plant is under development and would add an additional 0.021 Mtpa (21 ktpa) of CO2 capture. In addition, there are 15 pilot and demonstration plants – three completed, seven in operation and five at various stages of development.

These technologies do not currently play a major role in the IRENA 1.5°C Scenario. However, countries and investors are beginning to make financial commitments to large-scale DACCS projects, which – if successful in driving scale – would allow DACCS to offset some of the need for BECCS or could allow for more emissions elsewhere.

10.5 Carbon Capture in Norway

This chapter is based on the links:

Longship white paper

Langskip - fangst og lagring av CO2

10.5.1 Overview

This section is based on the links:

CCS Norway

Long ship

Government Norway (Carbon capture and storage - CCS)

Government Norway (Long ship project)

CSS Norway (Public and private cooperation)

Norway has the knowledge and many years of experience with CCS, not only in CCS technology such as CO^2 monitoring and storage but in essential related sectors such as geology, offshore engineering and industrial processes.

With a large, natural geological CO2 storage capacity area under the North Sea and more than 20 years of experience with CO2 storage, Norway is in a strong position to demonstrate CCS at scale.

The Government proposes September 21, 2021 to launch a carbon capture and storage (CCS) project in Norway. The project has been named 'Longship', in Norwegian 'Langskip'.

Longship seeks to fulfill the objectives of both Government and industry by reducing investment barriers for business and developing sustainable value creation opportunities.

Reducing barriers. Since the world has agreed on ambitious climate targets and there is a growing consensus among international bodies that CCS is needed to achieve them, why has CCS not already taken off?

To date there has been a lack of investment in CCS projects. The very same IEA, UN and EU reports which extol the virtues of CCS have also been quick to point this out.

This lack of commercialization has primarily been driven by several CCS specific market failures. So there is an obvious need for cooperation between the private and the public sectors to overcome market hurdles to increase investment in CCS.

How then, do we unlock this investment? The key lies in demonstrating CCS to prove that it is viable, building open-access CO2 infrastructure and developing public-private cooperation.

The Norwegian Contribution in the development of CCS. CCS has been proven to be technically viable in several existing projects around the world. Globally, there are large-scale CCUS projects already in operation, such as Equinor's Sleipner project, SaskPower's Boundary Dam project and Shell's Quest project.

All of these projects are incredibly useful and Longship will be building on the lessons that have been learned and shared as CCS technology has developed over the years. In addition, the Longship aims to address more of the market failures which have so far held up investment in CCS as a broad climate mitigation tool. Longship aims to do this by:

- Demonstrating the full CCS chain

- Establishing an open access transport and storage infrastructure
- Capturing CO2 from a cement factory and potentially from a Waste to Energy (WtE) plant
- Testing CCS under the condition of relevant EU regulation

Longship is also driven by public-private cooperation with a shared responsibility for investment. Each industrial partner is responsible for designing their own project, while the state coordinates and creates a framework for each partner's role.

10.5.2 Longship project

This section is based on the link:

Government Norway (Longship)

In a Government White Paper to the Norwegian parliament submitted 21/09/2020, the Government proposes to launch a carbon capture and storage (CCS) project in Norway. The project has been named 'Longship', in Norwegian 'Langskip'.

Longship is a milestone in the Government's industry and climate efforts. The project will lead to emission cuts, and facilitate development of new technology and thus new jobs.

Others must follow.

The Government proposes to first implement carbon capture at Norcem's cement factory in Brevik. In addition, the Government also intends to fund Fortum Oslo Varme's waste incineration facility in Oslo, providing that the project secures sufficient own funding as well as funding from the EU or other sources.

For Longship to be a successful climate project for the future, other countries also have to start using this technology.

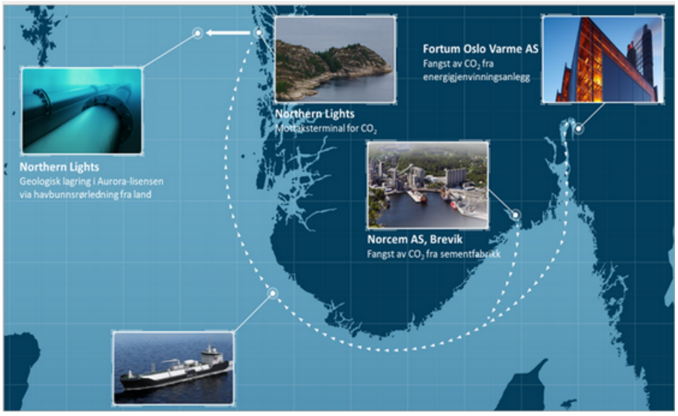
Longship also comprises funding for the transport and storage project Northern Lights, a joint project between Equinor, Shell and Total. Northern Lights will transport liquid CO^2 from capture facilities to a terminal at Øygarden in Vestland County. From there, CO2 will be pumped through pipelines to a reservoir beneath the sea bottom.

Bit by bit.

For many years, various Norwegian governments have supported technology development, test and pilot projects, and underscored the importance of carbon capture and storage as an important climate tool internationally. The present Government has followed up this work and made targeted efforts on CCS since 2013.

According to the UN Intergovernmental Panel on Climate Change, CCS will be necessary to reduce global greenhouse gas emissions in line with the climate targets at the lowest possible cost. There are currently few facilities in operation on a global basis. We therefore need more projects that bring learning and technological development. In turn, they will help reduce costs. If CCS is to become an efficient climate policy instrument, new facilities must be established in Europe and globally.

Figure 10.7: CSS projects in Norway



Source: Gassnova

A necessary climate measure.

Norway has committed itself to cutting domestic emissions by 50-55 precent by 2030.

For the world to achieve the goals that we have committed ourselves to in the Paris Agreement, we need large-scale carbon capture and storage. Not all emissions can be cut by applying renewable energy. In several industrial processes, such as production of cement, CCS is the only technology that can cut emissions. With Longship, Norway will support development of climate solutions for the future.

Norway is in a good position to contribute to the development of CCS. The country has a strong technological community in the field of carbon capture, transport and storage. For decades, the development and operation of the CO2 storage projects on the Sleipner and Snøhvit fields have demonstrated safe carbon storage on the Norwegian continental shelf.

Effective climate policies must be positive industrial policies. Through Longship, the Government will strengthen Norwegian industry by enabling enterprises to meet the climate requirements of the future. The project is an important contribution to green growth and will secure and create new jobs in the industry.

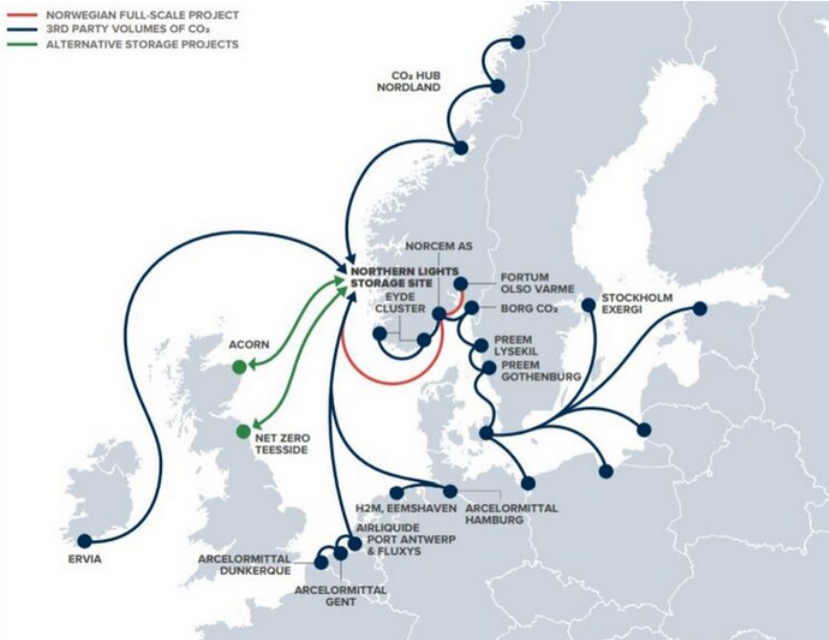
Longship facilitates the further development of CCS both in Norway and Europe. The project has been matured to a level required for an investment decision, and the decision basis shows that all parts of the project are feasible.

The project also involves risks. For Longship to have the desired effect, an ambitious development of climate policies in Europe is needed. The risks are primarily connected to the economy of the project, such as the technical integration of the different parts of the project, the scope of following projects and necessary support schemes for such projects from the EU and individual countries. What is not at risk is the safety and integrity of the storage solution for CO^2.

25 billion NOK.

The total investments in Longship are estimated at NOK 17.1 billion. This includes both Norcem, Fortum Oslo Varme as well as Northern Lights. The operating costs for ten years of operation are estimated at NOK 8 billion. The total cost estimate is thus NOK 25.1 billion.

Figure 10.8: Northern Lights project



Source: Equinor

Longship will receive state aid in accordance with negotiated agreements. The state's part of these costs are estimated at NOK 16.8 billion.

10.5.3 CO^2 transport and storage: Northern Lights project

This section is based on the links:

CCS Norway (Northern Lights)

Northern Lights

Equinor (Northern Lights)

Equinor is the operator of the Northern Lights project, which also includes **Shell** and **Total** (figure: 10.8). They will build an open access CO2 transport and storage infrastructure that provides capacity above and beyond that required for the **Norcem** and **Fortum** capture sites.

As a part of the Longship CCS project, we share the experience from previous and ongoing CCS projects like Northern Lights. By increasing the knowledge of CCS technologies, we aim to speed up the development and demonstrate that carbon capture and storage can be executed at large scale.

The Northern Lights project is developing a CCS technology where the CO^2 will be stored in pressurized tanks before being pumped offshore through a pipeline to one or more injection wells that are located on the seafloor. No offshore platform is required for these wells and they will be controlled using existing oil and gas infrastructure on the Norwegian continental shelf. Much of the design and operations of these facilities is similar to the ones used for liquid petroleum gas (LPG), with the exception of the fire hazard, which is absent for CO^2.

Space to grow – CO^2 transportation from across Europe.

Given the ambition to transport CO^2 from across the European Continent, the receiving terminal has been designed with future expansion in mind. The number of pressure tanks can be increased and there is even an option for building a second jetty to be able to receive two tankers at a time. The pipeline from the receiving terminal can transport the volumes of CO^2 required and additional wells can be connected to the end of the pipeline.

Regulation.

Equinor was awarded a permit to develop the CO^2 storage site on behalf of the Northern Lights consortium in January 2019. The acreage lies to the south of the giant Troll hydrocarbon field, west of Bergen, and represents a prime location for the geological storage of CO^2 deep below the seafloor.

Northern Lights drilled a well to confirm the properties of the storage reservoir in Q1 2020 and this will also serve as the injector well once CO^2 starts flowing from the capture plants when the project begins.

However, before injection of CO^2 can commence, the Northern Lights consortium will also need to obtain a CO^2 Storage permit from the Environmental Protection Agency, which has a mandate to protect the natural environment on the seafloor and in the sea itself.

In order to adhere to the regulations that come with these permits, Equinor and their partners will put in place a robust monitoring system, similar to the ones they have used for many years at the Sleipner and Snøhvit storage fields.

10.5.4 Carbon capture: Fortum Oslo Varme

This section is based on the links:

Fortum web page

CCS Norway (Fortum Oslo Varme)

Fortum Oslo Varme's **Waste-to-energy plant** at Klemetsrud on the outskirts of Oslo, Norway's capital could be the world's first of its kind with full-scale carbon capture. The plant will be able to capture 400,000 tonnes of CO^2 a year, and provide transfer opportunities to other industrial plants in the Nordic region and Europe. Fortum Oslo Varme's CCS project shows how cities across Europe best possibly can handle waste that should not or cannot be recycled. The excess heat from the end treatment of residual waste is used to produce electricity, district heating and soon cooling to the city of Oslo.

The flue gas from the end treatment of waste is currently cleaned of dioxins, NOX and CO. Now Fortum wants to capture the CO^2. A 5500 hour pilot in 2019 demonstrated the possibility to capturing **more than** 90% **of all** CO^2 **in the flue gas**. Estimately 50% of the waste incinerated at the plant is of biological origin such as non-recyclable food scraps, paper and wood, making the plant carbon-negative. When capturing CO^2 from biological origin, it means that CO^2 is taken out of the atmosphere. This is also known as bio-CCS, or BECCS, something that both the European Commission, the UN and the International Energy Agency all emphasize is of the utmost importance for achieving the world's climate goals.

The City of Oslo has ambitious climate targets and needs CO^2 capture at the waste-to-energy plant to reach its goal. The carbon capture project is also strongly rooted in Fortum's strategy to build a cleaner world.

City solutions by responsible waste handling:

- Goal to capture about 400 000 tonnes CO2 per year, 90% cleaning of CO2.
- CCS at Waste-to-Energy plants will capture both fossil and biological CO2 (50% BECCS).
- CO2 transport to port via emission free trucks: WtE-plant not at port.
- Successful pilot testing on real flue gas: 5500 test hours, up to 95% capture.
- Technology supplier with full-scale experience (Shell's amine), EPC contractor TechnipFMC.
- Feasibility, Concept and FEED studies completed 2015-2019.
- Fortum Oslo Varme's carbon capture project is one of 70 projects that in the March of 2021 was qualified for a final and more comprehensive application round for support from the EU Innovation Fund.
- The application for the second stage was submitted June 23rd 2021.
- The European Commission's allocation of funds is made in the Q4 of 2021.

10.5.5 Carbon capture: Norcem

This section is based on the links:

CSS Norway (Norcem)

Norcem web page

A good video about "Green cement" is in the next link:
CNBC Green cement

Norcem AS is the sole **producer of cement** in Norway, and is an experienced international supplier of cement. Norcem has an ambitious plan to capture the carbon emissions derived from the production of cement, and it participate actively in the **Northern Lights project**.

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Chapter 11

Sustainable development. Sustainable Development Goal 7: Affordable and Clean Energy

11.1 Introduction

In this chapter we will focus on the analysis of the Sustainable Development Goal 7: Energy. In particular, we focus on four points: Access to electricity; access to clean fules and technologies for cooking; renewable energy; and energy efficiency. We will stablish bridges between SDG7 and other Sustainable Development Goals. The chapter is organized as follows:

1. Access to electricity.
2. Access to clean fuels and technologies for cooking.
3. Renewable energy.
4. Energy efficiency.
5. Questions to summarize the chapter.

This chapter is based on the document "Tracking SDG 7: The energy progress report 2020."

11.2 Access to electricity

11.2.1 Main trends

The global trend: The world has made striking progress over the past decade—far more than in previous decades—in increasing access to electricity. The share of the world's population having access to electricity grew **from 83 percent in 2010 to 90 percent in 2018**. An increase of more than a billion people. During this period, the number of people without access to electricity fell from about 1.2 billion to 789 million, outpacing the overall increase in population. Trends from 2016 to 2018 show accelerated electrification (with the average annual rate of electrification increasing to 0.82 percentage points) compared with 2010–16 (0.77 points) (figure 11.1).

Target for 2030: Despite accelerated progress in recent years, the world **will fall short of SDG indicator 7, which aims for 100 percent access to electricity by 2030**, if the current rate is maintained. Due to the many challenges facing access-deficit countries, **the latest projection shows that about 620 million people would still lack access to electricity**

Figure 11.1: Percentage of population with access to electricity

Source: World Bank (2020a)

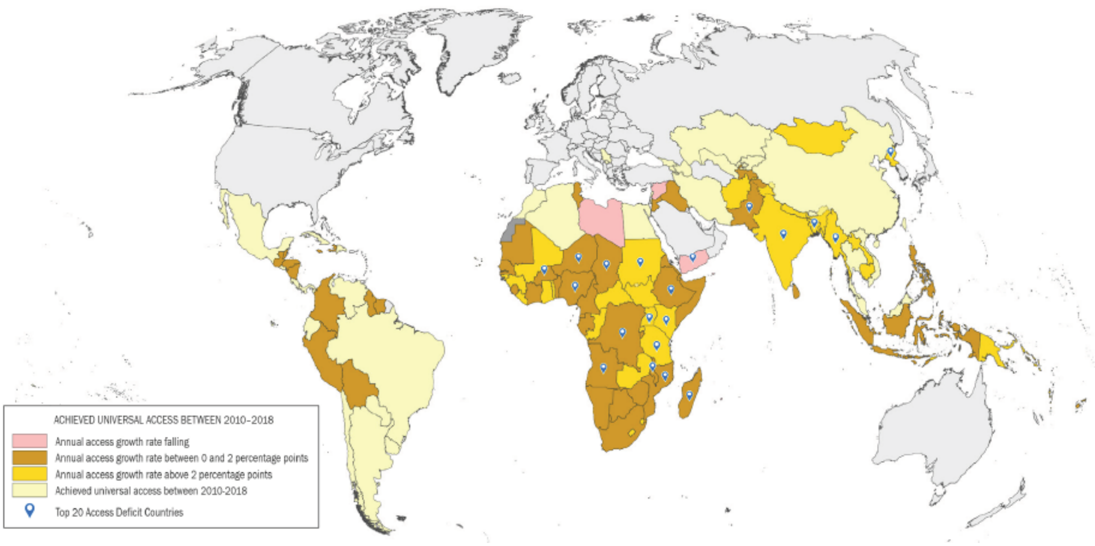
in 2030 (IEA 2019a). To close the gap, the annual rate of electrification would have to rise from the current 0.82 percentage points to 0.87 percentage points for the years 2019 to 2030. Moreover, this projection does not account for the disruptions of covid-19. These have not yet been quantified, but they will likely affect electrification, slowing and in some cases even reversing advances (e.g., as utilities and off-grid service providers face financial difficulties). Governments, hand in hand with the international community, should be prepared to mitigate these adverse effects to safeguard the gains in access.

