Energy Strategy Reviews 24 (2019) 38–50

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

The role of renewable energy in the global energy transformation

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ARTICLE INFO

Keywords:
Energy transition
Sustainable development
Energy policy

ABSTRACT

This paper explores the technical and economic characteristics of an accelerated energy transition to 2050, using new datasets for renewable energy. The analysis indicates that energy efficiency and renewable energy technologies are the core elements of that transition, and their synergies are likewise important. Favourable economics, ubiquitous resources, scalable technology, and significant socio-economic benefits underpin such a transition. Renewable energy can supply two-thirds of the total global energy demand, and contribute to the bulk of the greenhouse gas emissions reduction that is needed between now and 2050 for limiting average global surface temperature increase below 2 °C. Enabling policy and regulatory frameworks will need to be adjusted to mobilise the six-fold acceleration of renewables growth that is needed, with the highest growth estimated for wind and solar PV technologies, complemented by a high level of energy efficiency. Still, to ensure the eventual elimination of carbon dioxide emissions will require new technology and innovation, notably for the transport and manufacturing sectors, which remain largely ignored in the international debate. More attention is needed for emerging infrastructure issues such as charging infrastructure and other sector coupling implications.

1. Introduction

The Sustainable Development Goals (SDGs), adopted by the United Nations General Assembly (UNGA) in 2015, provide a powerful framework for international cooperation to achieve a sustainable future for the planet. The 17 SDGs and their 169 targets, at the heart of “Agenda 2030“, define a path to end extreme poverty, fight inequality and injustice, and protect the planets environment. Sustainable energy is central to the success of Agenda 2030. The global goal on energy - SDG 7 - encompasses three key targets: ensure affordable, reliable and universal access to modern energy services; increase substantially the share of renewable energy in the global energy mix; and double the global rate of improvement in energy efficiency [1]. The different targets of the SDG 7 contribute to the achievement of other SDG goals and recently this has been the focus of an increasing number of studies [2–7].

Earlier analysis of future energy pathways shows that it is technically possible to achieve improved energy access, air quality, and energy security simultaneously while avoiding dangerous climate change. In fact, a number of alternative combinations of resources, technologies, and policies are found capable of attaining these objectives [69]. Although a successful transformation is found to be technically possible, it will require the rapid introduction of policies and fundamental political changes toward concerted and coordinated efforts to integrate global concerns, such as climate change, into local and national policy priorities (such as health and pollution, energy access, and energy security). An integrated policy design will thus be necessary in order to identify cost-effective “win-win” solutions that can deliver on multiple objectives simultaneously.

Land, energy and water are among our most precious resources, but the manner and extent to which they are exploited contributes to climate change. Meanwhile, the systems that provide these resources are themselves highly vulnerable to changes in climate. Efficient resource management is therefore of great importance, both for mitigation and for adaptation purposes. The lack of integration in resource assessments and policy-making leads to inconsistent strategies and inefficient use of resources. A holistic view of climate, land-use, energy and water strategies can help to remedy some of these shortcomings [70].

A global energy transition is urgently needed to meet the objectives of limiting average global surface temperature increase below 2° Celsius. The implications of the Paris agreement for the energy sector will be profound to an extent that is not yet fully captured by existing

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https://doi.org/10.1016/j.esr.2019.01.006
Received 4 June 2018; Received in revised form 4 January 2019; Accepted 19 January 2019
Available online 31 January 2019

energy scenarios [28]. A transition away from fossil fuels to low-carbon solutions will play an essential role, as energy-related carbon dioxide (CO_2) emissions represent two-thirds of all greenhouse gases (GHG) [8].[1] This energy transition will be enabled by technological innovation, notably in the field of renewable energy. Record new additions of installed renewable energy power capacity can be attributed to rapidly falling costs and competitiveness, particularly for solar photovoltaics (PV) and wind power. A quarter of all electricity worldwide was produced from renewables in 2017. However, the transition is not happening fast enough: following three years of constant CO_2 energy emissions from 2014 to 2016, they rose in 2017 by 1.4% [9–12].[2]

Predicting the timing and the extent of energy transitions is not straightforward. The age of nuclear [13] and the age of hydrogen [14] were "announced" but have not yet come to pass. Recent examples of other projections that have not proven accurate include inflated natural gas projections and structural underestimations of renewables growth [15–17]. Experience has shown that an energy transition takes time, typically half a century from first market uptake to majority market share for energy transition [18]. Previous energy transitions were driven by technological change, economics, access to resources, or superior energy service for consumers [19]. Therefore business opportunities, energy transition benefits or self-determination of individuals were at the heart of the change [20,21].

National energy transition narratives include learnings from both successes and failures. Success stories show that energy transitions that build on enabling energy policy frameworks designed by governments that can accelerate energy transitions and determine their direction. Well-designed transition policies consider energy systems characteristics and encompass energy supply and demand [22]. Lessons from several countries and regions are examples to this. In Brazil, the *Proalcool programme* was started in 1975 and a mix of policy instruments that evolve over time were used to address the needs of both supply and demand sides. It remains the case that government blending mandates are driving biomass-based ethanol demand [23], but the sector's long-term success continuous to be impacted by economic cycles and changing government priorities [77]. In Germany, the *Energiewende* is the result of a national consensus to abandon nuclear and reduce greenhouse gas (GHG) emissions by 80% by 2050 through an accelerated uptake of renewables [24,25]. However, the *Energiewende* still remains as a power sector transition policy with small impact on coal-fired generation and for accelerating transition in heating and transport sectors [78]. In Denmark, there also is a consensus on climate objectives in combination with tacit renewable supply industry support policy [26].

Ambitions of renewable energy targets are consistently raised in many countries for other reasons. For instance, the European Union has adjusted its 2030 binding target of 27% that was set back in 2014 to 32% in June 2018. The new target includes an article stating that in 2023 countries will reconvene to discuss an update upwards [71]. The Government of India set an ambitious renewable energy target of 175 GW by 2022 which includes 60 GW of wind and 100 GW of solar energy [76]. As the country made good progress, the Government of India has raised the target to 227 GW by 2027. Despite the heterogeneity in its energy sector and distinct differences and priorities of each actor that compromises individual energy markets regulated across each of its 50 states and with more than 3000 utilities, the United States offers a successful story of energy transition. Domestic production of natural gas and a determined policy effort at federal and state levels driven by mechanisms like tax incentives for renewables have transformed the country's energy sector. 11% of the total energy demand and 17% of all electricity generation in the United States is supplied from renewable energy resources according to the latest data for 2017 from the U.S. Energy Information Administration [81]. This was also enabled strong by grid planning and innovation. For instance, Hawaii in the United States aims to reach 70% energy independence by 2030, out of which 40% of this will be represented by renewable energy. The case of the United States also shows the importance of continuous updates and improvement of energy transition policies where electricity and transport sectors show similarity in the way that the scope of their policies has been repeatedly expanded and their timelines have been extended beyond the original targets [79].

As the largest energy producer and consumer, China has a critical role in the global energy transition. China has turned to renewables to meet its growing energy demand and reduce air pollution. China has also set targets to reduce its carbon emissions per unit of gross domestic product by 60–65% by 2030 from the 2005 levels where renewables will play a pivotal role. The target for non-fossil fuel share in total energy demand is 20% by 2030 [75]. China has accounted for more than half of all global solar PV capacity additions of 94 GW in 2017. However, in 2018, the Government of China introduced solar PV deployment quotas and decided to phase out feed-in tariffs which is expected to reduce capacity installations [80].

Several other large energy users are taking part in the global energy transition. The Russian Federation that owns one of the largest fossil fuel resources in the world is accelerating the deployment of solar and wind through auctions to create benefits for employment, science, technology and energy security for isolated populations [72]. More than 5 GW wind and solar capacity have been awarded since 2013, indicating that the country will most likely surpass its 2024 target of 5.9 GW installed renewable energy capacity (including geothermal) [72,73]. As an emerging economy Turkey is also exploring ways to increase solar and wind share with the urgent need to reduce its energy imports that compromises three-quarters of the country's current account deficit. To realise its short-term renewable energy targets to 2023, feed-in tariffs were in place which proved successful for solar PV to reach the 5 GW installed capacity target already in 2018. However, unclarity in planning after 2023 and the growing weight of large-scale capacity auctions that primarily aim for creating a local renewable energy equipment industry have pushed small-scale players outside the market and suffer from lack of financing [74].

In view of energy transition's central role to climate change mitigation that builds on the two pillars of energy efficiency and renewable energy, the objectives of this paper are to:

- Outline the technical characteristics of the ongoing global energy transition, with a focus on the renewable energy component;
- Outline an energy transition scenario for sustainable development between now and 2050, and the role renewable energy can play in such global energy transition, using the latest datasets for renewable energy and comparison of transition scenarios from different sources;
- Assess the cost and benefits of an accelerated energy transition;
- Outline the synergies between accelerated energy efficiency and renewable energy deployment;
- Specify the main challenges and research priorities arising.

The results add new insights into the scientific debate on the ongoing global energy transition by identifying action areas and the innovation gaps at technology and sector levels. While the paper shows where more policy attention is needed, a detailed assessment of detailed policy design is beyond the scope of this paper. The results presented in this paper stem from the International Renewable Energy Agency's (IRENA) in-depth global energy modelling framework -

[1] This data refers to the situation in 2010 and it includes emissions from industrial processes. Emissions from latter are released during the physical and chemical transformation of materials like clinker production. Since these industrial production processes are also consumers of energy, here we made the choice to combine them with CO_2 emissions from fossil fuel combustion.

[2] Recent analysis by the Global Carbon Project and data released by the International Energy Agency show that CO_2 emissions have risen again in 2017.

REmap [27], and is an update of the results published in the joint study by IRENA and the International Energy Agency (IEA) [28].[3]

The rest of this paper is organised as follows: Section 2 provides a brief overview of the REmap global energy modelling framework methodology. Section 3 considers low-carbon energy technology trends. Section 4 considers an accelerated transition. Section 5 presents some of the costs and benefits of the energy transition. Section 6 presents the contours of an accelerated transition for renewable energy and energy efficiency. Section 7 covers areas related to innovation, and Section 8 draws conclusions.

2. Methodology overview

REmap is based on a unique technology and project cost dataset. Technology costs and cost projections were derived from a comprehensive and publicly accessible database of renewable energy technology cost [29,30]. Also a number of IRENA datasets have been developed in recent years at different levels of spatial resolution that detail the economic and technical potentials of various renewable resource types and strategies how to enhance and deploy these potentials in the future in a cost-effective manner.

Regarding the technology deployment potentials in the 2030 and 2050 timeframe, extensive consultations took place with country experts and this information was combined with model analysis for power sector transformation. It includes potentials and market information from 150 countries as well as the most recent national energy plans of 70 countries collected directly from governments [31,32]. provide additional insights into the methodology, strengths and limitations of the REmap global energy modelling framework by comparing its application with the findings of national IEA-ETSAP models as well as other scenarios acknowledged by the global energy and climate community. Annex 1 provides further methodological details of REmap. In recent years, IRENA has worked together with the governments and their national experts to contribute to the renewable energy planning and target setting of 70 countries through implementation of the REmap approach. It has been deployed for the Group of Twenty (G20) countries [33,42] and for various regional settings such as Association of Southeast Asian Nations (ASEAN) [34], the Africa Renewable Energy Initiative (AREI) [35], the European Union (EU) [36,37] and the United Arab Emirates [38,39].

Numerous global, regional and national tools and models exist to assess low-carbon and energy transition pathways [89–93]. REmap findings for the year 2030 are found to be comparable with other scenario analyses that use different techniques but similar assumptions on technologies, costs etc [31,32]. The strength of the REmap approach is to allow IRENA national experts to develop their own scenarios and review data and assumptions of the analyses. By using a simpler accounting framework than complex integrated assessment models, REmap creates country engagement and dialogue, and is able to provide direct feedback to countries about technology pathways, investments and policy making. The idea is not to be prescriptive of a technology mix but communicate results with a diverse group of audience. These are important assets REmap brings to the energy scenario debate while generally the support of sophisticated models dedicated certain tasks are required to enhance REmap's technical capabilities, such as the analyses of grids, infrastructure and biomass supply [32]. Earlier examples of such soft-linking of REmap with other models have yield successful results, for instance in the analyses of the European Union's power system [37].

Decarbonisation can stimulate employment and economic growth. If synergies between energy, climate and other economic policies are leveraged, it can lead to overall higher GDP and have positive net employment impacts. For this analysis, the E3ME global macro-econometric model that considers the energy system (based on the REmap energy mix) and the world economies has been used. Model has been used to estimate the impacts of energy transition on employment, GDP and structural changes in the economy. E3ME simulates the economy based on post-Keynesian principles, in which behavioral parameters are estimated from historical time series data. Interactions across sectors are based on input/output relations obtained from national economic statistics. The model includes 24 technologies used for electricity generation and 43 sectors of the economy. In total, 59 countries and regions are covered but more countries can be added to the model [28].

3. Low-carbon energy technology trends

This section provides an overview of the latest trends for the key renewable energy and energy efficiency technologies that are needed for the global energy transition. Progress in reducing the energy intensity of the global economy continued to accelerate, improving by a 2.1% compound average annual growth rate between 2010 and 2016 [41].[4] In 2015, the share of renewable energy in total final energy consumption climbed to reach nearly 19%, continuing the slight acceleration of trends evident since 2010 [28].

In terms of power generation, renewables have accounted for more than half of all global capacity additions since 2012. In 2017, newly installed renewable power capacity in the world achieved a new record of 167 GW. This was another record year where more than 60% of all new electricity capacity was from renewables. Solar PV capacity has experienced a growth more than any other source of electricity generation [10]. Global new investment in renewables amounted to USD 241.6 billion in 2016; 2017 was the fifth consecutive year that new investment in renewable power generating capacity was roughly double the one in fossil power generation capacity. At the root of this acceleration are substantial reductions in renewable technology costs [9].

The levelized cost of electricity from solar photovoltaics has fallen by an astounding 73% between 2010 and 2017, and for electricity from onshore wind cost have fallen by 23%. IRENA analysis estimates that by 2020, all renewables technologies currently in commercial use will be cost-competitive with fossil-fuels in many parts of the world, and even undercut them significantly in many cases. Policy mechanisms such as auctions have contributed to lowering prices. World-wide recent tenders have resulted in record-breaking prices: in recent years utility scale solar PV and onshore wind projects are offered at US cents 2–3 per kWh under the best conditions. These prices are below this of conventional fossil and nuclear generation, in some cases even below the operating cost of existing conventional plant.

According to the REmap analysis, share of renewables in power generation would need to increase from around one-quarter in 2015 to around 60% by 2030 and 85% by 2050 for energy sector decarbonisation. The substantial annual growth rate of 0.7% of renewables in total generation over the past five years needs to more than double to realise these [27].

Countries around the world are in the midst of an energy transition that appears to favour electricity as the preferred final energy carrier. This is favourable from the perspective of both renewables and energy efficiency. Electricity is an efficient energy carrier and it becomes a clean source of energy when it is sourced from renewables. Electricity's share in total global final energy consumption (TFEC) is around one-fifth, but it is much higher in high-income countries and it is rising fast in developing countries [43]. Especially in the residential sector, a conversion to all-electric solutions is conceivable [44]. Electricity for

[3] Results similar to those presented here have been earlier published by IRENA and IEA [27]. This peer-reviewed study was commissioned by the 2017 German Presidency of the Group of Twenty (G20) to inform its energy and climate agenda [41].