Regional highlights: The global advance in access to electricity since 2010 masks unequal progress across regions, with attention now focusing on Sub-Saharan Africa. Latin America and the Caribbean and Eastern Asia and South-eastern Asia approached universal access, exceeding 98 percent access to electricity by 2018. In Central Asia and Southern Asia, more than 92 percent of the population had access by 2018. The world's access deficit is increasingly concentrated in Sub-Saharan Africa, which, in 2018, was home to about 548 million people who lacked access—more than half of the region's population and nearly 70 percent of the global population without access. After 2010, access advances in Sub-Saharan Africa outpaced population growth, but the trend has reversed recently. Between 2016 and 2018, the number of people in the region lacking access remained almost stable (figure 11.2).

Urban-rural distribution in access: Rural populations made up about 85 percent (668 million people) of the global access deficit in 2018. But, since 2010, they have seen more progress than the urban deficit populations. Globally, the access rate in rural areas grew from about 70 percent in 2010 to 80 percent in 2018. During the same period, the rate of urban electrification grew from 95 to 97 percent. While approaching universal access, urban electrification nevertheless faces policy and technical challenges. The obstacles to supplying electricity to surging urban populations have slowed gains since 2010. Unstable distribution networks have made it difficult to connect pockets of people in urban cores and in sprawling settlements that ring large cities. In the coming years, the access rate is more likely to advance in rural areas than in cities (figure 11.3).

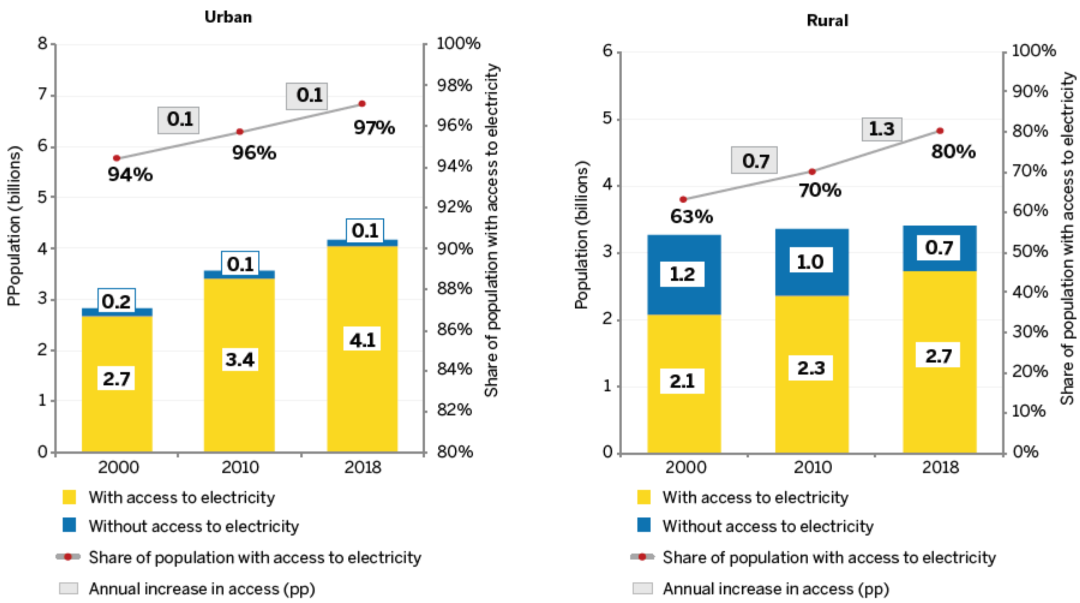
The top 20 countries with access deficits: In 2018, 20 countries accounted for 617 million people without access—78 percent of the worldwide deficit in that year. Achieving universal access will require sustained effort to bridge electrification gaps in these countries. Nigeria and the Democratic Republic of Congo had the world's largest access deficits in 2018, with 85 and 68 million people, respectively, lacking access. India was third with about 64 million people. Over the 2010–18 period, electrification efforts in Nigeria and the Democratic Republic of Congo

Figure 11.2: Annual increase in access to electricity rate in access-deficit countries, 2010-18



Source: World Bank (2020a)

Figure 11.3: Gains in electricity access in urban and rural areas, 2000, 2010, and 2018



Source: World Bank (2020a)

(DRC) lost ground to population growth, leading to net increases of 3 million and 12 million people, respectively, lacking access to electricity by 2018. Among the 20 largest access-deficit countries, Bangladesh, Kenya, and Uganda showed the most improvement since 2010. Expansion of access kept pace with population growth in just 8 of the 20 countries during the period; in addition to the three just mentioned, those countries were India, Democratic People's Republic of Korea, Myanmar, Sudan, and Tanzania.

11.2.2 Providing electricity to record numbers of forcibly displaced people

Today, forcible displacement affects a record number of **75 million people around the world**, including almost 24 million refugees and asylum seekers. Of the 75 million forcibly displaced people at the end of 2018, about 20 million were refugees and over 3.5 million were asylum seekers (UNHCR, 2019).

Historically, humanitarian and development actors do not provide access to electricity among refugee households. They lack the expertise and funding to do so, for a start. Some host governments are reluctant to authorize long-term infrastructure for refugee settlements that are optimistically considered temporary. Electricity access for displaced populations is now receiving growing attention, though reliable information and monitoring are scarce. The best globally comparable data presently available come from the Integrated Refugee and Forcibly Displaced Energy Information System of the United Nations High Commissioner for Refugees (UNHCR). The system is a global monitoring toolkit accessible at https://eis.unhcr.org/about.

Existing data shows that refugees have disproportionately lower access to grid electricity than their surrounding host communities. According to the UNHCR findings, the most striking cases were in Rwanda (Gihembe, Kigeme, Mugombwa, Nyabiheke) and Tanzania (Nyarugusu), where just **10 percent of refugees had access to the electricity grid in 2018, compared with 25–37 percent in the host communities**. In Cameroon (Douala, Gbiti, Kette, Meiganga, Minawao), only **5 percent of the refugees had access to the grid in 2018, compared with 25 percent in the host communities**. In Bangladesh, the gap between the refugees in 10 camps in Cox's Bazar and the host community was particularly stark: **no refugees had access to grid power, whereas up to 80 percent of the host community had access**. In other countries, including Burkina Faso (Gandafabou, Goudebo, Mentao), Chad (Aradib, Djabal, Goz Amer), and South Sudan (Doro, Ezo, Gendrassa, Kaya, Lasu, Yusuf Batil), neither refugees nor the host communities had access, underlining the poverty of areas hosting refugees in many countries.

11.2.3 Energizing women

Access to electricity plays a critical role in **poverty reduction for women and girls**. Women's employment and leisure will improve with increased access to electricity. Poor electricity supply was pinpointed as the biggest obstacle to growth by 25 percent of female-headed enterprises surveyed in Tanzania and 19 percent in Ghana. Statistical data from these countries show a positive relationship between the productive use of electricity and women's economic empowerment. Use of electrical appliances allowed for diversification in products for sale and helped female entrepreneurs attract more customers. The provision of electric light amplifies time savings by increasing efficiency and adding flexibility in the scheduling of household tasks. Freeing up women's time is a prerequisite for investments in their education and life choices, encouraging them to seize economic opportunities and participate in economic, political, and social life (World Bank 2012).

Electrification projects can promote gender equality in several ways. For example, ensuring that the upfront cost of electricity provision and electric appliances is affordable to women and women-led businesses—who are less likely to have access to finance—would facilitate grid and off-grid connections and the use of energy services. Also, gender disparities can be ameliorated with approaches that ensure women have the same opportunity as men to benefit from improved income-generating activities. With a focus on closing gender gaps in employment and skills development, projects can also address **women's underrepresentation in the energy sector workforce**. IRENA's online gender survey from 2018 highlighted access to training and skills development programs. In fact, these were seen as a key measure to improve women's engagement in deploying renewables for energy access (IRENA, 2019).To ensure that gender is factored into energy projects, specific actions throughout the project cycle are required: a gender-gap assessment, a plan of action for interventions, and a focus on monitoring and evaluation that tracks the narrowing of gender gaps. An in-country example from Ethiopia—where the government has launched a reform of its energy sector to reach universal electrification by 2025—aims to create more equitable institutions and equal benefits for women. A first-of its-kind approach, the NEP and NEP 2.0 initiatives established new ways of looking at gender, focusing on constraints in employment, child care, sexual harassment, female entrepreneurship, and consumer-level affordability (World Bank, 2020b).

11.2.4 Supporting other SDGs by supplying power to education facilities and health centers

Providing electricity to schools and health centers offers broad benefits that will assist in reaching objectives codified in a range of SDGs, most directly **SDG 3 (health)** and **4 (education)** but also **SDG 5 (gender)** and **SDG 8 (work and economic growth)**. The Multi-Tier Framework (MTF) team collected information from public institutions including health and education facilities as a part of the household survey.

Education facilities.

In 2018, the Multi-Tier Framework (MTF) survey compiled data in public institutions in Cambodia, Ethiopia, Kenya, Myanmar, Nepal, and Niger. The data were collected at the facility level by interviewing officers best positioned to respond at the institutions.

In the surveyed countries, 31 percent of educational facilities are electrified through an on-grid source of electricity and 9 percent through off-grid systems; 60 percent have no access to electricity.

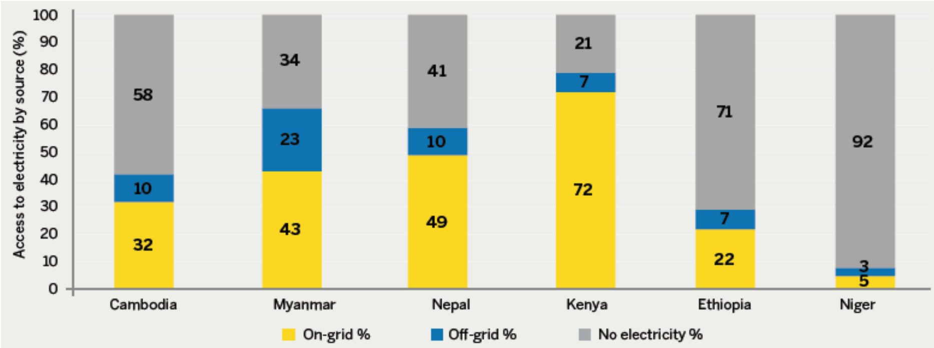
The national public grid is the primary source of electricity for educational facilities with access to power. More specifically, 49 percent of schools in Nepal are electrified through the public grid, 72 percent in Kenya, and only 22 percent in Ethiopia. An exception to this trend is Niger, where solar energy sources, including solar home/lighting systems, mini grids, and batteries, are primary providers of electricity for 3 percent of schools. Education facilities also rely on solar as backup power to cover urgent energy demand. This is the case for 86 percent of facilities in Cambodia and 15 percent of schools in Kenya (figure 11.4).

Health centers.

The covid-19 pandemic highlights the need for reliable and affordable electricity to health centers. MTF collected data across 730 health centers, including clinics and hospitals in Cambodia, Ethiopia, Kenya, Myanmar, Nepal, and Niger.

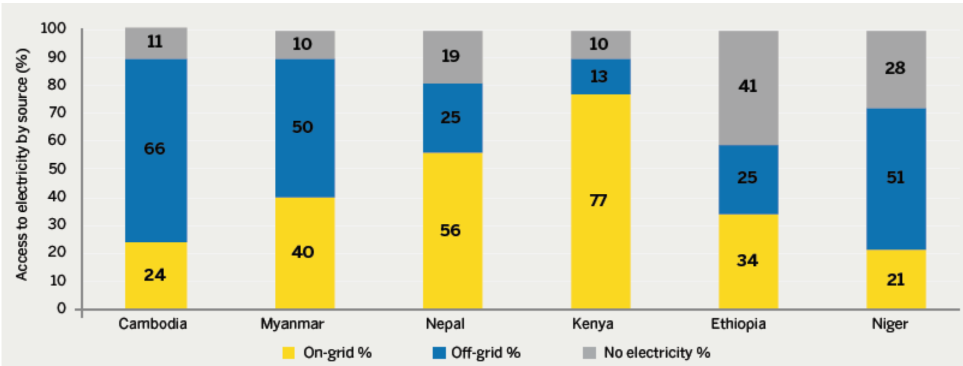
Across the surveyed countries, around 75 percent of health facilities have access to a primary

Figure 11.4: Electrification of schools, by source



Source: World Bank (2020a)

Figure 11.5: Electrification of health centers, by source



Source: World Bank (2020a)

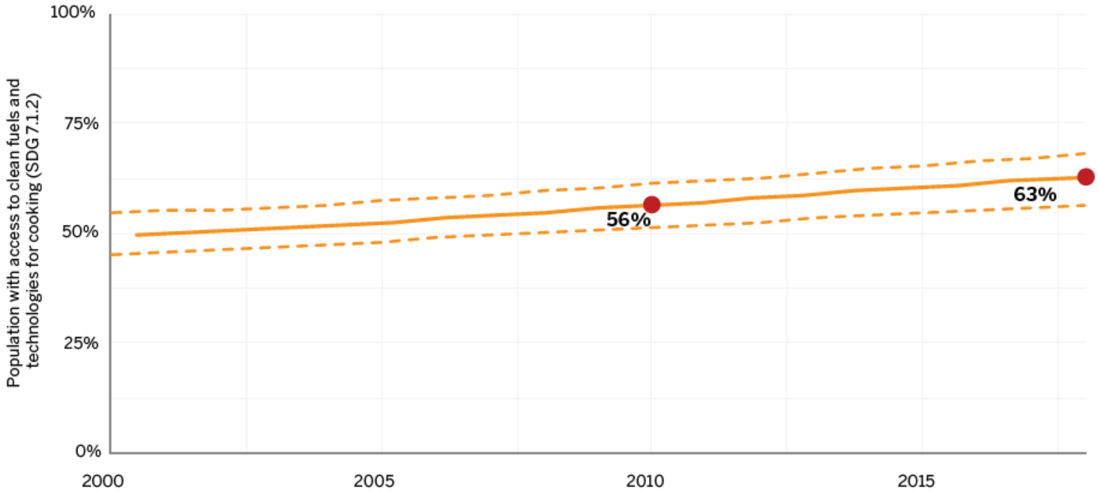
source of electricity (42 percent through grid access, 33 percent through off-grid solutions), while 25 percent remain unelectrified. These aggregate results mask large discrepancies at the country level, as well as quality and reliability of supply.

In Kenya, 77 percent of health centers rely on the public national grid to cover their primary electricity needs. At the same time, 66 percent of health centers in Cambodia use off-grid solutions to cover their primary electricity demand, and 83 percent of them use solar systems as a backup power source (figure 11.5).

The health centers use electricity mainly for lighting (57 percent), refrigerators for vaccines (40 percent), and fans or evaporative air-cooling systems (28 percent). They also reported, however, that the use of electric powered medical appliances is limited owing to no availability, high cost, and insufficient energy.

In every country analyzed, the power supply is compromised by unscheduled interruptions and voltage fluctuations. Twenty-five percent of health facilities reported that unscheduled outages affect the capacity to deliver essential health services. Damage to equipment caused by poor-quality connections and frequent voltage fluctuations are also constraints for 28 percent of health centers.

Figure 11.6: The global population with access to clean cooking (in percentages)



Source: World Bank (2020a)

11.3 Access to clean fuels and technologies for cooking

11.3.1 Main trends

Status of access: In 2018, 63 percent of the global population had access to clean cooking fuels and technologies; the global population without access was 2.8 billion people. Without prompt action, universal access will fall short of SDG goals by almost 30 percent. Meanwhile, exposure to household air pollution will continue to contribute to millions of deaths from noncommunicable diseases (including heart disease, stroke, and cancer) and pneumonia. Household air pollution will continue to worsen climate change (figure 11.6).