[4] Energy intensity is defined as the ratio of total primary energy supply per unit of gross domestic product measured in purchasing power parity.

cooking, water and space heating, and cooling is available today. Light industry and the service sectors are areas where electricity can make similar significant inroads [45]. However, in heavy industry, electricity use is limited to specific processes, such as smelting or electrolysis. Generally, new electric solutions are technically feasible but often not economic [46].

In transport, significant growth in the use of electricity once seemed a long shot. But a rapid progress in electric vehicles (EVs) has been seen over the last couple of years. In 2016, around 1% of all car sales were EVs. The rate of EV sales growth is high, and nearly 2 million EVs are on the road today [47]. Also, the number of electric two- and three-wheelers is rising rapidly, with around 300 million in operation worldwide [48]. Passenger cars account for around half of transport's energy use, so electrification can bring major reductions in GHG emissions [49]. The other half consists of trucks, aviation, shipping and railways. While electric delivery trucks are making inroads, there is no such solution around the corner for aviation, shipping or long-range trucking. Those would require technology breakthrough solutions in electricity storage. However, there is a clear trend towards fuel cells with electric drives for trucks and ships [50].

4. Energy transition pathways

Climate change and local air pollution are among the key drivers for energy transition worldwide. Local air pollution is a main driver in countries such as China and India. But also in Europe, there is increasing attention for the harmful health effects of air pollution, largely related to energy supply and use.

Whereas local air pollution can in certain cases be tackled with end-of-pipe technologies, this is not the case with the bulk of CO_2 emissions from energy use. Around two-thirds of global GHG emissions is attributed to fossil fuel energy supply and use [8]. The agreed Paris Climate target of well below 2° implies zero energy CO_2 emissions in the coming fifty years. A more ambitious target of only 1.5° implies even faster reductions.

The energy transition must reduce emissions substantially, while ensuring that sufficient energy is available for economic growth. The analysis shows that the CO_2 emissions intensity of global economic activity needs to be reduced by 85% between 2015 and 2050, and CO_2 emissions need to decline by more than 70% compared to the Reference Case in 2050. The result is an annual decline of energy related CO_2 emissions by 2.6% on average, or 0.6 Gigatonnes (Gt) on absolute terms, resulting in 9.7 Gt of energy CO_2 emissions per year in 2050. This is represented by the REmap Case. This scenario is compared to the Reference Case that represents the developments in energy use and its mix if the world follows policies that are currently in place and under consideration. According to the baseline, or the so-called Reference Case of IRENA, energy CO_2 emissions increases by 6% from 33 Gt in 2015 to 35 Gt in 2050 (Fig. 1).[5]

Higher energy efficiency and much a higher share of renewable energy are the two pillars of energy transition in the REmap Case. Fig. 1 shows that renewable energy and energy efficiency measures can potentially achieve 94% of the required emissions reductions by 2050 compared to the Reference Case. The remaining 6% would be achieved by the other options for reduction of energy related CO_2 emissions, i.e. fossil fuel switching, continued use of nuclear energy and carbon capture and storage (CCS) [28] (Fig. 1). Between 41% and 54% of the total reduction can be directly attributed to renewables. The range indicates the contribution of electrification based on increased use of renewable electricity, which simultaneously raises energy efficiency and renewable energy shares. Potential for CCS is only considered for the industry sector where some emissions from energy-intensive sectors are very challenging to mitigate, such as iron and steel or cement production. CCS is not considered as an option for the power sector.

The power sector would contribute more than 10 Gt to the 25 Gt emissions reduction in 2050. The remainder would be accounted for by reduction of direct emission sin buildings, industry and transport and to a lesser extent district heating (Fig. 1). The G20 countries would account for 85% of renewables deployment including China 26%, United States 15%, India 12%, European Union 9%. This limited number of actors plays a critical role for the energy transition.

The share of renewable energy in total primary energy supply would rise from 14% in 2015 to 63% in 2050. This is equivalent to an average annual growth rate of 1.4%, a six-fold increase from recent years. At the same time the fossil fuel share would drop from 86% to 37%. Energy use would be nearly constant between 2015 and 2050 while economic activity nearly triples (Fig. 2).

The prospects for renewable energy at country level would vary widely [27,28]. This is a result of energy resource endowment, the energy demand projection, the current renewables share and other factors. However, for all economies the share of renewables must grow substantially. Flattening of primary energy supply is possible by accelerating the improvements in energy intensity from its current level of 1.8% to as high as 2.8% per year until 2030. This is consistent with the energy efficiency target of the SDG 7. This effort needs to continue further until 2050. Improvements in energy intensity will come from introducing energy efficiency measures (including electrification) as well as the energy savings from more efficient renewable energy technologies. Several recent independent studies come to the same conclusions, with minor differences [28,52].

Fig. 3 provides a breakdown of renewables deployment. In total 222 EJ (EJ) renewable energy is deployed in final energy terms. The power sector accounts for 58%. This includes growth of renewable power consumption related to electrification (notably electric vehicles and heat pumps). This type of renewables deployment could also be attributed to the end use sectors. In terms of total renewables deployment, the key role of bioenergy (32% incl. district heating) and wind (24%) deserves special attention.

The findings presented here based on IRENA's REmap analysis are comparable with energy scenarios from other major studies like IEA's World Energy Outlook. Table 1 compares IRENA and IEA scenarios for energy transition that were developed independently. Both studies point to the key importance of energy efficiency and renewable energy for the global energy transition, while IEA is somewhat more optimistic on the prospects of fossil fuels with CCS and nuclear energy. The fact that the results are so close indicates a convergence regarding the desirable energy transition direction. However, both analyses also indicate that such transition is not a given, and that the current pace of the transition is too slow.

The Shell Sky scenario is also indicated in Table 1. This scenario is less ambitious in terms of emissions reduction till 2050, it banks on negative emissions post-2050. But also this scenario indicates a 43% renewable energy share in total final consumption by 2050. Because total energy use levels are much higher, renewables deployment is even higher in absolute terms in the Sky scenario than in the other two scenarios. The comparison shows a consensus that renewables growth is a key pillar for energy transition, but opinions diverge regarding the potential role of energy efficiency.

5. Cost and benefits of energy transition

Our analysis shows that the decarbonisation of the energy system is affordable. While overall energy investment requirements are substantial, the incremental investment needs associated with the transition to a low-carbon energy sector amount to 0.4% of global GDP in 2050. The additional cumulative investments over the 2015–2050 period would be 27 trillion USD, equivalent to 0.77 trillion USD per

[5] The Reference Case is based on the national energy plans of the 19 G20 countries and the European Union as a whole [51] which together represent three-quarters of the current global energy demand.