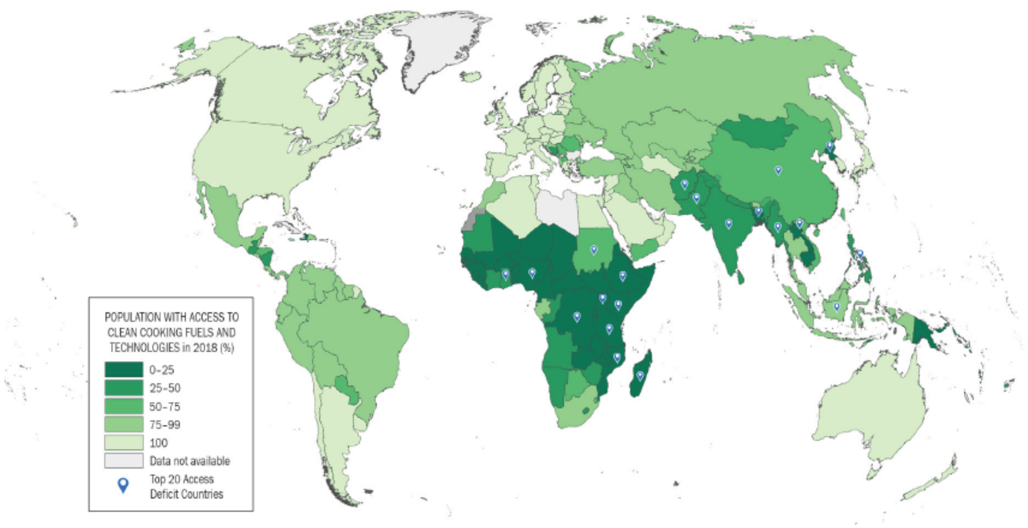
Access and the 2030 target: The annual rate of access to clean cooking fuels and technologies from 2010 to 2018 increased by less than one percentage point (pp) as population growth outpaced the number of those with access. In the decade leading up to 2030, increases in excess of 3pp per year are required to achieve the goal of universal access to clean fuels and technologies by 2030.

Regional highlights: Greater access to clean cooking was achieved largely in two regions of Asia. From 2010 to 2018, Eastern Asia and South-eastern Asia saw annualized increases in access of 1.6pp—while the numbers of people lacking access fell from 1.0 billion to 0.8 billion. Central Asia and Southern Asia also saw improved access to clean cooking, with annualized increases of 1.5pp. The 1.11 billion people without access dropped to 1.0 billion. In Sub-Saharan Africa, meanwhile, a stagnant access rate (annualized increase of 0.4pp) combined with rapid population growth have meant that the numbers of people without access have risen from 750 million people to 890 million people (figure 11.7).

Over the period 2014-2018, population growth in Sub-Saharan Africa outstripped growth in the number of people with access to clean cooking—by around 18 million people each year. Thus, in this region 894 million (874–911) people, or around 85 percent of the population, lack access to clean fuels and technologies for cooking.

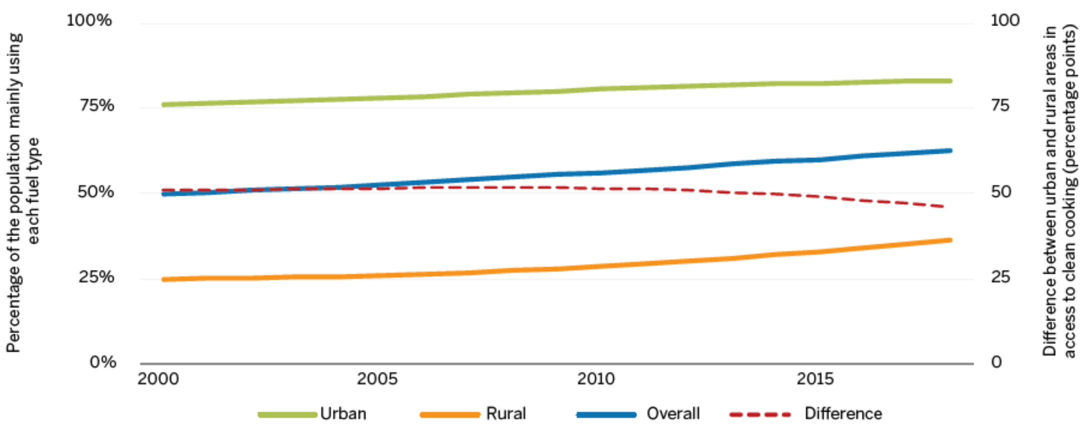
As a result, in 2018, around 3 billion people lacked access to clean fuels and technologies for cooking. Furthermore, if trends continue without changes in policy, the access deficit will shrink

Figure 11.7: Regional populations, by rate of access to clean cooking fuels and technologies, 2018



Source: World Bank (2020a)

Figure 11.8: Clean cooking access in urban areas, rural areas, and overall



Source: World Bank (2020a)

from 2.8 to 2.7 billion people (2.0–3.5) by 2030, about half of them in Sub-Saharan Africa and a quarter of them in Central Asia and Southern Asia. Using IEA's Stated Policies Scenario, 2.3 billion people will still lack access in 2030 under current and planned policies (IEA 2019). Action is urgently needed.

Urban-rural divide: There are urban-rural discrepancies worldwide in access to clean cooking fuels and technologies: 83 percent of the people living in urban areas have access to clean fuels and technologies, compared with 37 percent of those living in the countryside. These discrepancies have been shrinking since 2010 owing, first, to increased access in rural areas, and, second, to population growth in the cities that is beginning to outpace access.

Between 2000 and 2010 the disparity between urban areas and rural areas in access to clean cooking was fairly constant at just over 50 percentage points (52pp [45–57] in 2010), but this has steadily fallen over the past decade, to 46pp (36–55) in 2018. This is explained by trend changes in the annual increase in access to clean fuels and technologies for urban and rural areas.

In rural areas, the annual increase has risen consistently, from only 0.2pp between 2000 and 2001 to 1.2pp between 2017 and 2018. In contrast, the annual increase in urban areas has fallen consistently over the past decade, from a high of 0.6pp between 2007 and 2008 to only 0.2pp between 2017 and 2018. This means that while access has accelerated in the countryside, it has been decelerating in urban areas. In fact, if observed trends continue and population growth outpaces access to clean fuels, the proportion with access to clean cooking is projected to decline in urban areas as the new decade begins. Meanwhile, some countries with rapid access growth will reach near-universal access, from which point increased access is no longer possible.

The top 20 countries with access deficits: From 2014 to 2018, 20 countries accounted for more than 80 percent of the global population without access to clean cooking fuel.17 In terms of the percentage of the national population lacking access, 19 of the 20 countries with the lowest percentage of the population having access were least-developed countries in Africa. Of these, 15 had annualized increases in access over the same period of less than 0.1pp, with some of these displaying potential decreases in access.

Fuel trends: In low- and middle-income countries of Central Asia and Southern Asia, Eastern and South-eastern Asia, Latin America and the Caribbean, Oceania, Sub-Saharan Africa, and Western Asia and Northern Africa, the use of **gaseous fuels** (liquefied petroleum gas [LPG], natural gas, and biogas) continues to increase. Since 2010, gas has overtaken unprocessed biomass fuels as the dominant fuel worldwide. (Unprocessed biomass, charcoal, coal, and kerosene are considered polluting fuels.) In **urban areas**, the use of **electricity** for cooking has risen, but gas remains the most common fuel. In **rural areas**, meanwhile, a decline in the use of polluting fuel, particularly raw coal, has been accompanied by increased use of **gas**, though **unprocessed biomass fuels** remain dominant. Finally, the global proportion using charcoal is low, but charcoal has overtaken unprocessed biomass in Sub-Saharan cities.

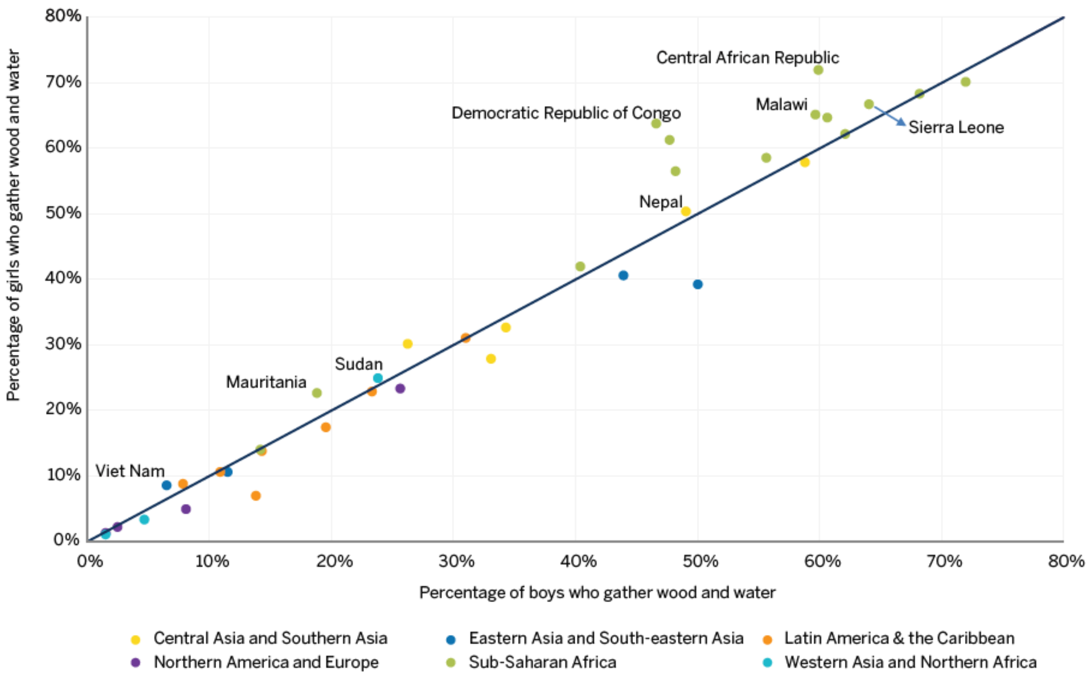
Outlook: Since 2010, only small improvements in access to clean fuels and technologies for cooking have been realized. Although Asia has made notable gains, stagnant growth in access, combined with rapid population growth, have brought progress in Sub-Saharan Africa to a standstill. If this trend continues, any hope of achieving universal access rates by 2030 will be quashed, leaving a third of the global population vulnerable not only to adverse health effects but also to social and economic disadvantages. The latter is especially true for women and children, who shoulder time-consuming household tasks of gathering fuel and tending smoky stoves. These tasks take them away from remunerative work on the one hand while on the other subject them to adverse environmental conditions. That said, universal access remains achievable if serious efforts were made toward accelerating the transition to clean cooking worldwide, and particularly in Sub-Saharan Africa.

11.3.2 Youth, gender, and health implications

During 2018, 2.8 billion people were exposed to household air pollution. This exposure has been previously linked to high blood pressure and respiratory and cardiovascular disease. The use of polluting fuels increases the risk of burns, injuries, poisoning, chronic headaches, and many other ills. The most vulnerable group thus exposed are **women and children**, as they are traditionally the procurers and users of polluting household fuels.

In access-deficit countries in Sub-Saharan Africa, a sizable percentage of children spend time gathering fuels. In addition, based on WHO statistics, the **procurement of fuels is predominantly done by girls over boys** (figure 11.9). This imbalance creates a bias from an early age as girls spend more time procuring fuels instead of other activities, for example, receiving education.

Figure 11.9: Percentages of girls and boys who gather wood and water



Source: World Bank (2020a)

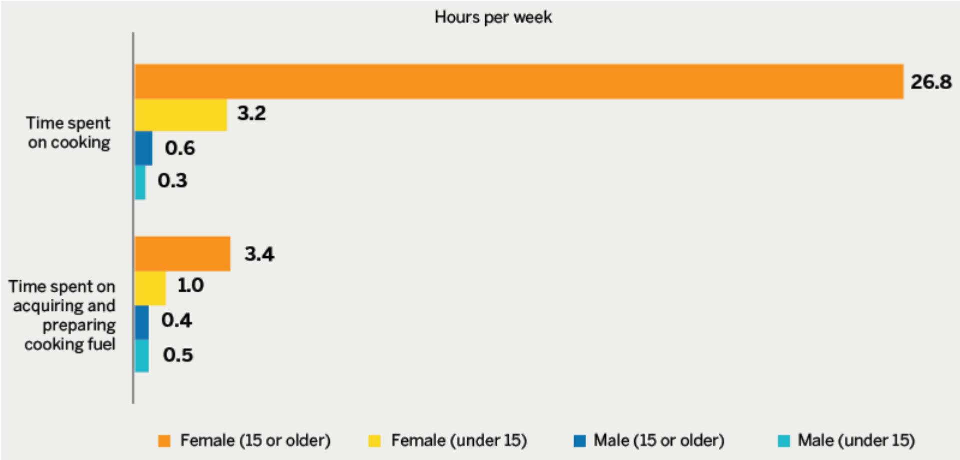
The degradation of household air quality because of polluting cooking fuels affects all household members. Some studies show, however, that the concentration of particles in the air increases drastically during meal preparation. This has an outsized effect on women and children because they are traditionally tasked with cooking.

Universal access to clean cooking fuels and technologies would also help attain other SDGs. The benefits of access to clean fuels and technologies include: **better health and well-being** (SDG 3), **education** (SDG 4), **fewer gender inequalities** (SDG 5), **affordable and clean energy** (SDG 7), **economic growth** (SDG8), **sustainable cities and communities** (SDG 11), and **climate action** (SDG 13).

11.3.3 Clean cooking and gender

In developing countries around the world, millions of women and girls live in energy poverty, risking their lives every day by working long, arduous hours to secure the energy needed by their households to cook their family's meals. The time spent cooking over inefficient stoves and procuring fuel restricts women's ability to partake in paid, as well as educational, political, and social activities, thereby perpetuating gender inequality, economic poverty, and a persistent drudgery trap. In addition to cooking, women also endure incredible hardships for fuel acquisition—walking long distances searching for fuel and carrying heavy loads of firewood and water. Displaced women have even worse burdens, in many cases having to walk for hours to find firewood, sometimes spending the night outside of camps set up for displaced people, and thus increasing their vulnerability to physical and sexual attack, dehydration, and other injuries. As the primary cooks in most developing-country households, women are more susceptible than men to household air pollution, as they are more likely to inhale toxic smoke from inefficient cooking fires.

Figure 11.10: Time spent acquiring fuel and preparing food, by gender



Source: World Bank (2020a)

An in-depth analysis using data from Uganda shows that although female- and male-headed households show similar rates of access to clean cooking (at the country level, as well as in urban and rural areas), female headed households tend to have better access to clean cooking than male-headed households as household expenditure level increases. Among the richest 40 percent of households, women have greater access to improved cookstoves and clean-fuel stoves than men. In terms of **household time spent on cooking**, women and girls spend much more time than men and boys. In Uganda, women (15 years and older) spend on average 3.8 hours per day cooking, and girls spend close to 30 minutes. In contrast, men and boys are virtually not involved in cooking. Similarly, female household members will often spend much more time **acquiring and preparing fuel** than men and boys. In Uganda, women spend 3.4 hours per week in cooking fuel acquisition and preparation—over 7.5 times more time than men (figure 11.10).

The introduction of clean cooking fuels can drastically reduce the time women spend on unpaid household meal preparation; clean cooking also promotes more cost-efficient fuels and thus financial savings in the long term. The time and income recovered from these household activities free up space and opportunities for women and girls, helping to lift them out of energy poverty. Time spent collecting fuelwood can be intensive: in India, time spent collecting firewood ranges from three to ten hours per week. Nigerian households spend an average of 1.7 hours per day gathering firewood (WHO 2019). In Kenya, households working with improved cookstoves saw the time spent collecting fuel drop from an average of 12 hours per week to 5 hours— and most participants reported using the time saved for economically productive tasks (WLPGA 2014).

Case studies have shown that when women receive **empowerment training to sell stoves**, they can dramatically increase sales. For example, in Nepal and Kenya women doubled sales after training. In a pilot project supported by the Clean Cooking Alliance with the Girl Guides in Ghana, 200 girls received training in empowerment, entrepreneurship, and cooking technologies and fuels. Afterwards, each household purchased efficient cookstoves. As a result, the girls reported a 50 percent reduction in cooking time, as well as two hours saved per firewood collection trip. In 2014, a research study commissioned by the Clean Cooking Alliance in Kenya found that women cookstove entrepreneurs sold three times as many cookstoves as their male peers when given the same training and support. Additionally, women's networks provide access to consumers in hard-to reach markets, and women distributors better understand the needs of women and more easily approach their clients.