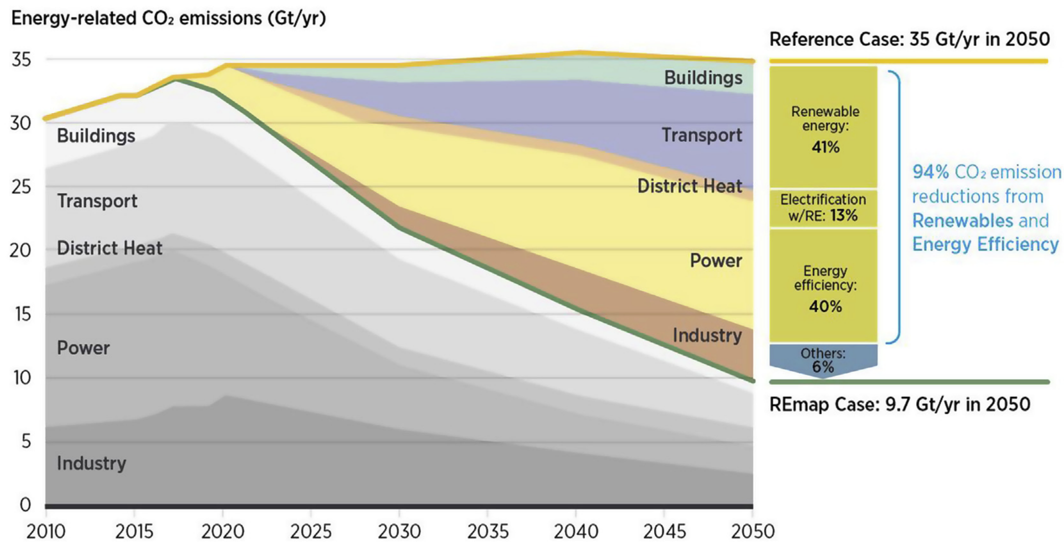

Fig. 1. CO_2 emission reduction potential by technology in the Reference Case and REmap, 2010–2050.
Note: Figure shows the breakdown of energy-related CO_2 emissions by technology in the REmap Case compared to the Reference Case. The figure excludes emissions from non-energy use (feedstocks).
Source: [27].

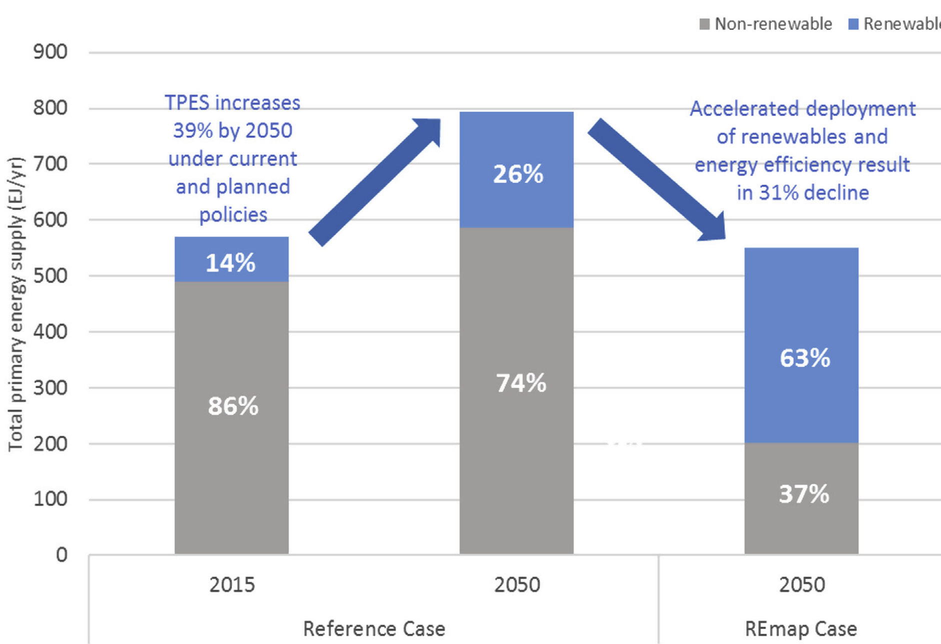

Fig. 2. Global total primary energy supply in the Reference Case and REmap between 2015 and 2050.
Note: includes non-energy use (feedstock).
Source: Based on [27].

year on average in the same period. This is in addition to the 93 trillion USD cumulative investments in the Reference Case, or 2.66 trillion USD per year on average (+29%). The additional investments that are required for energy sector decarbonisation are mainly concentrated in end-use sectors for improving energy efficiency (notably buildings and transport sectors) [27], but also includes investments for infrastructure (e.g. transmission and distribution lines, energy storage, recharging infrastructure for electric vehicles, and hydrogen and CO2 pipeline).

According to the E3ME econometric model used for the purpose of this analysis, REmap Case can boost global GDP by around 1% in 2050 compared to the Reference Case. The cumulative gain through increased GDP between 2015 and 2050 could amount to some USD 52 trillion. Increased economic growth is driven by the stimulus of higher investment in renewables and energy efficiency, and enhanced through pro-growth policies, the use of carbon pricing and recycling of its proceeds to lower income taxes.

The global energy transition and stronger overall economic growth according to the REmap Case could create around 19 million additional direct and indirect jobs in 2050 in the renewable energy, energy efficiency and grid enhancement and flexibility sector. Job losses in the fossil fuel sector (7.4 million) would be completely offset by new jobs in renewables alone, with more jobs being created by energy efficiency activities. Thus, the global energy transition results in 11.6 million additional direct and indirect jobs in the energy sector [27]. These include the millions of additional jobs that will be created in other sectors of the economy related to activities of deployment and maintenance of

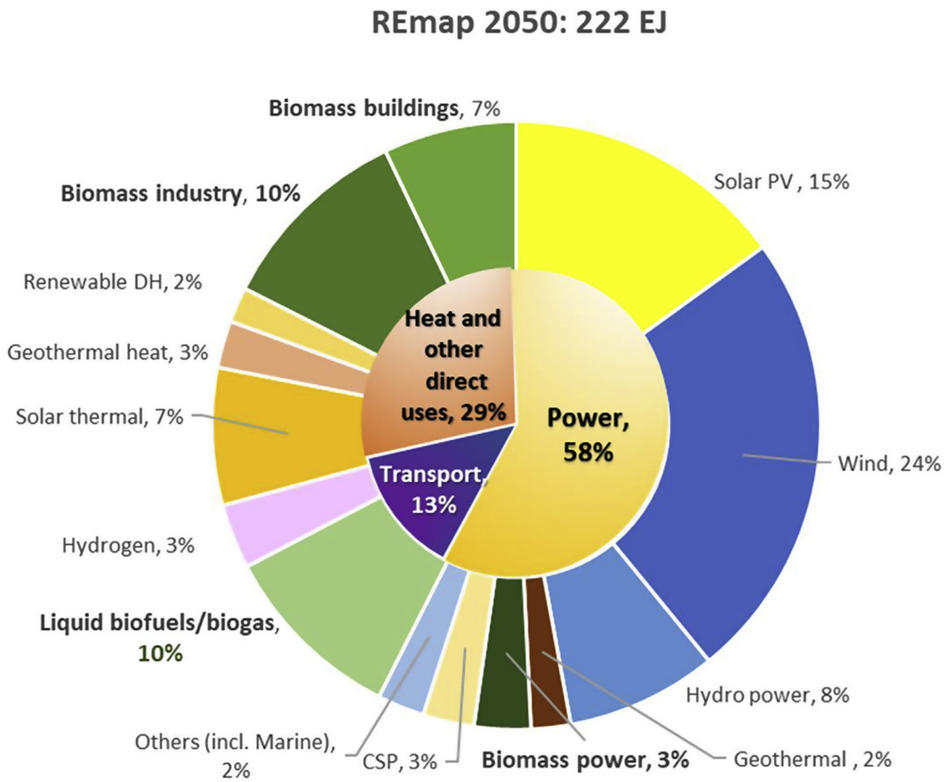

Fig. 3. Breakdown of renewables use in total final energy consumption terms, REmap 2050.
Note: Excludes non-energy use.
Source: Based on [27].

Table 1
Comparison of IEA, IRENA and Shell scenarios for global energy transition, 2050.
Sources [12,27,53].