When women are positioned as the critical stakeholders they are—both as users who will benefit from cleaner, more efficient stoves and fuels, and as entrepreneurs and employees in the value chain—their efforts clearly spur widespread adoption. Women have a role to play in every segment of the cooking value chain, and their involvement can scale adoption of cooking products and services, while boosting their livelihoods. Women's involvement in the clean cooking sector can spur widespread distribution and delivery of cooking fuels and technologies that will contribute to a thriving global industry.

11.4 Renewable energy

We have studied this topic in detail in chapter 4. In this section, I only present the main results in World Bank (2020a), since those results are based on the simulations done by the International Energy Agency, and they complement the analysis done in chapter 4.

The global trend: Sustainable Development Goal (SDG) 7 posits a substantial increase in the share of renewable energy in total final energy consumption (TFEC). Meeting this target will require the penetration of renewable energy to accelerate in all three **end uses—electricity**, **heat**, and **transport**. In 2017, the share of renewable energy in TFEC increased to 17.3 percent, up from 17.2 percent in 2016. This rise reflects a more rapid growth in renewables (2.5 percent) compared with the overall growth of TFEC (+1.8 percent). Renewable energy consumption **has grown fastest in the power sector**; growth of renewables consumption in the **heat and transport sectors has been much slower**. Excluding the traditional uses of biomass, the share of renewables in TFEC rose to 10.5 percent in 2017, up from 10.3 percent in 2016.

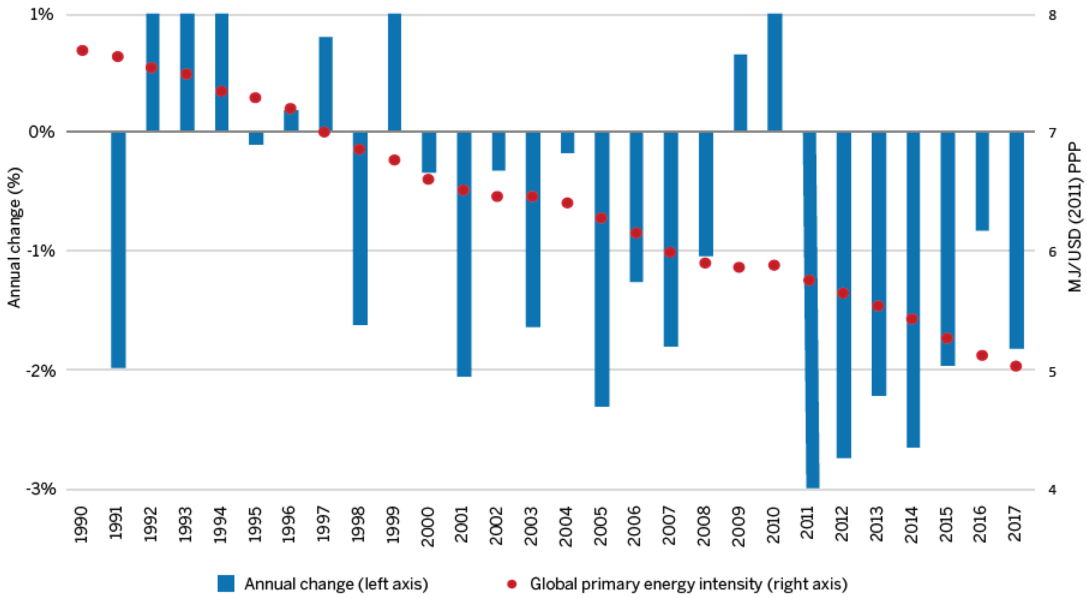
The target for 2030: Although there is no quantitative target for SDG 7.2, countries have agreed that the share of renewable energy would need to accelerate substantially to ensure access to affordable, reliable, sustainable, and modern energy for all. Despite impressive growth in renewable energy over the past decade, the world is not on track to meet the SDG 7 target.

Regional highlights: At 69 percent of TFEC, Sub-Saharan Africa continues to show, by far, the highest share of renewable energy. The traditional uses of biomass, however, still account for almost 85 percent of renewable energy consumption in the region, while modern renewable energy is below the world average. Latin America and the Caribbean, on the other hand, had the largest share of modern renewables (29 percent) thanks to the extensive use of modern bioenergy and hydropower. In Asia, modern renewable energy shares remained below the global average at around 8 percent of the regional TFEC.

The top 20 energy-consuming countries: The share of renewable consumption varies by country. Between 2010 to 2017, 13 out of the top 20 energy-consuming countries increased their share of renewables. The United Kingdom in particular saw the largest relative increase, led by wind energy. Yet in Brazil, India, Indonesia, Nigeria, Pakistan, and Turkey, renewables have grown more slowly than total energy consumption.

Electricity: Renewable electricity consumption increased by almost 6 percent year-on-year in 2017. In relative terms, this meant that the share of renewables in global electricity consumption reached 24.7 percent, the highest of all end-use sectors. With this growth, the renewables share in electricity surpassed its share in heat for the first time in history. In terms of growth rate, however, this represents a deceleration compared with the record year-on-year growth recorded in 2016. Lower hydropower output was the main reason behind the slower increase in renewables.

Figure 11.11: Global primary energy intensity and its annual change, 1990–2017



Source: World Bank (2020a)

Heat: Renewables used for heating increased by 1.1 percent, reaching 23.5 percent of total final heat consumption in 2017, including traditional uses of biomass. The growth was led by modern renewable energy uses, which grew by 2.3 percent year-on-year in 2017. Overall, the share of modern renewables reached 9.2 percent of heat consumed globally, up from 9.1 percent in 2016. Consumption of biomass for its traditional uses remained almost unchanged (+0.3 percent year-on-year) in 2017 compared with 2016, still accounting for more than 14 percent of global heat consumption.

Transport: The share of renewable energy in transport flattened in 2017, remaining at 3.3 percent in 2017. Most of the renewable energy consumed came in the form of liquid biofuels, mainly crop-based ethanol and biodiesel, thanks to policy support (among other factors) in Brazil, the European Union, and the United States. In 2017, consumption of electricity in the transport sector was 1.3 exajoules (EJ), of which 24 percent was renewable (0.3 EJ), representing 0.3 percent of global energy consumption in the transport sector.

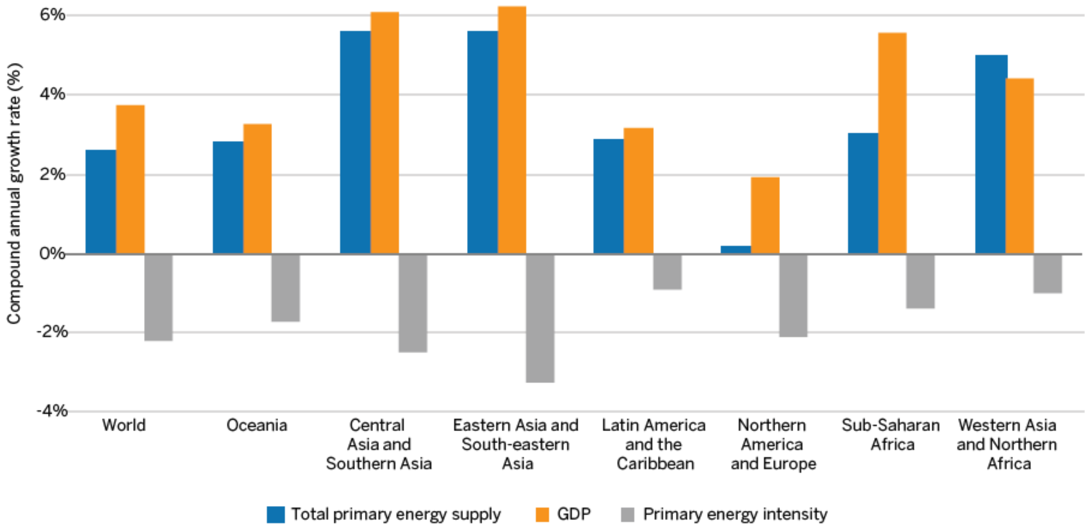
11.5 Energy efficiency

11.5.1 Main trends

Global trend: After a period of relative stability, the rate of global primary energy intensity—defined as the percentage decrease in the ratio of global total primary energy supply per unit of gross domestic product (GDP)— has slowed in recent years. Global primary energy intensity was 5.01 megajoules (MJ) per U.S. dollar (2011 PPP [purchasing power parity]) in 2017, a 1.7 percent improvement from 2016. This was the lowest rate of improvement since 2010 (figure 11.11).

2030 target: Energy intensity improvements are moving further away from the target set under the United Nations' Sustainable Development Goal (SDG) for 2030. Between 2010 and 2017 the average annual rate of improvement in global primary energy intensity was 2.2 percent. Although better than the rate of 1.3 percent between 1990 and 2010, it is well below the SDG 7 target of

Figure 11.12: Growth rate of GDP, primary energy demand, and regional energy intensity, 2010–17



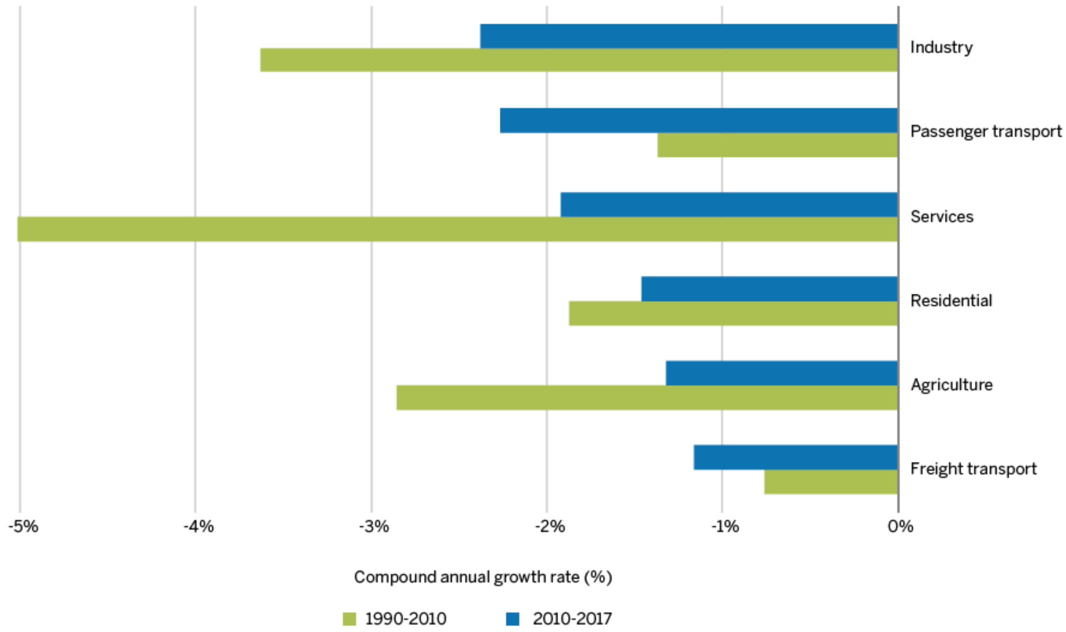
Source: World Bank (2020a)

2.6 percent—which would have doubled the historic trend. Annual improvement until 2030 will now need to average over 3 percent to meet the target set in SDG 7. Even a positive rebound, as indicated by a preliminary estimate of 2 percent for 2019, remains well below the 3 percent annual increases needed to reach SDG target 7—or even the 2.2 percent seen between 2010 and 2017.

Regional highlights: Asia is where more robust, continuous improvements are seen in energy intensity than in any other world region. Between 2010 and 2017, primary energy intensity in Eastern Asia and South-eastern Asia improved by an annual average rate of 3.3 percent. Similarly, in Central Asia and Southern Asia and Oceania, the average annual improvement rate of 2.5 percent between 2010 and 2017 was above the global average (2.2 percent) and an improvement on historic trends. Rates of improvement were just below the global average in Northern America and Europe (2.1 percent), with the lowest rates of improvement in Sub-Saharan Africa (1.3 percent), Western Asia and Northern Africa (1 percent), and Latin America (0.9 percent) (figure 11.12). Data on absolute energy intensity reveal wide regional differences: the most energy-intensive region is Sub-Saharan Africa, and Latin America and the Caribbean the least. These variations likely mirror not energy efficiency so much as economic structure, energy supply, and access.

End-use trends: Although global energy intensity improved across all sectors during the period 2010–17, the rate differs by sector. Using different intensity metrics, the rate of improvement declined compared with the period 1990–2010 in all sectors except transport, where fuel-efficiency standards drove improvements. The decline in the rate of improvement from one period to the other is most noticeable in services, agriculture, and, to a lesser extent, industry. All three of these sectors were strongly influenced by emerging economies, which experienced rapid improvements in energy intensity during the period 1990–2010 as they mechanized production and shifted to higher-value goods and services (figure 11.13).

Figure 11.13: Growth rate of energy intensity by sector, 1990–2010 and 2010–17



Source: World Bank (2020a)

Energy intensity is a measure of the energy inefficiency of an economy. It is calculated as units of **energy per unit of GDP**.

- **High energy intensities** indicate a high price or cost of converting energy into GDP.
- **Low energy intensity** indicates a lower price or cost of converting energy into GDP.

High energy intensity means high industrial output as portion of GDP. Countries with low energy intensity signifies labor intensive economy.

For more information about energy intensity, visit:

- Wikipedia (link 1).
- American Energy Department (link 2).

11.6 Questions to summarize the chapter

1. Access to electricity. Which population percentage does not have access to electricity in 2018? How many million people is that percentage?

The population percentage without access to electricity is 10 percent in 2018. The number of people **without access to electricity** is 789 million.

2. Access to electricity. Which is the access to electricity **objective of the SDG7 by 2030**? How many million people will not have access to electricity in 2030?

The SDG 7 aims for 100 percent access to electricity by 2030. However, **the latest projection shows that about 620 million people would still lack access to electricity in**

2030.

3. Access to electricity. At a regional level, which regions has achieve **universal access** and which ones are struggling to achieve that objective?

Latin America and the Caribbean and Eastern Asia and South-eastern Asia approached universal access, exceeding 98 percent access to electricity by 2018.

In **Central Asia and Southern Asia**, more than 92 percent of the population had access by 2018.

The world's access deficit is increasingly concentrated in **Sub-Saharan Africa**, which, in 2018, was home to about 548 million people who lacked access—more than half of the region's population and nearly 70 percent of the global population without access.

4. Access to electricity. Which is the percentage of population living in **rural areas** with universal access to electricity and in **urban areas**?

In **rural areas** only the 80% of the population has access to electricity. In **urban areas** the access is universal 97%.

5. Access to electricity. Women suffer particularly the lack of access to electricity. Can you enumerate some of the positive effects of guaranteeing **women universal access to electricity**?

Access to electricity plays a critical role in **poverty reduction for women and girls**.

Women's **employment** and **leisure** will improve with increased access to electricity.

Poor electricity supply was pinpointed as the biggest obstacle to growth by 25 percent of **female-headed enterprises** surveyed in Tanzania and 19 percent in Ghana.

Statistical data from these countries show a positive relationship between the **productive use of electricity and women's economic empowerment**.

Use of electrical appliances allowed for **diversification in products** for sale and helped female entrepreneurs attract more customers.

The provision of electric light **amplifies time savings** by increasing efficiency and adding flexibility in the scheduling of household tasks.

Freeing up women's time is a **prerequisite for investments in their education and life choices**, encouraging them to seize economic opportunities and participate in economic, political, and social life.

6. Access to electricity. Which is the relation between SDG7 and **other SDGs**? In particular, can you explain briefly how SDG7 affects to **education** and **health facilities**?

Providing electricity to schools and health centers offers broad benefits that will assist in reaching objectives codified in a range of SDGs, most directly **SDG 3 (health)** and **4 (education)** but also **SDG 5 (gender)** and **SDG 8 (work and economic growth)**.

Information about the access to electricity and education facilities and health facilities are in figures 11.4 and 11.5.

7. Access to clean fuels. Which population percentage does not have access to clean fuels in 2018? How many million people is that percentage?

The population percentage without access to clean fuels is 37 percent in 2018. The number of people **without access to electricity** is 2.8 billion.

8. Access to clean fuels. Which is the access to clean fuels **objective of the SDG7 by 2030**? For which percentage that objective will be short in 2030?

The objective of the SDG7 is to guarantee universal access to clean fuels. However, that objective will be shor by at least 30% in 2030.

9. Access to clean fuels. At the regional level, could you explain the access to clean fuels in **Asia** and **Africa**?

Greater access to clean cooking was achieved largely in **two regions of Asia**:

- From 2010 to 2018, **Eastern Asia and South-eastern Asia** saw annualized increases in access of 1.6pp—while the numbers of people lacking access fell from 1.0 billion to 0.8 billion
- **Central Asia and Southern Asia** also saw improved access to clean cooking, with annualized increases of 1.5pp. The 1.11 billion people without access dropped to 1.0 billion

In **Sub-Saharan Africa**, meanwhile, a stagnant access rate (annualized increase of 0.4pp) combined with rapid population growth have meant that the numbers of people without access have risen from 750 million people to 890 million people.

10. Access to clean fuels. Which percentage of the people living in **urban areas** and in **rural areas** have access to clean fuels and technologies?

There are urban-rural discrepancies worldwide in access to clean cooking fuels and technologies: **83 percent of the people living in urban areas** have access to clean fuels and technologies, compared with **37 percent of those living in the countryside**.

These **discrepancies have been shrinking since 2010 owing**:

- First, to **increased access in rural areas**
- Second, to **population growth in the cities** that is beginning to **outpace access**

11. Access to clean fuels. The percentage of girls allocating time to procurement of fuels and cooking is larger than the percentage of boys. Could you **quantify that difference**? In which countries that difference is larger? In the case of **Uganda**, could you determine the number of hours a week that girls spend gathering fuels and cooking?

In access-deficit countries in **Sub-Saharan Africa**, a sizable percentage of **children** spend time gathering fuels. In addition, based on WHO statistics, the **procurement of fuels is predominantly done by girls over boys** (figure 11.9).

In Uganda, women (15 years and older) spend on average 3.8 hours per day **cooking**, and girls spend close to 30 minutes. In contrast, men and boys are virtually not involved in cooking.

Female household members will often spend much more time **acquiring and preparing fuel** than men and boys. In Uganda, women spend 3.4 hours per week in cooking fuel acquisition and preparation—over 7.5 times more time than men (figure 11.10).

In Kenya, households working with improved cookstoves saw **the time spent collecting fuel drop from an average of 12 hours per week to 5 hours**— and most participants reported using the time saved for economically productive tasks.

12. Energy efficiency. Can you define the **concept of the energy intensity**?

Energy intensity is a measure of the energy inefficiency of an economy. It is calculated as units of **energy per unit of GDP**.

- **High energy intensities** indicate a high price or cost of converting energy into GDP.
- **Low energy intensity** indicates a lower price or cost of converting energy into GDP.

High energy intensity means high industrial output as portion of GDP. Countries with low energy intensity signifies labor intensive economy.

13. Energy efficiency. Can you explain the **evolution of the energy intensity** from 1990 to 2018?

In 1990, the energy intensity was close to 8 MJ/USD. In 2018, it was 5 MJ/USD.

14. Energy efficiency. Can you explain the **evolution of the energy intensity** at a regional level?

Asia is where more robust, continuous improvements are seen in energy intensity than in any other world region.

Between 2010 and 2017, primary energy intensity in **Eastern Asia and South-eastern Asia** improved by an annual average rate of 3.3 percent.

Similarly, in **Central Asia and Southern Asia and Oceania**, the average annual improvement rate of 2.5 percent between 2010 and 2017 was above the global average (2.2 percent) and an improvement on historic trends.

Rates of improvement were just below the global average in **Northern America and Europ**e (2.1 percent), with the lowest rates of improvement in **Sub-Saharan Africa** (1.3 percent), **Western Asia and Northern Africa** (1 percent), and **Latin America** (0.9 percent) (figure 11.12).

15. Energy efficiency. Can you explain the **evolution of the energy intensity** by sectors?

Although **global energy intensity improved across all sectors** during the period 2010–17, the rate differs by sector.

Using different intensity metrics, **the rate of improvement declined** compared with the period 1990–2010 in all sectors except transport, where fuel-efficiency standards drove improvements.

The decline in the rate of improvement from one period to the other is **most noticeable** in services, agriculture, and, to a lesser extent, industry.

All three of these sectors were strongly influenced by **emerging economies**, which experienced rapid improvements in energy intensity during the period 1990–2010 as they mechanized production and shifted to higher-value goods and services (figure 11.13).

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Chapter 12

Sustainable development. Sustainable Development Goal 5: Gender Equality

12.1 Introduction

In this chapter we study the relation between three different sustainable development goals: Sustainable Development Goal 5: Gender Equality; Sustainable Development Goal 7: Affordable and Clean Energy; and Sustainable Development Goal 8: Decent Work and Economic Growth.

The chapter is organized as follows:

1. **Background**
2. Women in renewable energy: **Modern energy context**
   a. Status and trends
   b. Barriers to entry
   c. Retention and career advancement challenges
   d. Policies and solutions
3. Women in renewable energy: **Access content**
   a. Status and trends
   b. Barriers and challenges
   c. Policies and solutions

This chapter is based on the document "Renewable energy: A gender perspective."

12.2 Background

IRENA estimates that the number of jobs in the renewable energy sector could increase from 10.3 million in 2017 to nearly 29 million in 2050. The sector offers diverse opportunities along the value chain, requiring different skill sets and talents.

In that context, increased women's engagement expands the **talent pool** for the renewables sector. Meanwhile, greater gender diversity also brings substantial co-benefits. Studies suggest that women bring **new perspectives to the workplace** and **improve collaboration**, while increasing the number of qualified women in an organisation's leadership yields **better performance overall**. In the context of energy access, engaging women as active agents in deploying off-grid renewable energy solutions is known to improve sustainability and gender outcomes.

The document "Renewable Energy: A Gender Perspective" (2019) aims to address this knowledge gap. It analyses the status of women's participation in the sector in two distinct deployment settings – **the modern context** (in which renewables displace or complement conventional energy) and **the energy access** context (which is characterised by efforts to expand access to modern energy services).

12.3 Women in renewable energy: Modern energy context

12.3.1 Status and trends

While it is true that renewable energy is subject to some of the same limitations and barriers that prevail in the energy sector at large, this report shows that **women already have a stronger presence in renewable energy than is the case in fossil fuels**. Furthermore, renewable energy offers a range of unprecedented opportunities. As a young and dynamic sector, it is open to change in ways that are harder to effect in an industry as set in its ways as the the relatively mature fossil fuel sector. In the unfolding energy transition, women will have the chance to garner a growing share of employment.

A better gender balance is not a zero-sum game in which women stand to gain while men lose. Studies have shown that an increase in the number of qualified women in an organisation's leadership yields **better performance overall** (Noland et al., 2016). Women are also likely to bring **new perspectives** into their work, are more likely to **act collaboratively** in the workplace and may contribute to **greater fairness** (Moodley et al., 2016). A better gender balance in male-dominated professions has been shown to contribute to the **improvement of working conditions** for both men and women, with positive effects on **well-being**, **work culture and productivity** (WISE, 2017).

1. Employment in renewable energy, gender related findings

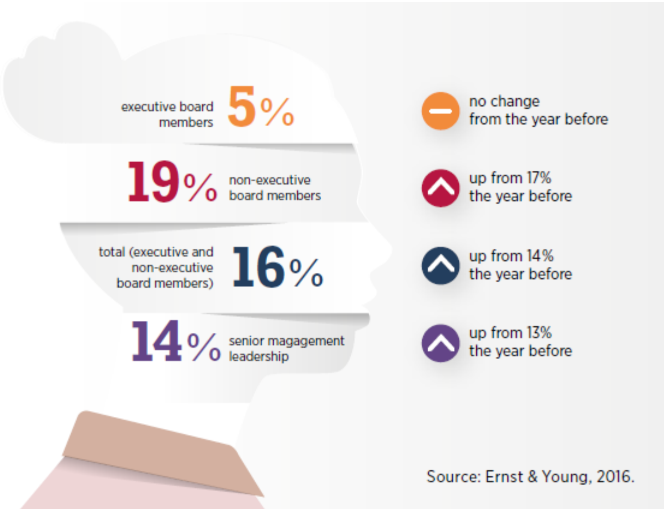
Available information strongly indicates that employment in the conventional energy industry is male dominated:

1. A 2017 study by the World Petroleum Council and Boston Consulting Group put **the share of women in the worldwide oil and gas workforce at** 22% – much lower than in manufacturing, finance, education, health and social work, and lower than the average in the overall workforce. **While women fill** 27% **of entry-level jobs** in the oil-and-gas sector that require a college degree and 25% **of midcareer-level jobs**, their share is only 17% **in senior and executive roles**. **Only one in a hundred CEOs in the sector is a woman** (Rick et al., 2017).

2. In 2015, the electricity, gas and water supply sector was found to have women in 22% of senior management roles, roughly half the share in the educational and social services sector (McCarthy, 2016).

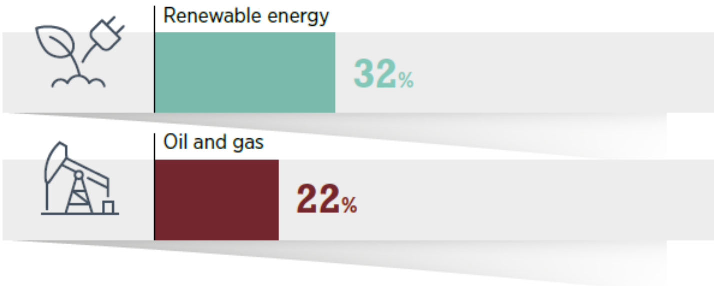
3. A study of the world's **200 largest utilities** found only 25 female board members, representing 16% of board members, and only 5% of executive board members (Ernst and Young, 2016) (figure 12.1).

Figure 12.1: Female board members at 200 of the world's largest utilities, 2016



Source: IRENA (2019)

Figure 12.2: Share of female full-time workforce in renewable energy and oil and gas



Source: IRENA (2019)

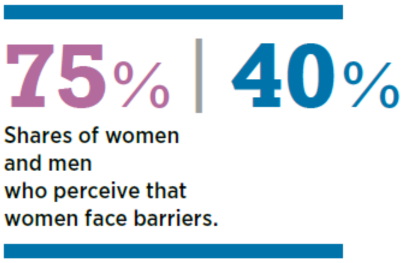
2. Gender composition of the workforce in the renewable energy sector

Studies to date confirm that women are also under-represented in the renewable energy sector. Reports from countries such as Canada, Germany, Italy, Spain and the United States suggest that typically less than 30% of jobs in the **renewable energy sector** are held by women. Women are more likely to be employed in lower paid, non-technical, administrative and public relations positions than in technical, managerial or policy making positions. This contrasts sharply with the fact that **women represent more than** 50% **of university students**, and **almost half the labour force in these countries**.

12.3.2 Barriers to entry

Almost two-thirds of all respondents think that women face some barriers to access to renewable energy works. However, this result is strongly driven by female respondents, three quarters of whom answered in the affirmative. By contrast, only 40% of male survey participants agreed (figure 12.3).

Figure 12.3: Shares of women and men who perceive that women face barriers



Source: IRENA (2019)

1. Perceptions of gender roles

Self-perception by women themselves and in part a set of assumptions among men about women's ability to succeed. Both are well-recognised in the literature as key impediments to women's hiring and advancement in certain careers in the energy industry and other sectors.

In a review of technical education for women in 120 countries, social, cultural and gender norms and misperceptions were identified as factors that erode girls' confidence, interest and willingness to engage in STEM (Science, technology, engineering and mathematics) subjects (UNESCO, 2017). Girls are often brought up to believe that STEM subjects are "masculine" topics and that women's ability is innately inferior to that of men.

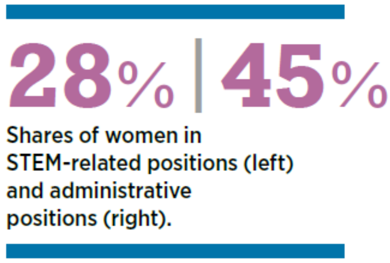
Despite concerted efforts over many years to address the gender imbalance in these fields, only 12% of engineers in the United Kingdom are women, compared with 47% of the overall workforce. Between 2015 and 2016, just 16% of those who started an engineering or technology degree in the United Kingdom were women, and only 25% of girls aged 16–19 said in a survey they would ever consider a career in engineering. Similar barriers of perception or interest have been identified in Australia, Belgium, Finland, Poland, Spain and Sweden (OECD Higher Education Programme, 2014).

2. Women's participation in STEM fields and misperceptions of career pathways

Driven by perceptions and misperceptions, only a low percentage of female students choose the STEM fields. The latest edition of the UNESCO Science Report, entitled Towards 2030 (UNESCO, 2015), offers the most recent statistics on women's participation in STEM fields. The share of women graduating in the fields of engineering, physics, mathematics and computer science is low in many industrialised countries. The roughly 20% share of women among engineering graduates in Canada, Finland, Germany and the United States is rather typical. In Japan and the Republic of Korea, women represent an even lower proportion – just 5% and 10% of engineers, respectively. There are some bright spots, however. In Cyprus and in the United Arab Emirates (UAE) women represent 50% of engineering graduates, in Denmark 38%, and in the Russian Federation 36%.

Gender imbalances among STEM students carry through to gender imbalances in STEM jobs in the renewable energy sector as elsewhere. IRENA's survey finds that women occupy 28% of STEM positions. While these percentages are close to the average share of 32% across the entire workforce, they are much lower than in administrative jobs (figure 12.4).

Figure 12.4: Shares of women in STEM-related positions (left) and administrative positions (right)



Source: IRENA (2019)

3. Lack of career information

An enduring disadvantage that women and girls face in comparison to their male counterparts is the lack of readily **accessible information about employment in non-traditional occupations**, including those in the energy sector. Personal networks are critical for entering and succeeding in many professions. But women have more difficulty accessing such networks on par with men in non traditional occupations and thus are at a disadvantage in receiving timely information about job openings (UNESCO, 2015).

Careers in renewables are generally still not promoted through formal channels such as career counsellors, student employment advisors, job centres, recruitment sessions and career fairs.

Because technical fields of study have been dominated by men for so long, a significant amount of information about job opportunities continues to travel through familial and **professional networks that often are inaccessible to women**.

4. Prevailing hiring practices and unequal access to career entry points

The literature on employment in the conventional energy sector and other non-traditional occupations such as mining and transportation confirms that men tend to apply for jobs even when they meet only some of the requirements, but **women tend not to apply for jobs unless they meet all requirements**. Women are also **less likely to negotiate salaries and benefits**. They must often outperform men in male-dominated industries just to fit in and certainly to progress.

In the countries of the Organisation for Economic Co-operation and Development (OECD), such as the United Kingdom, where women comprise 94% of childcare apprentices but under 4% of engineering trainees. Trades associated with energy industry occupations (wind turbine technician, solar energy system installer, electrician, energy auditor, energy retrofitter, etc.) remain heavily male-dominated. In Ireland, just 1% of apprentices in engineering and construction were women.

In most countries, securing a trade apprenticeship remains an unregulated process, with informal networking still the norm. This often translates into a barrier to women's entry into and advancement in these fields.

Figure 12.5: Gender composition of board of directors in the renewable energy sector

Source: IRENA (2019)

12.3.3 Retention and career advancement challenges

The key issues that condition and limit women's renewable energy careers include:

1. The **glass ceiling**.
2. **Mobility-related challenges** and **difficult work schedules**.
3. **Wage inequalities**.

1. The glass ceiling

All along the renewable energy value chain one finds persistent barriers to improving women's representation in senior executive positions and on boards of directors. The **lack of equal representation of women in decision-making roles is described as the "glass ceiling"**, where invisible barriers keep women from rising to influential positions, regardless of their qualifications.

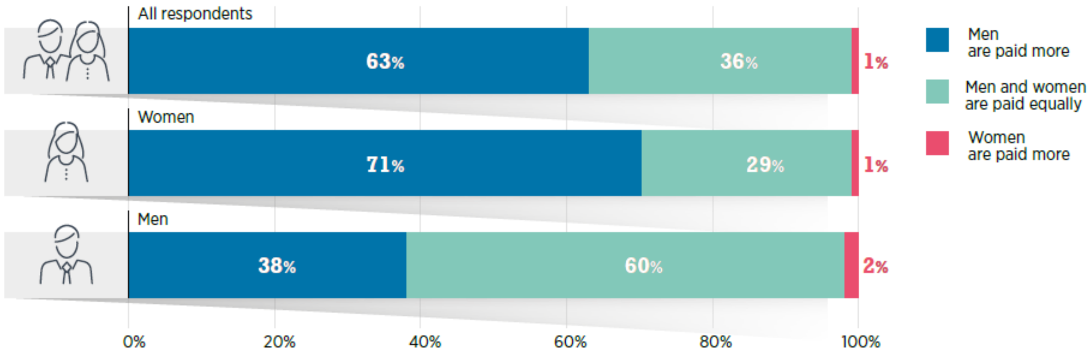
A recent McKinsey survey in the United States, for example, shows that the higher up the corporate ladder one moves, the fewer women one finds. For entry-level positions, women accounted for 48% of jobs. Among managers and senior managers, the share declined to 39% and 34%, respectively; for vice presidents, it was 30%, but for senior vice presidents and executive-suite positions, it was only 23%.

IRENA's survey provides evidence for different types of organisations working in the renewable energy sector. Survey responses indicate that men account for a majority of board members at 65% of participating private sector firms. In close to half of all firms, men represent at least three-quarters of directors. The distribution is also heavily male biased among national agencies and intergovernmental organisations in the sample, although almost a quarter of them have equal representation between the genders. In comparison, non-governmental organisations have a much better gender balance (figure 12.5).