		IRENA	IEA	Shell
		REmap	2°/66%	Sky
Total primary energy supply	[EJ/yr]	550	586	828
Total final consumption	[EJ/yr]	386	398	548
Renewable energy share in total primary energy supply	[%]	63	46	43
Fossil fuel CO_2 emissions in 2050				
Baseline*	[Gt/yr]	37	37	
Emissions 2050	[Gt/yr]	9.7	9	18
Contribution of abatement options				
Renewable energy	[%]	41	37	
Energy efficiency (including electrification)	[%]	53	35	
Others	[%]	6	29	
Investments for decarbonisation 2015-50 (excl. stranded assets)	[USD trln]	120	114	
Energy intensity improvements	[%/yr]	2.8	2.9	2
Electric mobility in transport	[%]	31	n/a	21
Total biomass demand	[EJ/yr]	128	147	55

Note: *includes non-energy use (feedstock).

renewables, construction, implementation of energy efficiency measures, manufacturing of required equipment, and bioenergy supply. The positive impacts of energy transition with more renewables and energy efficiency on net employment and economic growth are highlighted by other studies as well, but conclusions remain sensitive to model parameters and assumptions [84–87].

A comparison of cost and benefits shows favourable results for energy transition. While the system costs are higher, the health impacts are reduced and climate change is mitigated. Such externalities are typically not accounted for in economic assessments. The findings suggest that reduced external effects amount to two to six times the additional cost. Around two thirds of the benefits can be attributed to reduced health impacts. This creates a strong argument in favour of energy transition [27]. These findings are in line with other modelling studies that show health co-benefits are much higher than the policy cost of achieving the Paris Agreement goals [82,83].

6. Strategies for accelerated renewable energy and energy efficiency deployment

Renewable energy currently accounted for 19% of global final energy demand in 2015, having risen by 0.17% per year since 2010 [28,54]. This growth rate needs to accelerate seven-fold in order to reach a two-thirds renewable energy share in the total global final energy demand by 2050 that is needed for the global energy transition according to the REmap analysis. Based on the REmap energy mix, Table 2 represents the required growth of renewable energy technologies between 2015 and 2050 for energy transition.

The deployment rate of some key technologies is on track, such as for solar PV, wind power technologies. However, for other technology solutions the deployment growth rate needs to increase by several orders of magnitude such as biojet fuels (biokerosene), biofuels for road transport and solar heat for industrial processes [40]. Renewable power technologies that start from a low starting base require the highest annual growth rates. The same can be said for some end-use sector renewable technologies, such as solar heating and hydrogen. Biofuels require somewhat lower rates, as their use is already common in some sectors, such as buildings. Annual growth rates are indicated which reflect a slowing as markets mature. These figures indicate that achieving the required rate of growth of renewables to decarbonise the energy sector is challenging but conceivable.

Renewable power would account for 0.7% points annual average

Table 2
Breakdown of renewable energy growth in the REmap Case, 2017–2050.
Source: Based on [27].

Key renewable energy technologies	Units	Recent growth	Future growth requirement	Growth acceleration factor	Contribution to renewables share growth in total final consumption 2015–2050 (ppt/yr)*
		2017(e)	2018–50		
Wind	GW/yr	53	154	3	0.33
Solar PV	GW/yr	99	210	2	0.21
Modern biomass (end-use)					0.19
Liquid biofuels and biogas	billion liters/yr	5	24	5	0.12
Solar thermal	million m^2	30	283	9	0.10
Hydro	GW/yr	25	17	0.7	0.05
Hydrogen					0.05
Geothermal heat	PJ/yr	26	173	7	0.04
CSP	GW/yr	1	20	20	0.04
Others (incl. marine and hybrid)	GW/yr	0.1	28	280	0.04
Geothermal (power)	GW/yr	0.6	7	12	0.03
Bioenergy (power)	GW/yr	5	12	2	0.03
Traditional biomass					−0.22
Renewable energy: total					1.01
Energy efficiency measures					0.35
Total					1.4

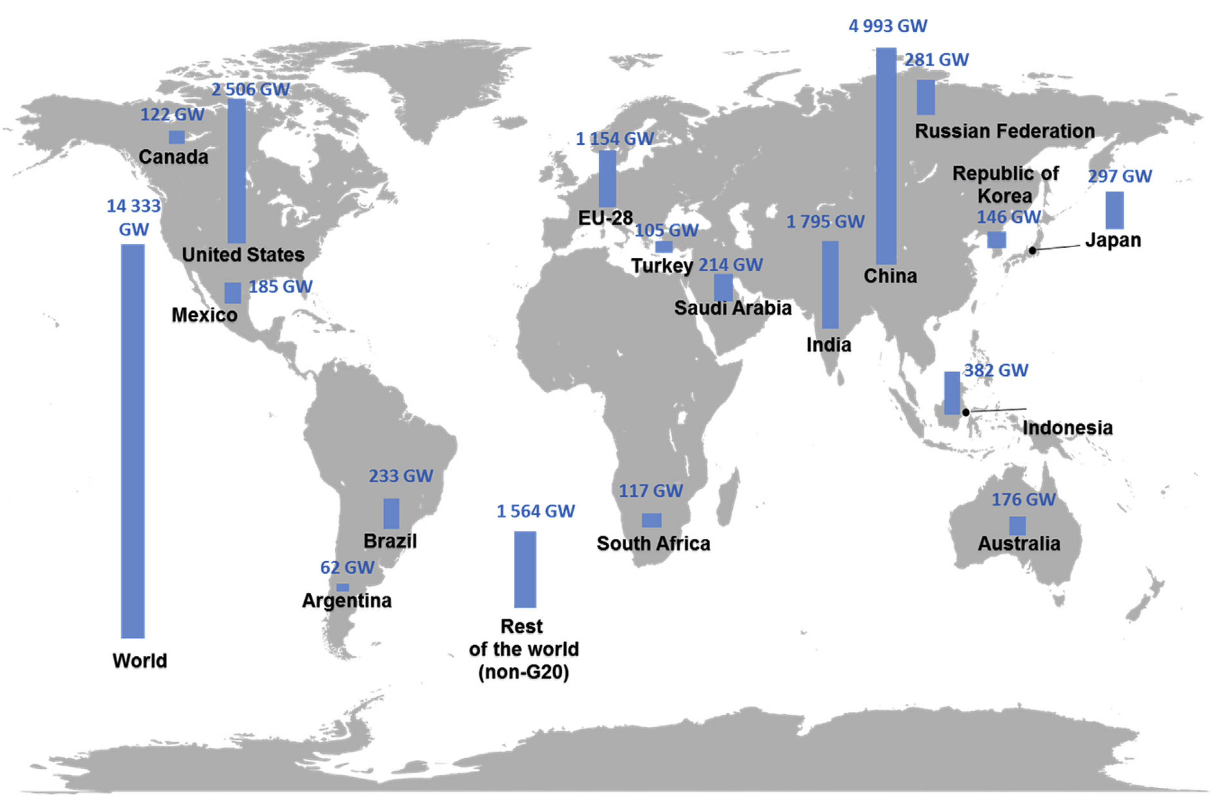

Fig. 4. Geographical breakdown of renewable power generation capacity additions 2018–2050.
Source: Based on [27].

renewables growth, half of the total (Table 2). Under the REmap Case, electricity consumption in end-use sectors would double by 2050 (relative to 2015 levels) to over 42,000 TWh, while the carbon intensity of the power sector would decline by 85%. Gross power generation will almost double with renewable energy providing 85% of electricity. Renewable power generation capacity would grow by eight times from around 2000 GW to 16,000 GW, including 7122 GW solar PV and 5445 GW wind power. Annual capacity additions of these two would double and triple, respectively, compared to 2017. No new coal plants should be commissioned and 95% of coal plants in operation today should be phased out. Investment in new renewable power capacity should increase to USD 500 billion per year over the period to 2050. In total, investment in decarbonisation of the power system will need to reach an average of nearly USD 1 trillion per year to 2050. Fig. 4 provides a geographical breakdown of the renewable power generation capacity additions. China accounts for over one third, followed by the United States, India and the European Union.