2. Work schedules and mobility requirements

Rigid work schedules were identified by survey respondents as one of the key barriers women face, given that, in many societies, they are expected not only to excel at work but also to reliably perform many tasks outside of work, including child rearing, other care-giving responsibilities and various household chores. "Having it all" is especially difficult when there is little flexibility

Figure 12.6: Beliefs about pay equity among men and women



Source: IRENA (2019)

at work.

An added burden is found in mobility requirements, particularly among those in the renewable energy sector who hold field jobs (project planners, installers, operators) and may thus be subject to frequent travel requirements, relocation and long periods of time away from home and family. While this can be challenging for men and women alike, women with care-giving responsibilities, especially for young children, face a particular disadvantage.

However, one must not assume that women would prefer not to hold such jobs. Many women already work in less-than-optimal environments, and for much less pay than they could make in renewables. Given the option, some women may prefer work in renewable energy simply because of the potential to earn higher wages. Because of persistent male-biased norms (often unintended or unconscious), even women who are able and willing to work may not be given the option to choose between difficult or dangerous working conditions with low pay and similar conditions with higher pay. Instead, women are tracked into feminised occupations in administrative and support services within the sector.

Assumptions about women's willingness or ability to work in certain occupations or working conditions can thus themselves become barriers to women's employment.

3. Wage inequities

Existing research on women's employment in renewable energy in OECD countries reveals that although average wages in the industry may be higher than in other sectors, **women continue to earn less than men across occupational categories**.

Close to two-thirds of IRENA survey respondents believe that women in renewable energy earn less than men for the same position, while one-third believe they earn the same, and just 1% believe women are paid more (figure 12.6). But the survey also indicates that perceptions about wage equity are strongly shaped by a gender bias. Among male respondents, just 37% say they think men are paid more, as opposed to 70% of female respondents. Some 60% of men have the perception that both genders are paid equally.

As in other sectors, the causes of the gender wage gap in renewable energy appear to be multifaceted. They include women's greater concentration in lower-paying, non-technical and administrative jobs and in junior positions; women's comparatively weaker negotiating positions; their greater likelihood of taking time off from their careers for parenting and care-giving; and the attitudes and values of employers. In addition, differences may in some cases be the result of pay discrimination.

12.3.4 Policies and solutions

1. Mainstreaming gender perspectives

To promote gender equality in renewable energy employment, it is important to assess whether gender perspectives enter into decision making. Gender audits can help answer this question in the context of public policy measures such as legislation and regulations, and in the private sector.

A **gender audit** is one aspect of what is referred to as “mainstreaming”: analysing legislation, regulations, taxation and specific projects for their effect on the status of women in society. **The basic assumption of gender audits is that public policy affects men and women differentially, stemming from the different roles women and men in the family and their status in the economy**. They are essential for constructing more gender-sensitive policy frameworks, for providing support services and other incentives to increase gender equity, and ultimately for increasing gender equality. **Gender audits of energy sector policy have been implemented in several developing countries, mainly with support from ENERGIA, the International Network on Gender and Sustainable Energy**.

2. Creating networks and supporting mentorship

Women are often effectively excluded from access to familial and professional networks that provide information about job openings and career opportunities. **Many of these networks have traditionally catered to the interests of men**. There is an urgent need to level the playing field by improving women’s access to such information and peer support. A measure the renewable energy industry could undertake is to “simulate” valuable personal connections through practices such as **mentoring programmes**, **outreach efforts**, **site tours** and **temporary work placements**.

Organisations advocating for greater gender equity in the renewable energy sector are already pursuing such strategies. They share in formation; create networks among representatives of government, industry, academia and non-profit groups; and offer mentoring, coaching and consulting services (figure 12.7; boxes below).

Figure 12.7: Selected organisations advocating for gender equity in renewable energy

Name	Year founded	Location of activity	Activities
ENERGIA (International Network on Gender and Sustainable Energy)	1996	22 African and Asian countries	Gender mainstreaming, strengthening women-led energy enterprises, advocacy
WRISE (Women of Renewable Industries and Sustainable Energy)	2005a	United States	Fellowships, awards, webinars, networking, training retreats, in-person and online mentoring
Hypatia	2010	Germany	Networking, events
WISE (Women in Solar Energy)	2011	United States	Education, capacity building, advocacy, strategic partnerships, networking, events
WICS (Women in Cleantech and Sustainability)	2011	United States	Fostering networks of professionals to advance women's role in the green economy (energy and other sectors)
WIRE (Women in Renewable Energy)	2013	Worldwide	Capacity-building field trips, networking, awards recognition programmes, student bursaries, speed mentoring
Women in Sustainability, Environment and Renewable Energy (WiSER)	2015	United Arab Emirates	Advocacy, education and training opportunities for women, platforms for dialogue, showcasing of women's contributions to sustainability
Renewable energy and energy efficiency Women's Network (REDMEREEE)	2016	Mexico	Networking, capacity building, training and events
Women in Sustainability (WiS)	2017	India	Advocacy, networking
GWNET (Global Women's Network for the Energy Transition)	2017	Worldwide	Interdisciplinary networking, advocacy, training, coaching and mentoring, and services related to projects and financing
Nordic Energy Equality Network (NEEN)	2017	Nordic and Baltic countries	Bringing together people who are interested in improving gender balance and promoting diversity in energy-related matters

Source: IRENA (2019)

GWNET: Offering online mentoring

The Global Women's Network for the Energy Transition (GWNET) began in early 2018 to offer a global **online mentoring programme for women** in junior and middle-management positions.

The 12-month cycle emphasises suitable match-ups between mentors and mentees. Participants in the 2018 cycle – mentees and mentors – hail from Africa, China, Europe and the Middle East, as well as North and Latin America.

The programme is set up to **run remotely**; however, several mentees have managed to meet with their mentors in person. Each duo establishes an agreement on the frequency of interactions and the mode of communication.

Beside the bilateral interaction, mentees have access to tailored knowledge **webinars** to assist in personal and professional growth. Webinars focus on the development of the energy sector, women's entrepreneurship and personal development. The programme concludes with an **interactive web-based graduation meeting**.

The Pink to Green Toolkit: Wider Opportunities for Women

Wider Opportunities for Women advocates for gender equity in employment in the United States. Its Pink to Green Toolkit includes **presentations**, **trainings**, **webinars**, **curriculum guides and modules**, **briefs**, **templates**, **tip sheets**, and planning documents designed to maximise capacity building in recruiting, assessing, placing and retaining women in green occupations.

The toolkit is organised into **five categories**: outreach and recruitment of women, assessment and case management for women, building critical skills of job readiness, gender-inclusive and gender-focused training design, and sexual harassment.

The **resources** in the toolkit include a myths-and-facts worksheet about common stereotypes, presentations about the benefits of green jobs for women, an assessment of a company's or organisation's capacity to serve and recruit women, a tip sheet to plan a career fair, a module on building skill and confidence of women to perform well in interviews, modules addressing communication and learning styles of women, and many more.

The toolkit can be a valuable resource for organisations working on equity in renewable energy and the broader green economy in other countries.

A range of **measures can help create greater awareness of career opportunities**, including:

1. Ensuring that information about renewable energy jobs and careers is **publicly available** through online bulletin boards and other measures.
2. Supporting the establishment of **mentorship programmes**.
3. Working with educational institutions to reach out to women by publicising **training opportunities**, including **apprenticeships**.

New job entrants can be inspired by, and learn from, those women who already have established a career in the sector. Showcasing their accomplishments not only recognises their trail-blazing work, but also highlights opportunities for women joining the renewable energy workforce. Several **dedicated awards** have been instituted to recognise women's accomplishments in the renewable energy sector (boxes below).

C3E Women of Distinction Award

The Clean Energy Education and Empowerment (C3E) Initiative was launched in 2010 by the Clean Energy Ministerial, a global consortium with representation from 24 countries.

The C3E initiative seeks to increase women's participation and leadership in clean energy, especially in the **STEM fields**.

The US C3E programme, initiated in 2012, is led by the **US Department of Energy** and **three university partners**: the MIT Energy Initiative, the Stanford Precourt Institute for Energy, and the Texas AM Energy Institute.

Among its **pillars** of activity are an annual symposium that provides networking opportunities for professional women, students and government representatives, and awards for outstanding mid-career women in education, research, business, entrepreneurship, advocacy, government, law and finance, among others.

WiRE Women of Distinction Award

Woman in Energy Renewable (WiRE) was launched in 2013 in Canada and is now active internationally.

To advance the role and recognition of women in the renewable energy sector, it **offers** mentoring, provides networking opportunities in partnership with government agencies and renewable energy associations, and organises capacity-building field trips.

WiRE supports the Leadership Accord for Gender Diversity in Canada's Electricity Sector, a 2017 commitment by employers, educators, unions and governments to increase the representation of women in the electricity and renewable energy sectors.

WiRE also supports the **Equal by 30 Campaign** for equal pay, equal leadership and equal opportunities for women by 2030.

The organisation presents a **"WiRE Woman of the Year"** award, plus **"Woman of Distinction"** awards in the solar, wind and hydropower sectors.

The awards recognise accomplishments in a variety of areas, including leadership, policy and advocacy, technical advancement and R&D, project development, community adoption of renewable energy technologies, and contributing to the advancement of women in the energy sector by volunteering or serving as a role model.

3. Access to education and training

1. **University curricula** can be adapted to be more open to women.

   - At the University of California, **Berkeley**, 2014 was the first year that more women than men enrolled in an introductory computer science course. An important factor was that the curriculum had begun to **emphasise group projects and creative thinking in addition to programming**.

   - At the Massachusetts Institute of Technology, female enrolment in the Department of Electrical Engineering and Computer Science doubled between 2011 and 2017 and the share of female majors rose from 30% to 38%. In parallel, the institution's Department of Mechanical Engineering has seen sustained female major enrolment rates of more than 40% over the past five years. In both departments the number of female students increased markedly following **changes in the curriculum**, **content** and **pedagogy**. The most rapid period of growth in female students also coincided with the **department being headed for the first time by a woman**.

2. **Scholarships, internships and enrolment targets can attract women into clean energy careers**.

- Supported by several governments, the **C3E initiative** provides opportunities for scholarships, internships and academic and industry research appointments.
- Another example is the Women in Science Initiative established at **King's College London** in 2013 to address the imbalance of women working and studying in in STEM fields. The initiative established Women in Science Scholarships for undergraduates in mathematics, physics, computer science and chemistry. Further, a gender equality student fund was established to support innovative projects, activities and events that promote gender equality in STEM.

3. It is also important to widen **opportunities for women in vocational training**.

- An application scorecard developed by the **South African Renewable Energy Technology Centre**, for example, allocates double points for female applicants.
- In Kenya, the **Strathmore Energy Research Centre (SERC)** has conducted training courses for solar PV technicians with the express purpose of enlarging the pool of female solar PV technicians.

4. Gender targets and quotas

Numerical goals for gender diversity and equity can be an important indicator of progress. They include targets for recruitment of new staff, as well as greater gender balance in the overall workforce. For example:

- **Engineers Canada** ad opted its "30-by-30" programme in 2011 to raise the number of newly licensed female engineers in Canada to 30% by 2030.
- In 2017, **Engineers Australia** announced a target to have women make up 30% of its 100 000 member organisation by 2020.
- A McKinsey review of 118 US companies and 30 000 employees found that **companies with gender targets made the most tangible progress toward gender balance and equity, while those without targets lost ground**.

Several **OECD countries** have adopted nationwide **goals or targets** to increase the number of women in engineering and technical fields. **Countries that have instituted mandatory quotas have achieved a high er level of representation of women in the boardroom, and done so more rapidly, than countries that have opted instead to encourage gender diversity via a "comply or explain"** approach, which requires them to adopt mechanisms that consider the representation of women or explain the reason for not doing so. Some examples:

- In **France**, for example, women held 37.6% of the board seats at companies surveyed in 2016 by Morgan Stanley Capital International, representing substantial progress toward the country's mandatory 40% quota to be met by 2017.

- In **Germany**, which has implemented a quota of 30% by 2017, women held 26.7% of board seats in 2016.
- In **Norway**, which requires that women make up 40% of the board, 39% of the board seats were held by women.

5. Workplace practices, policies and regulations

To actually achieve a **better gender balance** in the workplace requires careful **implementation**:

1. Fair and transparent internal processes governing **employee appraisal and promotion**, and establishment of **appropriate systems to measure and track progress**.
2. **Mentorship programmes** can help make the workplace more welcoming to women and supportive of their career development by helping them to overcome hesitations in the face of traditional perceptions and stereotypes and, once hired, allowing them to thrive with the support of experienced colleagues and peers.
3. Understanding and addressing **wage gaps** is another important issue. This chapter has already pointed to the perception of inequities. To some extent, wage differentials reflect the general gender bias in the workforce structure, i.e., women predominantly occupying non-technical and lower paid positions. However, there is also a need to ensure that **equal work receives equal pay**.
4. All publicly and privately held renewable energy employers should be encouraged to adopt policies to make **wage information more transparent**. Even anonymised salary data grouped by qualifications, skills and years of experience would enable applicants to understand what fair salaries are like at specific career stages.

   All entry-level workers should be able to understand the **career trajectories** and possibilities for advancement specific to their sector. This would help level the playing field for women who, as explained earlier, are more likely to lack the familial and social connections that often provide men with information about **career and salary trajectories**.

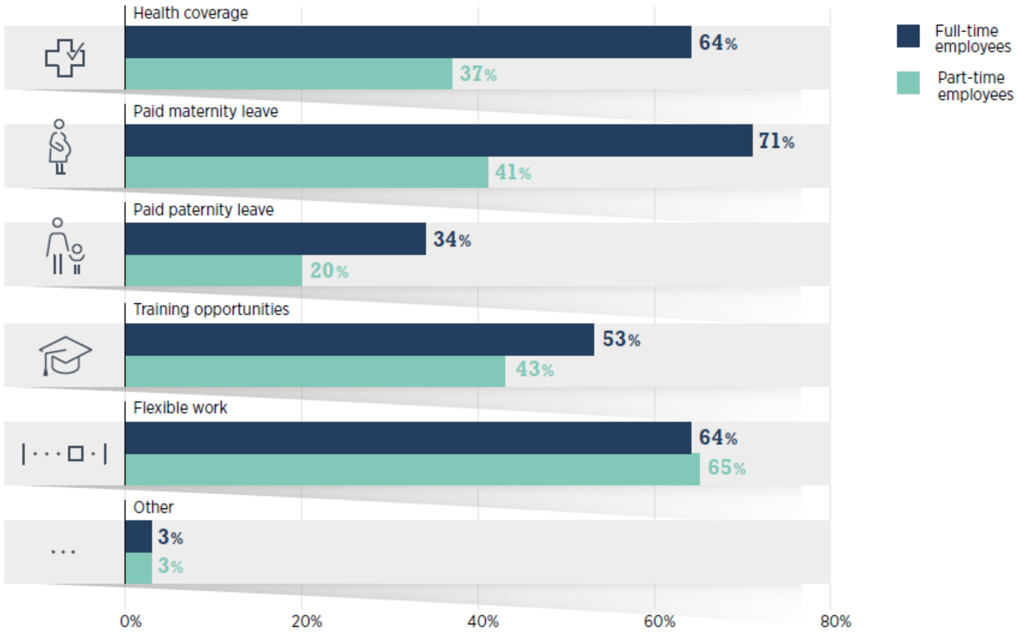
6. Work-life balance

1. **Part-time employment**, **flexi-time** and **job-sharing arrangements** can, in principle, provide a degree of "time sovereignty" to female workers, making it easier for them to enter and remain in the labour force. Both part-time and flexi-time arrangements are among the most-favoured options among survey respondents. By contrast, job sharing was ranked low among options already offered in workplaces and in the list of measures desired by respondents.

The survey shows that 63% of all organisations participating in the survey offer part-time work and survey participants indicated that this can be important in reducing gender barriers. Availability varies. While NGOs score highest at 84%, only 40% of governments and IGOs allow part-time work (or similar measures such as working from home and flexi-time). Private sector companies perform better than public sector entities, with an average of 62%. Survey results confirm that the availability of part-time slightly increases the share of women in the workforce. Compared with their 32% share of full-time employment, women account for 36% of part-time workers. However, part-time work offers less work and social benefits (figure 12.8).