Around 85% renewables in the power sectors with a large share from intermittent solar PV and wind is not possible without some strong combination of flexible dispatchable power, transmission interconnection, storage, smart grids and demand-side management. Innovative technologies, operational practices, market designs and business models are needed. Digital technologies open up new opportunities that yield new forms of flexibility such as aggregators that bundle services from small systems into marketable packages or consumer real-time price signals. In 2017, 50 Hz the grid operator in eastern Germany recorded an annual average of 53.4% variable renewable energy. This indicates that it is possible to operate grids with high shares of variable renewables.

The growth of direct use of renewables in end use sectors (buildings, industry and transport) would contribute 0.3% points annual renewables share growth, around a quarter of the total. Biomass alone would account for two-thirds of direct use of renewable energy in 2050. This includes modern biomass heating applications and liquid biofuels. In primary energy terms annual bioenergy supply would roughly double from present levels to around 116 EJ in 2050. This includes a shift away from traditional biomass use to modern applications, including modern cooking stoves. Direct use from production of liquid transportation fuels would account for around one third, followed by industrial applications and conversion into electricity and district heat.

Finally significant synergies exist between energy efficiency and renewable energy. In fact energy efficiency contributes 0.35% points to the overall growth of renewables. The reason is that the same absolute amount of renewable energy yields a higher renewable energy share, if energy demand growth is diminished because of energy efficiency.

As for energy intensity, the annual gain has jumped from an average of 1.3% between 1990 and 2010 to 2.2% for the period 2014–2016, whole falling to 1.7% in 2017 [12]. Technical efficiency gains can account for about 70% of the incremental improvement from 1.8% per year in the Reference Case to around 2.8% on average for the period until 2050 [28,54]. Renewables can contribute to the remainder 30% of the energy intensity improvements between now and 2050, for instance through renewables-based electrification for heating and cooking or 100% efficient solar PV and wind power compared to 30–40% efficient coal power generation (Fig. 5). Fig. 5 excludes improvements in structural changes, as for example transport-mode shift from private cars to public transport or bicycles. Therefore the energy efficiency decarbonisation potential can be even higher. Examples of such shifts include for example the high speed train connections in France and elsewhere that have cut down significantly in short and medium range air traffic. The development of metro systems in urban centres, for example in China, is another example of shifts towards public transportation. In a US context, electric scooters have been deployed widely.

The synergies between energy efficiency and renewables are evident when energy sectors are coupled, as it the case of renewable power and transport, as electrification of transport represents close to a-quarter of the improvements in energy intensity between the Reference Case and the REmap Case in 2050.

Electrification emerges as a key area that offers synergies between efficiency and renewables as well as for coupling sectors. Latter is particularly important for integration of variable renewable energy sources in the power system (see Box 1). In each end-use sector, there are applications where renewable electricity can substitute direct use of fossil fuels, often with substantial efficiency gains. An electric vehicle is typically three times as efficient as a comparable ICE. In the REmap Case, the share of electricity in total final energy consumption increases from around 20% in 2015 to 40% in 2050. Enabling technologies such as EVs have seen breakthroughs with many GW-scale battery factories coming online in China, the United States and elsewhere [55]. This type of sector coupling requires smart charging and smart grids, to facilitate VRE integration and ensure sufficient flexibility in the power system operation. Heat pumps can play a similarly important role for buildings. Ultimately, electrification would slow down the growth of final and primary energy demand because of higher variable renewable energy shares in power generation (that are accounted with 100% efficiency) and higher efficiency of final energy use).

In IRENA analysis, ambitious decarbonisation can see the share of electricity in all of transport sector energy rise from just above 1% in 2015 to 33% in 2050, 85% of which is renewable, with over one billion electric vehicles on the road, which is equivalent to today's total passenger vehicles fleet. Building share of electricity could reach about 56% by 2050 under IRENA's REmap Case, with a 10x increase in electric heat pump units (to over 250 million) and electric cooking technologies able to cut the energy demand of cooking by three to five times. Industry share of electricity could reach about 42% by 2050 under IRENA's REmap Case, with a 80-fold increase in electric heat pump units to over 80 million units, which would meet about 7% of global industrial heat demand.

Up to 20% of the energy intensity improvements can be attributed to the increased use of renewable energy (Fig. 5). Hydro, solar PV and

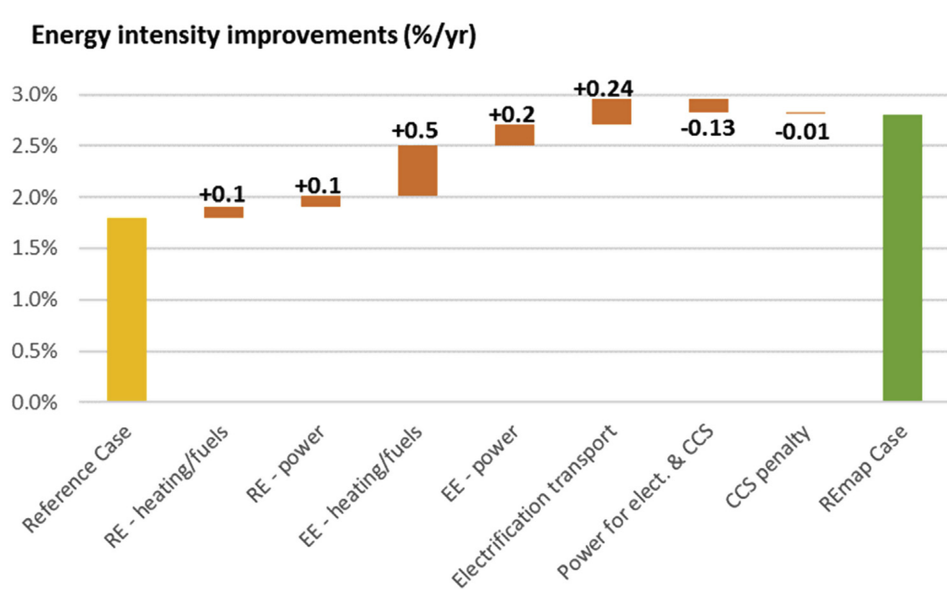

Fig. 5. Energy intensity by factor in the Reference Case and Remap, 2050.
Note: EE – power refers to efficiency of electricity use.
Source: Based on [27].

Box 1
EV charging impact on Hamburg distribution grid

A mass adoption of EVs has an impact on the electricity infrastructure. Bottlenecks or grid congestions may occur when the existing transmission and/or distribution lines, or transformers, are unable to accommodate all required load during periods of high demand -such as simultaneous charging of thousands of EV- or during emergency load conditions, such as when an adjacent line is taken out of service.

Hamburg is at present 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 expects to install 1000 public charging points by the beginning of 2019. Electrification of public buses and EVs growth are the most critical drivers in the load development in the city. The majority of EVs will be in the suburbs where, in Hamburg's case, the grid is weaker (Pfarrherr, 2018).

Local DSO, Stromnetz Hamburg ran a load development analysis to identify critical situations for uncontrolled charging of EVs with charging point load of 11 kW and 22 kW. Stromnetz Hamburg assessed two scenarios:

- *Scenario 1:* 3% EV share corresponding to 20.000 EVs loading in private infrastructure will cause 200 bottlenecks. This would cause issues in the low voltage grid.
- *Scenario 2:* 9% EV share corresponding to 60.000 EVs loading in private infrastructure will cause bottlenecks in 800 out of 6,000, or 15% of the feeders in the city's distribution network (Pfarrherr, 2018).