2. **Adequate paid parental leave policies** can help to ensure that women do not incur unfair disadvantages from childbirth and child-rearing. Such leave should not be limited to

Figure 12.8: Comparison of benefits among full- and part-time employees



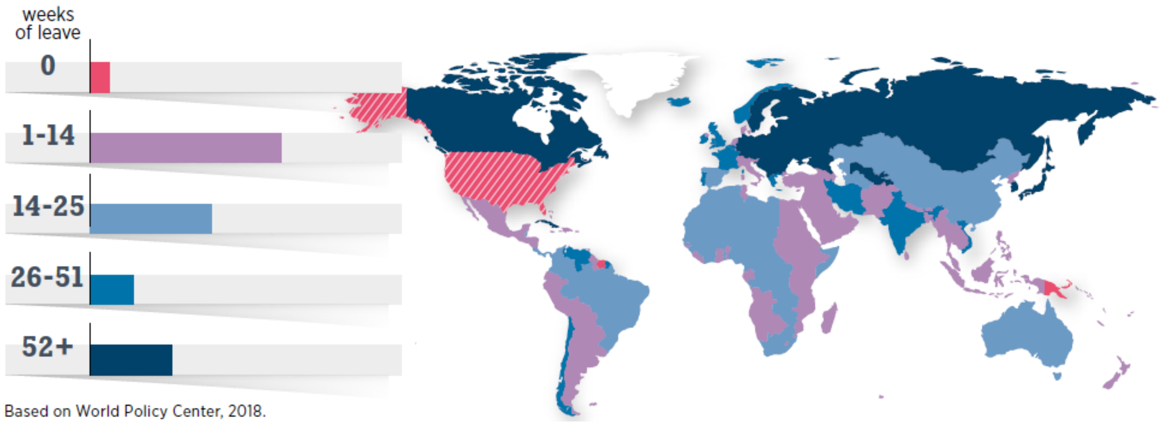
Source: IRENA (2019)

women; **paternal leave can help parents** share the burden of child rearing. But such policies need to be coupled with public policy measures or corporate undertakings to allow women (and men) to resume the positions they held previously without sidelining their career prospects. In addition, on-site childcare facilities can provide a good transition back to the workplace after a period of parental leave.

Policies vary widely among different countries and regions. Corporate practices may in many cases merely reflect local legal requirements. As of 2014, a total of 83 countries offer paid maternity leave of up to 14 weeks; another 53 provide 14-25 weeks, 18 offer 26-51 weeks, while 36 offer 52 weeks or more (figure 12.9). Some 70 countries worldwide also offer paid paternity leave.

By sharp contrast, the United States is one of just nine countries worldwide that have no legal requirement of paid maternity leave at all. In those countries, private executives decide how hospitable their workplace will be to women.

Figure 12.9: Paid maternal leave, in weeks



Source: IRENA (2019)

<u>Definitions of part-time work, flexi-time, and job-sharing</u>

Part-time work is usually defined as a specific number of work hours that make up less than a full work week, but the threshold varies among countries. The specific distribution of work hours across a week, month or year can vary strongly. The share of part-time workers in overall employment has generally increased in developed countries but remains low in most developing countries. **Women are believed to represent close to 60% of all part-time workers, a much higher portion than their share of the total workforce**.

Flexi-time (also called flex-time) is a system in which people work a set number of hours within a given period, but the starting and finishing times are chosen by the employee within agreed limits (e.g., core working hours are not subject to flexi-time arrangements). Pay and benefits should in principle be unaffected, since there is no net reduction of working hours.

Job sharing is an arrangement under which two people voluntarily share the responsibilities of one full time job. The individuals involved work as a team to complete a given task and share responsibility for the overall workload. Job sharing may involve people working half days, alternate days or alternate weeks. Total working hours are typically divided equally among job sharers, who receive salary and benefits on pro-rata basis.

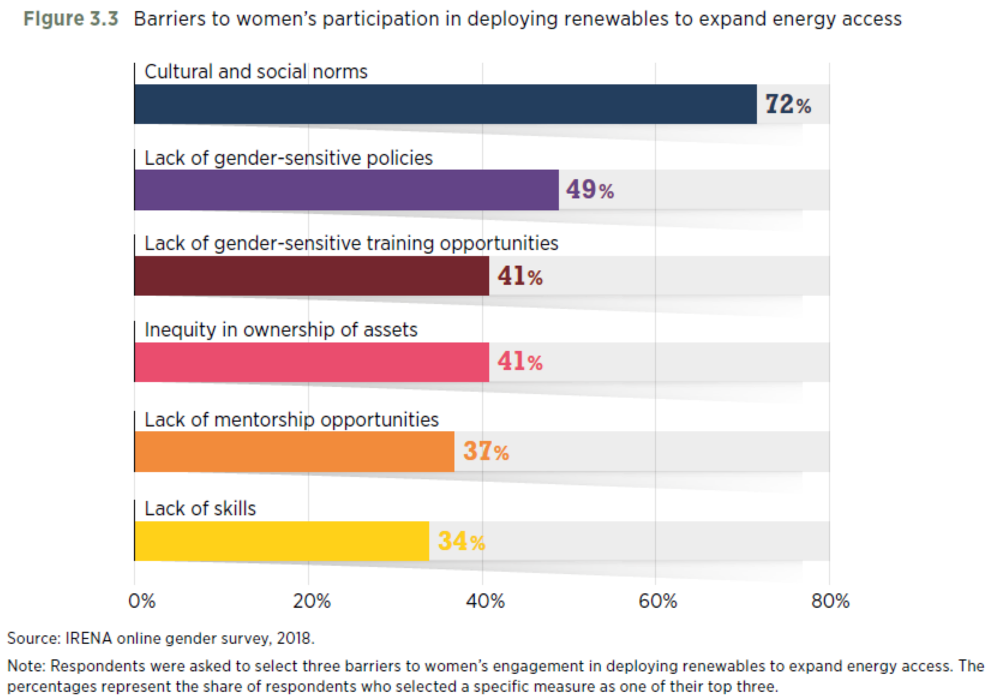
12.4 Women in renewable energy: Access context

12.4.1 Background

Globally, the number of **people without access to electricity fell below 1 billion** for the first time in 2016. The number without access to clean cooking facilities has been gradually declining, but still accounted for nearly 3 billion globally in 2016 (World Bank, 2018).

The lack of access to modern energy **affects women and children disproportionately**. A large amount of their time and labour is spent on unpaid care work, subsistence and productive tasks (e.g., **gathering fuelwood for cooking, fetching water, manually processing grain or other food**) (World Bank, 2017).

Figure 12.10: Barriers to women's participation in deploying renewables to expand energy access



Source: IRENA (2019)

Indoor air pollution resulting from the use of traditional fuels for cooking and limitations on the delivery of healthcare, education, water and other basic public services owing to the lack of modern energy also has a far greater impact on women and children than on men.

Access to affordable, reliable and sustainable modern energy can have a transformative **impact on productivity, incomes and overall well-being**. It frees up time for women collecting fuelwood and enables time-shifting of tasks with access to lighting, opening new opportunities for leisure, part time work and income-generating activities. There are also strong cross cutting links to other sectors, including improved education opportunities for girls, safety, and access to media.

This chapter focuses on the gender dimension in the deployment of **off grid renewable energy solutions** for improving access to modern energy.

12.4.2 Barriers and challenges

Over **two-thirds (66%) of survey respondents** stated their belief that women working or seeking work in expanding access through renewable energy faced **barriers**.

The barriers were associated with several factors. Cultural and social norms were cited by respondents as the most common barrier to women's participation in the access sector, followed by lack of gender-sensitive policies and training opportunities and inequity in ownership of assets (figure 12.10). Security and the remoteness of field locations were also mentioned as other barriers to women's participation.

1. Cultural and social norms

The gender division of labour results in women allotting a significant amount of their time to **household work and childcare (and elderly care)** responsibilities, and consequently having **limited skills and time to engage in formal, paid activities** that predominantly employ men (SEforAll, 2018). In some cases, **women (and children)** spend on average 1.4 hours a day collecting solid fuels and several hours cooking with inefficient stoves, leaving them less time to pursue other economic, family or leisure activities (UN Women, 2018).

Women also tend to have **less access to information, skills, training and labour markets, while facing greater risks of violence**. This **influences their decision-making power** and exercise of voice and agency, and constrains their access to land and productive resources, technology and information, and education and health services.

Cultural and social norms and power hierarchies strongly influence women's ability to participate in energy access programmes. As an example, **women are often disadvantaged in gaining access to energy by the fact that men typically make the purchasing decisions within the household**. Since kerosene, diesel and other fossil fuels tend to be expensive, men are often more willing to purchase or seek financing for technologies such as solar lighting systems that can save money (and are perceived to be beneficial for the entire family) than technologies such as clean cookstoves that reduce women's drudgery and "time poverty".

Understanding how **intra-household gender hierarchies influence technology access** is crucial for designing effective responses to address them. Women may also use different communication and information channels than men, as they have lower literacy rates, less access to television and radio, and less time to attend public meetings. They may even be reluctant to express their views at meetings.

As **primary users of energy** in the household, women's direct engagement in renewable energy projects is critical to ensuring that the projects have a positive impact and are widely used and accepted by their intended beneficiaries. Because women are typically responsible for cooking, they often have a **comparative advantage in reaching out to other end-users of clean cookstoves**.

Making normative assumptions about women's nurturing roles perpetuates and deepens gender divides through a feminisation of certain responsibilities and obligations. Organisations in the renewable energy sector should avoid the rhetoric of cooking technologies as women's needs. They should describe and promote them as general human needs.

2. Lack of gender sensitive programmes and policies

Gender-blind energy sector policies and programmes **fail to integrate women's experiences, expertise and capacities**, and risk further exacerbating the gender gap between men and women in the energy access context. An examination of renewable energy policies in 33 countries by the United States Agency for International Development (USAID) and ENERGIA found that **only 6 policies (18%) included gender keywords** and considerations.

Moreover, when referring to themes on energy access and women's engagement in the sector, the policies often referred to gender issues through terms such as **"vulnerable", "recipients" and "beneficiaries"**. The acknowledgement of women as **passive beneficiaries** does not make these programmes gender sensitive, although progress is being made to address such concerns.

For energy projects to have an effective gender-sensitive approach, it is essential that they **highlight the participatory and active role of women in programme implementation** and adequate budgetary provisions are in place within relevant ministries, programmes and schemes to support gender related activities.

3. Lack of skills and gender-specific training opportunities

The lack of skills is a key barrier faced by women seeking to participate in efforts to expand modern energy access through off-grid renewable energy solutions. To overcome it, **over** 40% **of the respondents highlighted the importance of tailored training** opportunities for women.

Training opportunities are often not equally accessible by men and women. One reason relates to cultural and social norms, especially where such norms are deeply entrenched. Even if women have the enthusiasm and motivation to be engaged in the off-grid renewables supply chain (e.g., as distributors), they may be discouraged by others in the household from attending/ continuing the training, or from working after completing the training.

Social norms often also broaden the gender gap in measures of human capital such as financial literacy and entrepreneurial management. As such, women are more likely to partake in minor income-generating activities in informal sectors related to cooking and sewing, and less likely to participate in more technical sectors such as renewable energy. The low profitability of these womenled businesses in the informal sector results in a lower likelihood that households will invest in women's education and training. This creates a vicious cycle that relegates women to informal and unpaid work.

12.4.3 Policies and solutions

In seeking solutions to improve women's engagement in the renewables sector for energy access, survey respondents highlighted first the importance of access to training and skills-development programmes. Over half the respondents also cited improving access to finance and mainstreaming the gender perspective in energy access programmes as important to improve women's engagement (see figure 12.11).

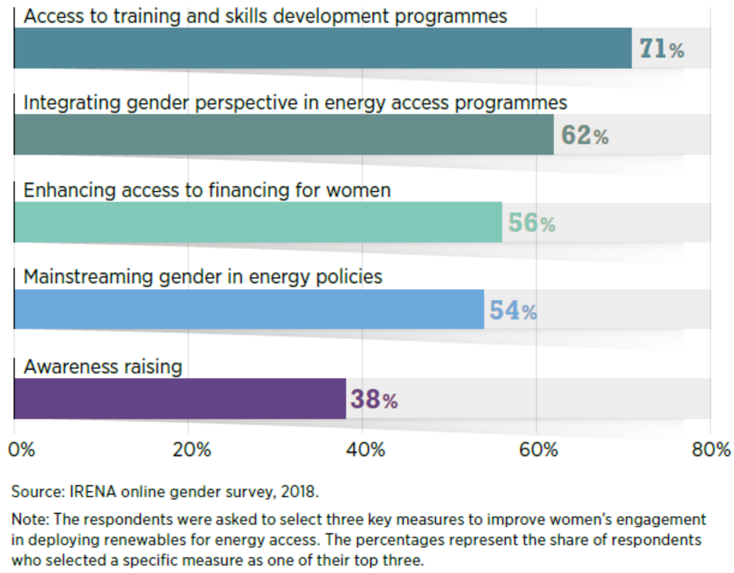
1. Improving access to training and skills development programmes

Women's participation in the energy sector cannot be enabled without adequate capacity building and training conducted at all levels of entry into the industry (ADB, 2018). A key prerequisite, if women are to play an active role in the deployment of off-grid renewable energy solutions, is **awareness of opportunities and access to necessary technical, business or leadership skills**.

Cultural and social norms, and to the traditional roles fulfilled by women in rural communities need to be taken into account while conducting training programs. For instance, training sessions must be scheduled around women's childcare responsibilities and be sensitive to mobility constraints and security concerns; programmes must consider social restrictions that may prohibit women from participating actively (UN Women, 2016).

Broader training is needed in business, **financing and leadership skills, product standards, and quality control**, among other areas. **Marketing skills** are especially needed for renewable energy technologies such as solar home systems and solar lanterns that are sold to households.

Figure 12.11: Measures to improve women's engagement in deploying renewables for energy access



Source: IRENA (2019)

Training solar grandmothers: The case of Barefoot College

The "solar mama" programme at the Barefoot College is a well-documented example of the democratising power of **off-grid renewable energy solutions** and the transformative potential of training women in **rural areas**. The programme has trained over 1000 women from more than 80 countries, leading to the deployment of at least 18000 solar systems.

The trainees are often **illiterate or semi-literate women** who maintain strong roots in their rural villages and have the potential to play a key role in bringing **off-grid solar solutions to remote, inaccessible villages**. The initiative works to demystify the technology and place it in the hands of local communities.

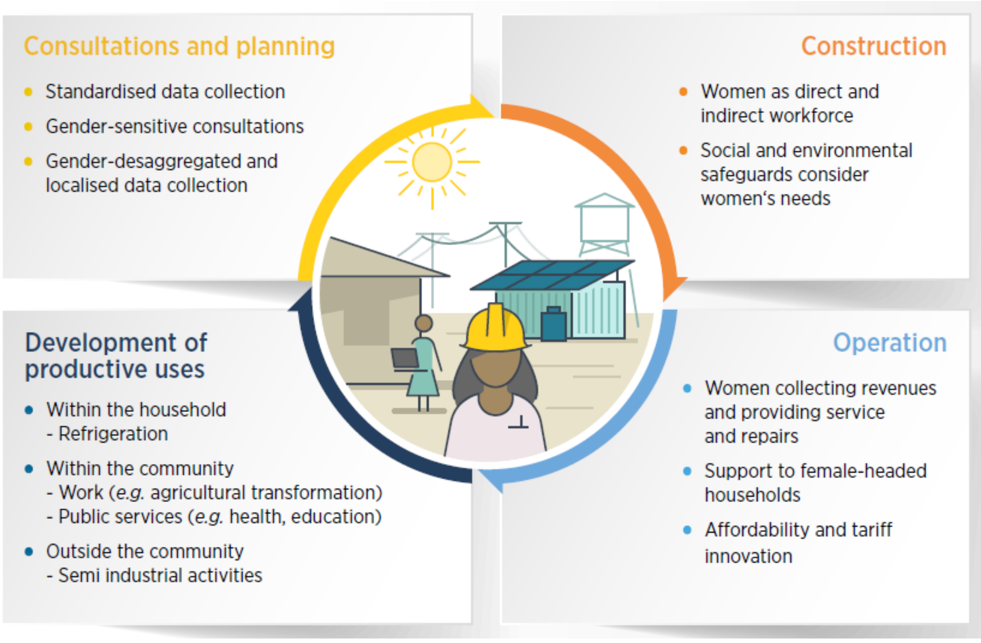
Over a period of six months, trainees receive instruction on **assembly, installation, operation and maintenance of solar lanterns, lamps, parabolic cookers, water heaters and other devices**. The women return to their villages with equipment to deliver sustainable electricity to their community and become role models for other women in the village.

2. Integrating gender in energy access programmes

Promoting interaction between different sectors, such as primary health, education and water, is key for women's economic empowerment and advancement and can help formulate solutions that look at the entire ecosystem and maximise the benefits.

Development financing institutions and agencies that often design, manage, implement and finance energy access programmes strongly influence practices related to gender mainstreaming in the sector. Several such institutions and agencies have taken steps to integrate gender within their respective energy access programmes.

Figure 12.12: Illustrating gender entry points in the development of renewable energy mini-grids



Source: IRENA (2019)

Training and skills-building are also effective means of engaging women in the construction and maintenance of off grid renewable energy technologies, as well as in promoting productive end-uses that support local socio economic development. Figure 12.12 illustrates the different entry points for women's engagement in the development of a renewable energy mini-grid.

Gender mainstreaming at the programme level:
The case of Hivos' domestic biogas programme and Sumba Island Initiative

In 2011, Hivos, a Dutch development aid organisation, was engaged in eight domestic biogas and two improved cookstove programmes in Africa and Asia. After assessing gender mainstreaming in policy and practice, it concluded that core issues of gender inequality were not always being addressed sufficiently. It called for a better understanding of gender issues in all programmes and **identified concrete opportunities for mainstreaming**.

The cooking energy programmes, including the African Biogas Partnership Programme and Program Biogas Rumah in Indonesia, had not all defined gender goals from their inception. Gender equality was integrated in the programme's planning, implementation, monitoring and institutional set-up from 2011 onwards. For instance, **training approaches within biogas programmes have been adapted to address gender issues more effectively** to ensure that women and men are equally engaged. In all countries, the **proportion of women trainees has gone up significantly**, with positive outcomes for long-term sustainability and socio-economic benefits.

As part of its Sumba Island Initiative in Indonesia, Hivos is working with the local and national government to devise approaches to integrate gender in the renewable energy sector. Hivos has capacitated four local civil society organisations who coach or mentor local entrepreneurs and users of renewable energy systems on **identifying gender gaps and ways to address them including building shared-vision between husband and wife** from the energy access they have for better a livelihood. At the national level, Hivos has engaged Ministry of Women Empowerment and Child Protection, to together identify potential gender integration models in the sector with two test locations: Sumba and Salatiga, Central Java.

3. Fostering women entrepreneurs and improving access to finance

1. Women's entrepreneurship within the energy sector has the potential to significantly enhance economic growth and promote their social inclusion and empowerment. Women-led enterprises tend to have a stronger emphasis on social value.

Women are also more **easily able to reach out to and interact with female end-users**, especially in situations where women are primary users and also in areas where cultural and social norms inhibit public engagement with women.

As women become engaged in delivering energy solutions, they take on more leadership in their communities and consequently facilitate a gradual paradigm shift in the social and cultural norms that traditionally acted as barriers to their agency. Active engagement further contributes to women's economic and financial independence by increasing income-generating opportunities and enhancing women's social and political status (box below).

Empowering women brewers in Burkina Faso through energy-efficient cookstoves

Burkina Faso's traditional small-scale beer-brewing sector is predominantly **led by women and is an important source of income for rural women**. But poorly designed, inefficient cookstoves cause health problems and require longer cooking times and higher fuel consumption.

In 2012, a programme to install over 500 energy-efficient cookstoves reached an estimated 800 women by helping them **build clusters** that **identify and promote their business development priorities** including financial management, technology upgrading and improving the hygiene of the production. The women were **grouped together in associations and encouraged to use self-help groups to finance the purchase of improved cook stoves**. The programme also establishes a credit risk guarantee mechanism to help women access additional financing. They were also trained on how to operate and maintain the energy-efficient cookstoves. The women were also motivated to initiate the formation of a nationwide federation for beer brewers to pursue the common interests of women working in the sector.

Following the implementation of the project, women's profits and income increased and they had more social standing within their communities. The **high efficiency of the cookstoves** also reduced the amount of firewood required by over 40%, thus also reducing the health risks and physical or sexual assault risks to women collecting firewood.

2. In order to scale up women's engagement in entrepreneurship, **training and mentoring programmes** focusing on technical, financial and leadership skills are essential for developing stable energy businesses (box below). Such programmes enable women to identify viable business opportunities, form useful networks to expand their business activities and devise effective market strategies to run successful businesses. Mentorship and training opportunities ease women's inhibitions about taking on leadership roles and bridge the gap between women and the formal, more-male-dominated sector of the economy (SEforAll, 2017).

Empowering women entrepreneurs to deliver off-grid renewable energy solutions:
The case of Solar Sister

Solar Sister is a training and job creation initiative for women that distributes portable solar lights in rural Sub-Saharan Africa through female entrepreneurs. Entrepreneurs are trained to **sell solar lanterns and are given the opportunity to build sales and a cash flow by earning a commission**, which they then re-invest in new inventory.

Solar Sister equips women to build **their own technology-driven businesses** and provides a holistic package of inputs (including business and technical training, a quality brand, access to world class products and service, marketing support and ongoing coaching).

As of 2018, it has benefitted 3554 entrepreneurs, of whom 83% are women.

3. **Access to finance** is another binding constraint women face in setting up small and medium-sized enterprises. Although 48% of business owners in Kenya are women, only 7% have access to formal credit. Women are also less likely to have bank accounts than men, particularly

due to the lack of bank branches in rural areas (SEforAll, 2017).

4. Various solutions are emerging, including **dedicated credit lines**, **crowdfunding** and **local community organisations and cooperatives**. In **Kenya**, for instance, women-led enterprises unable to access funding from traditional financing institutions have raised financing through crowdfunding platforms that utilise mobile payments. Despite the success enjoyed by some such innovations, inadequate access to affordable financing remains a major impediment for women setting up small businesses in the energy access context.

5. **Mentoring programmes** are essential in guiding women who are interested in the energy sector and encouraging them to overcome hesitations and barriers associated with traditional socio-cultural perceptions and stereotypes.

6. The **private sector** also has an important role to play in supporting women-led enterprises. Partnering with women entrepreneurs is a mutually beneficial option, as women often have extensive local networks, specialised skills and an in-depth understanding of local markets that can help the private sector address market barriers.

IFC's Lighting Asia programme in India, for example, has facilitated partnerships and networking between Indian solar distributors and women entrepreneurs in rural areas. Through the development of these networks and partnerships, distributors have been able to overcome cost and market barriers in last-mile communities and increase sales of solar lighting products by approximately 30%.

7. It is important to provide the **right type of support for women-led enterprises**, but it is also important to remember that entrepreneurship is often not a realistic livelihood strategy for some women, and even well-intentioned and well-designed interventions by governments, private sector organisations and social enterprises may fail to convince them to become entrepreneurs. Women from the poorest households are generally averse to entrepreneurship, often because they have no capital to invest and no collateral against which to borrow. They are much more likely to pursue employment opportunities in renewable energy if they can earn incomes without becoming indebted. Acquiring new skills – such as learning to build and repair renewable energy technologies – is often better suited to their economic realities and limitations.

Social enterprises and non-govern mental organisations (NGOs) that disseminate renewable energy technologies to low-income populations are aware of this fact and some have started to offer training in such skills.

4. Improving the collection of gender disaggregated data

The lack of gender-disaggregated data exacerbates the gender gap within the energy access field because it distorts perceptions of the level of gender inequality within the sector. This hinders **baseline evaluations of gender inequality** which underpin the development of gender-sensitive targets and indicators, the same targets and indicators that subsequently inform gender-sensitive programmes and policies. The result is a decrease in the effectiveness and accuracy of gender-responsive strategies.

For the differences between men and women across social, economic, environmental, political and cultural dimensions to be fully grasped, both **qualitative and quantitative data collection** and analyses are necessary. Progress is being made and a greater attention is being paid to the collection and reporting of gender disaggregated data (box below).

Gathering gender-disaggregated data through household surveys

Household survey data provide a better picture of energy access than data from service providers. By capturing more indicators, such surveys enable analysis of access trends across **socio-economic segments** (e.g., urban vs. rural, male- vs. female-headed households). The World Bank's Global Poverty Working Group Database analyses datasets of household-level data, including household electrification status and gender of head of household, allowing valuable insights on how (and where) access varies.

Gender-disaggregated data show that **electricity access for male- and female-headed households differs only slightly** overall – 33% and 31%, respectively. **Disparities emerge for some countries**, however. In some countries (Ethiopia, Mali, Nigeria), access rates for female-headed households are two percentage points higher; in others (Angola, Bangladesh, Chad, Sudan, Zambia), male-headed households enjoy substantially higher access rates.

12.5 Questions to summarize the chapter

1. Concerning the women in the **modern renewable energy sector**:
   a. Which is the **status and main trends** in that sector?
   b. Which are the main **barriers** that women face to enter in that sector?
   c. Which are the main **barriers** that women face in the **retention in the sector** and in their **careers advancement**?
   d. Which are the **policies** that could facilitate women's participation in the modern renewable energy sector?
2. Concerning the women in the **access to renewable energy**:
   a. Which is the **status and main trends**?
   b. Which are the main **barriers** that women face to access to renewable energy?
   c. Which are the **policies** that could facilitate women's access to renewable energy?

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Chapter 13

Sustainable development. Sustainable Development Goal 11: Sustainable cities and communities

The 21st century has been called the "urban century" by UN-Habitat (the United Nations agency responsible for sustainable human settlements) and by many others. In fact, over 50% of the global population now lives in urban areas, and this trend will continue. This chapter studies the key role that cities can play mitigating climate change by introducing innovative transport, recycling and building policies.

This chapter is still under development. The chapter is based in McCormick et al. (2015). I provide a very basic overview of the topic, and some useful links that I will explore and develop in the future.

13.1 Cities

Street Plans

UN Habitat

(One planet cities WWF).

LSE cities (link).

LSE Cities, Copenhagen (link).

LSE Cities, Stockholm (link).

ICLEI - Local Governments for Sustainability (link).

Cities C40 (link)

Oslo (link).

City index, The Economist (link).

European Green City index (link).

Mälmo, Europe's first carbon neutral neighborhood - Smart Cities - Horizons (link).

Project for Public Spaces (link).

13.2 Processes of sustainable urban transformation

The 21st century has been called the "urban century" by UN-Habitat (the United Nations agency responsible for sustainable human settlements) and by many others. In fact, over 50% of the global population now lives in urban areas, and this trend will continue.

There are three key areas to discuss when it comes to sustainable urban transformation: Governance and planning, innovation and business, and lifestyles and consumption.

1. **Governance and planning:** Effective strategic planning and integration of policy instruments is essential. Such efforts should be interconnected across sectors and adapted for specific urban and national policy conditions to ensure empowerment, engagement and collaboration of relevant stakeholders.

   In order for strategic planning to be effective, however, three key policy challenges have to be taken into account:

   (a) Policies must be ambitious but politically and economically realistic;
   (b) Policies must be developed quickly and with flexibility for rapidly changing urban conditions;
   (c) Contradictory policies have to be eliminated.

2. **Innovation and business:** There are significant challenges in reconciling economic growth and maintaining or restoring local and global environment. Innovation and clean technology are key parts of a green economy, but also for fostering urban competitiveness in a globalising economy.

3. **Lifestyles and consumption:** Negative implications of over-consumption are particularly evident in cities.

13.3 Climate governance and urban experiments

From the early 2000s, we can identify a new wave of action. Over the past decade, we have seen a greater range and diversity of cities getting involved with responses to climate change. A number of city networks (such as ICLEI – Local Governments for Sustainability and the C40 Cities Climate Leadership Group) formed, through which municipal governments co-operate internationally, and a whole host of partners from the private sector to civil society are getting involved in trying to address climate change at the urban level.

Part of the reason for this shift is a change in how climate change is seen as a policy problem. Rather than focusing on targets for reducing greenhouse gas emissions, we now see an increasing emphasis on the need for decarbonisation, i.e., for uncoupling economic growth and social well-being from the use of fossil carbon-based fuels. As this requires more systematic change across urban areas and infrastructure networks, there has been a shift in how and where climate governance is taking place in the city.

Looking at climate governance in this way has helped us to recognise a new phenomenon – the growth of urban **experiments designed to respond to climate change**. Why is experimentation taking place as a means of governing climate change at the urban scale?

1. **Municipal governments** have limited powers to act on climate change alone and need to develop projects or specific interventions that attract other organisations to work with them.

2. **Private sector and community actors** also find urban environments an important site for action, but lack the power or capacity to intervene at the level of the city as a whole.

3. **Projects** that might have taken place in the past without being thought about in climate change terms are increasingly seen through a climate change lens. In a sense, climate change has come to be a ubiquitous reason for taking different and disparate forms of action at the urban level.

Some links about experiments taken place in urban areas:

One planet cities WWF

ICLEI - Local Governments for Sustainability

Cities C40

Some useful reports about urban design in cities:

LSE cities

LSE Cities, Copenhagen

LSE Cities, Stockholm

13.4 Urban infrastructure and planning

Municipal and city planners are challenged with how to plan structural transformations and they are exploring how urban infrastructure can play a part in greening the economy. Urban infrastructure is the basic physical and organizational structures needed for the operation of a city or urban area. It is also the **services and facilities** necessary for society and the economy to function. This can include **infrastructure** for water, waste, shelter, energy, telecommunications, and mobility, including streets, buildings, sewers, parks and energy systems. Importantly, urban infrastructure can advance sustainability and green economies, or, adversely, it can lock in unsustainable systems and prevent sustainable urban transformation.

To learn more about infrastructure and planning, **urban mobility** is a good example to examine.

- In 2013, there were over 5,000 electric vehicles in the urban area of **Oslo** in Norway. Electric vehicles in Norway are powered by hydro-electricity, resulting in low emissions, improved air quality and less noise. The city council hopes to grow the numbers of electric vehicles through innovative policy and additional infrastructure, for example by continuing to add to the over 700 public and free charging stations already provided in the city. The City of Oslo leads by example in buying only zero emission electric vehicles for its municipal fleet. Electric vehicles are also encouraged through city transport rules allowing them to use bus transit lanes as well as national level taxes on fossil fuels and road charge exemptions for electric vehicles. Of course, electric vehicles help with reducing emissions, but congestion still remains a challenge. For this reason, the City of Oslo is also working with its public transportation system.

- Greener city planning encourages people to act sustainably without thinking about the environment. For example, in **Copenhagen**, most people bike for the convenience of it, rather than its environmental benefits. In fact, the top two reasons for biking in the city are said to be convenience and health. The environment is number three. This is made possible by making biking as convenient as possible and giving it priority in planning across Copenhagen.
- In order to make public transport a competitive alternative that can take you conveniently from your front door to your intended destination, **the connection between different sustainable transport modes needs to be as seamless as possible**. An important challenge is to build transport hubs where, for example, bus, train and subway stations are located next to each other, preferably with access to convenient bicycle par king nearby.
- Another possibility is to integrate **information and communication technology** with public transport and to provide passengers with real-time information and other online services.

Some links to study urban infrastructure and planning:

Oslo

City index, The Economist

European Green City Index

13.5 Sustainable neighbourhoods

Sustainable lifestyles and neighbourhoods can have an impact on sustainable urban development overall. The lifestyles of eco-villages (often developed in rural contexts with strong sustainability principles) are increasingly utilised in mainstream practice in sustainable urban development in Scandinavia. In contrast to rural eco-villages, cities and sustainable neighbourhoods concentrate higher numbers of people in one area, which enables more sustainable services like public transportation and recycling.

We have introduced the example of the Western Harbour in Malmö, Sweden, as a leading sustainable neighbourhood. The Western Harbour was formerly contaminated industrial land which housed a variety of warehouses and factories. The area has since been re-designed as a new neighbour hood with good public transport links and pedestrian and cycle ways to discourage car dependency. There are a mix of buildings for different uses around squares where people can gather. There are systems for managing waste and water sustainably, and renewable energy technologies integrated in the area.

Four **key principles** characterising sustainable neighbourhoods:

1. **Energy systems:** Most sustainable neighbourhoods have shared ownership of renewable energy technologies and low energy demands. For example, residents can build and live in passive energy-saving multi-dwelling buildings. They can have adopted innovative solutions to reduce resource use and stimulate recycling, and they manage water and waste resources sustainably.
2. **Socio-economic balance:** Sustainable neighbourhoods often have local – and organic – food cooperatives which are run by residents. These neighbourhoods often have a strong ”social ecology” element that includes direct democracy, transparency and tolerance. They

can have trading systems in which local goods and services are traded without the use of money. Furthermore, they have a strong emphasis on the local economy and the local community.

3. **Transport and mobility:** Many sustainable neighbour hoods have efficient public transport connections and might not even allow cars in the area. They promote cycling and walking, and they plan for a compact building layout in order to minimise travel distances. Transport and mobility is there fore closely connected to the urban design and planning of sustainable neighbourhoods.

4. **Urban design:** Most sustainable neighbourhoods have multi-purpose community spaces that promote a variety of social activities, such as central plazas where people can meet, green spaces, public spaces, pedestrian streets, and bike trails. Overall, the design of sustainable neighbourhoods is critical to achieving goals on energy, socio-economic balance and transport.

Some links about successful sustainable neighbourhood experiences:

Mälmo, Europe's first carbon neutral neighbourhood

Project for Public Spaces

13.6 Bibliography

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