To avoid these critical situations, Stromnetz Hamburg assessed the investment needs for reinforcing the local grids. Scenario 2 would require reinforcing approximately 10,000 km of 0.4 kV cable lines resulting in an investment of at least EUR 20 million (around EUR 200/meter of cable). This investment estimate does not include the replacement if overloaded transformers, which would be quite significant as well. In addition to the costs for reinforcing the local grids, one more challenge, perhaps more complex than the monetary implications, would be finding the workforce capacity to reinforce the grid, to obtain the permits, and the public acceptance to works that require closing many roads in the city to change underground cables for periods of several months or even years.

Given the magnitude of the challenge and costs needed to reinforce the local grids, Stromnetz Hamburg is exploring an alternative solution to address the problem. For that, a smart solution is being tested, which includes:

- Every household with a charging point has to report it to the DSO. This information has not been required yet.
- Measure the loads on the 0.4 kV cables, which at the moment is not required in the city of Hamburg either. This will permit to identify the bottleneck problem as soon as it emerges
- A real-time communication system that enables the DSO 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 A to 8 A, allowing EVs to be charged but in a longer period of time.

30 control and monitoring units help to anticipate congestion issues and plan the network based on the load profiles. A strong IT and communications infrastructure is being established between the Charging Point Operators and the grid.

A full implementation would require the engagement of consumers as well as the more than 400 electricity retailers in the City of Hamburg to use an e.g. Time-of-Use price incentive to allow the DSO to control their charging points based on the local grid needs. This case shows not only the impact that EVs may have on local grids, but the potential solutions to address it that may require a combination of digital technologies, new business models and market regulation to engage all the needed actors.

wind power are generated with 100% efficiency. When these renewables replace fossil fuel power generation with 25–60% efficiency, the efficiency improves. Also net efficiency gains are created through solar heating systems offering 100% efficiency and some biofuel-fired boilers and furnaces that are more efficient than their fossil fuel equivalents.

Finally, electrification with renewable power accounts for another 24% of the energy efficiency gain. In total 20–44% of the energy intensity improvement can be attributed to renewables. However, it can be debated whether this should be attributed to efficiency or renewables since technologies that fall into this category provide benefits to both sides. For instance a heat pump or an electric vehicle is much more efficient than an energy device that uses fossil fuels to deliver the same service. Provided that these electricity-based technologies are sourced with renewable power, they increase the renewable energy share in both the power sector and the sectors they belong to, heating or transport.

7. Innovation and R&D to enable the energy transition

As shown in Fig. 2, renewable energy share would be equivalent to two-thirds of the total global primary energy supply in 2050 according to the REmap Case. This would represent a significant acceleration compared to the Reference Case that would only yield 24% renewable energy by 2050. Technologies are available today to significantly advance the transition till 2030, however, according to the REmap analysis around one-third of all total primary energy would still be sourced from non-renewable energy sources in 2050. For these applications, solutions are either not yet available at scale or their costs are too high. Therefore, there are still major technology challenges to complete the transition into an energy supply that is based on renewables by the middle of the century. Innovation has historically been and will continue to be sitting in the driving seat of this transition. There are two important next steps to enable this: (i) for those applications where technology solutions exist, the important next step is to enabling frameworks are needed to scale up their deployment, and (ii) for applications where solutions are today either at their early stage of commercialisation or do not exist, the next step is to foster technology innovation, along with enabling policy, social and financial measures, to rapidly bring the emerging clean technologies to the marketplace [32,56].

Technology breakthroughs can be reflected in patent filings, so IRENA has developed a database of International Standards and Patents In Renewable Energy (INSPIRE) to track them. The patterns of patent filing over time offer interesting insights into where renewable energy technologies are headed [57]. The data show for example a gradual shift in patenting activity over recent years, away from supply side to sector coupling.

The sectors with the most significant challenges are energy-intensive industry sectors such as iron and steel making, chemical and petrochemical, and cement making. It also includes road freight transport, shipping and aviation [40,58–61]. These are all end-use sectors where addressing the innovation challenge to improve existing technologies, develop breakthroughs and major shifts is most urgent. There is an urgent need to act today to change this situation for these sectors, as a full-scale energy transition takes decades due to the different technology development steps and the long lifespans of the existing capital stock. In these sectors, biomass could play a role as the only renewable energy carrier with carbon content (for hydrocarbon products and chemical reactions) that can be stored with a high energy density (for transport) [62–64]. But this is not an obvious transition: the economics are not attractive today and sustainable, affordable and reliable feedstock supply is a major issue. According to a recent study, supplying the volume of biomass like estimates here for the iron and steel, cement and chemical and petrochemical sectors alone would require the mobilisation of around 1000 million tonnes of feedstock. This compares with today's feedstock demand for all types of modern heating, transport and electricity applications from biomass worldwide. For the United States alone, the biomass feedstock potential is a one billion tons (ORNL, 2016), global potentials are at least four times higher.

Ramping up supply to these levels is challenging and would still remain insufficient to decarbonise the industry sector, thereby requiring options like electrification, renewable hydrogen and CCS [88]. Some efforts are also still focusing on hydrogen for the transport sector or its derivatives such as formic acid [63,65] or ammonia [64,66]. Electrification on the other hand is a limited option for those sectors, as technologies that use electricity coupled with renewable power may not always provide a low-carbon solution.

Infrastructure will be needed to integrate technologies. These will include smart charging networks for electric vehicles; new low-losses cross-border electricity interconnections; super high-voltage transmission lines – possibly underground - to dispatch massive amounts of power from areas with abundant wind or solar resources to demand centres; district heating networks; and biomass feedstock management strategies. Without this infrastructure, the commercialisation and mass deployment of low-carbon technologies for the energy transition will not occur on time. The coupling of different energy applications also creates opportunities for the integration of clean technologies. An example is the power and transport sectors through electric vehicles. Today, especially interesting opportunities exist at the crossroads of ICT and energy technology, as well as in the areas of new high-performance materials, new battery formulations, and other challenges of materials science [56]. New business models are emerging, notably elated to electricity markets. This includes virtual power plants, aggregators for electricity storage services. They need to be combined with new market designs with more precise time and place of use pricing for consumers, new operational practices, and new smart grid technologies (Fig. 6). Around thirty types of innovations have been identified, covering several hundred discrete cases. The most successful cases usually deploy several innovations at once [67].

Ultimately the benefits of energy transition will by far exceed the cost, but todays markets are heavily distorted in favour of the incumbents. This transition will depend on the creation of the right policy signals. This includes removal of market distortions but also strengthened support for innovation and technology.

For those end-use sectors with no clear technology solutions commercially available, basic science research and engineering efforts are called for. Innovation requires funding; and over the past seven years, government and corporate investment in clean energy technology research and development (R&D) has been stagnant. While investment volumes for renewable energy have risen to around USD 300 billion per year, R&D expenditures for clean energy amount to USD 10 billion per year. The 3% R&D investment share is well below other innovative sectors such as ICT and vehicle manufacturing. Additional R&D efforts will result in additional low-carbon technology solutions, further bring down the costs technologies and thereby decrease the overall costs of the energy transition. Today most R&D investment flows into the power sector (such as solar and wind) rather than into end-use technologies such as bioenergy and solar thermal, where the urgency is higher.

Innovation can be strengthened by global cooperation. Recent international initiatives have been established with the aim of fostering R &D and innovation for clean energy technologies, including Clean Energy Ministerial, the Breakthrough Energy Coalition and Mission Innovation, an international initiative announced at the COP21 that sets a target of doubling government R&D investment in clean energy technologies [68]. These initiatives build on clusters of priority areas which are all relevant to accelerating the energy transition plan outlined in this paper. Mission Innovation has defined eight challenges to date. Smart grids, sustainable biofuels, offgrid, heating and cooling and renewable and clean hydrogen are all directly relevant to the main technology deployment needs that have been identified in REmap. Direct sunlight conversion, materials are the two other ongoing challenges. To date efforts are mainly aimed at information exchange but some bilateral cooperation programmes have started to emerge, and public R&D budgets have risen in participating countries.

Energy transition will require a holistic innovation approach tailored to the needs of each renewable energy and energy efficiency technology since a wide range of approaches will be required across all sectors of the energy system. While aiming at increasing investment in R&D for low-carbon technologies benefits the energy transition, more attention can be paid to monitoring and verifying that those investments have the desired impact and R&D budgets and priorities are impact driven.

While many innovative solutions exist on a lab or pilot scale, upscaling of economically viable robust solutions is often still a challenge. Governments have an important role to play during the early stages of this transition as these solutions struggle to reach scale and descend on the learning cost curve.

Furthermore, the innovation challenge goes beyond traditional government energy R&D. The sectors with the lowest progress in innovation for decarbonisation, such as heavy industry as well as freight transport and aviation, are those where proper policy incentives and long-term perspectives are lacking [61]. This challenge cannot be addressed by increased R&D investment alone. Innovation also entails a fundamental rethink of production processes and energy technologies required for the energy transition. While there are add-on solutions, such as the use of CCS for smokestack emissions, these approaches are limited in their field of application, and in the foreseeable future they will increase the costs of the energy transition.

8. Conclusions

An increasing number of indicators point to an accelerating energy transition that can have profound implications for energy supply and demand in the coming decades.

As the analysis shows, rapid innovation is taking place that facilitates the ongoing transition through falling costs of renewable technologies and also enabling technologies such as batteries. Along with the new policy imperatives, innovation strengthens the momentum of energy transition. As technology improvements are permanent, they reduce the risk of policy volatility. The progress for solar and wind technology is a prime example that the future can be steered in a certain direction through technology policy.

The share of renewable energy can grow from 15% in 2015 to 63% of total primary energy supply in 2050 as this paper shows. Such renewables growth in combination with higher energy efficiency can provide 94% of the emissions reduction that is needed to stay within the limits of the Paris Climate Agreement. While absolute numbers vary there is consensus across recent scenario studies that renewable energy and energy efficiency is the most feasible direction to meet climate

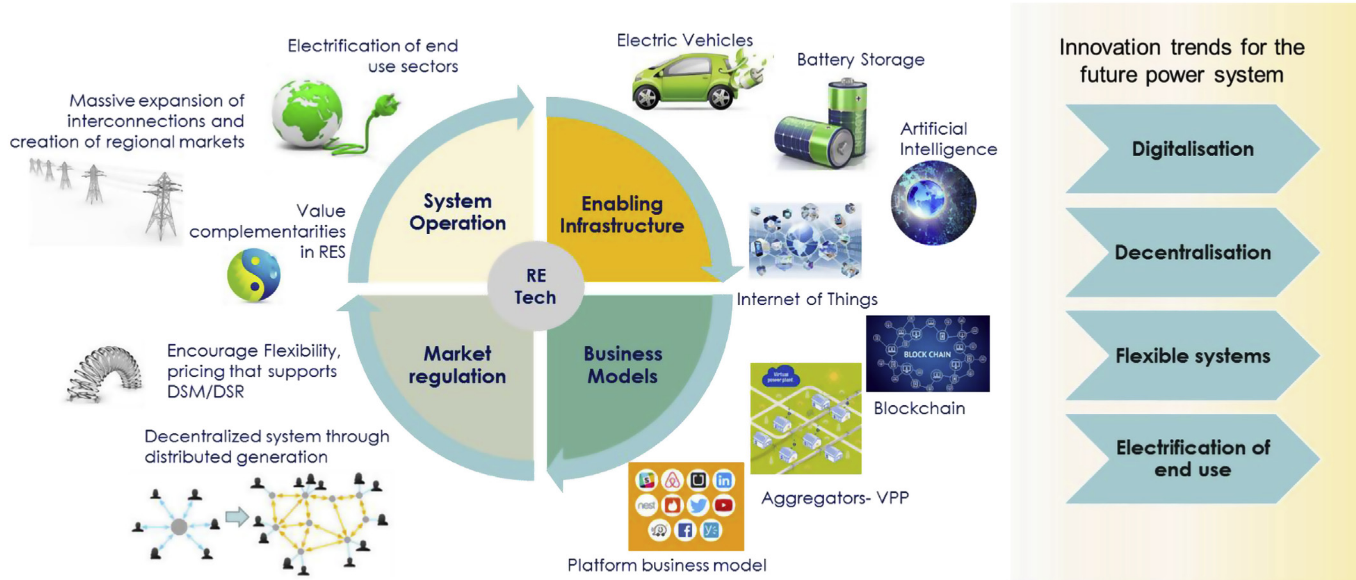

Fig. 6. Power system innovations.
Source: Based on [67].

objectives.

The policy decisions to accelerate energy transition will need to be aligned with the development of enabling infrastructure. Infrastructure planning early on will be of paramount importance because of its carbon lock-in effect due to long life span and inertia. More attention is needed for emerging infrastructure issues such as smart charging of EVs, distribution grid reinforcements and the role of shifting demand and smart grids. Financing for both energy generation capacity and infrastructure will also be crucial through carefully drafted policies that create a credible, predictable and transparent investment environment. There is a need to mobilise public and private sector resources and develop innovative financing models that can mitigate investment risks.

However, the speed of energy transition is not commensurate with the agreed sustainable development goals. Scenario studies suggest that especially for renewable energy more efforts are needed. A six-fold acceleration is needed of renewables growth, compared to Business-*as*-Usual. Wind, solar PV, modern bioenergy and solar thermal can contribute the bulk of renewables growth on the supply side. More energy efficiency tempers demand growth and therefore contributes about one quarter to the overall growth of renewables share in total final energy consumption. At the same time 20–44% of the energy intensity improvement can be attributed to the growth of renewable energy. These numbers indicate that important synergies exist between higher energy efficiency and higher shares of renewable energy, both solutions should therefore be pursued jointly.

Renewable power would account for 58% of total renewables deployment in 2050. Variable renewable power would account for 60% of total power generation, up from around 10% today. Such high shares of variable renewable power generation require a paradigm shift in the power sector. Best practice in leading countries shows that such systems can be operated successfully, though changes are needed. The systems flexibility that is required can only be mobilized through a systemic approach that mobilizes all types of innovations. Technology innovation must be combined with new market designs and business models that build on the new technology characteristics.

In certain end use sectors, new scalable and affordable solutions will be needed. Sector coupling, notably tailored electrification of end-use sectors will play an increasingly important role. The electricity share in final energy use will more than double to a level of 40%–50%. Due to the high efficiency of electricity use, the share of useful energy is even higher. Electric vehicles are a prime example of such transition, with profound effects on the way that transportation is organised and all its developmental consequences. The share of electricity or electricity derivatives such as hydrogen must grow substantially in the final energy use of buildings, industry and transport. A significant part of transport and industry challenge is largely ignored in the current international debate. Significant uncertainty remains what solutions will prevail.

The potential of this energy transition is not yet fully appreciated by many decision makers and analysts. Yet it is critical to the achievement many of the sustainable development goals and it offers a prospect of just and fair growth, that would result in USD 27 trillion additional investments by 2050, 1% higher GDP, 0.15% more jobs and environmental benefits that dwarf the increased cost. The socioeconomic benefits are substantial and provide a strong policy rationale.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Annex 1

REmap (Renewable Energy Roadmap) is IRENA's global energy modelling framework. Modelling is carried out at the level of countries. The REmap approach involves a techno-economic assessment of the energy system developments for energy supply and demand by energy transformation (power and district heat generation) and end-use sectors (residential and service buildings, industry and transport), and for each energy carrier in the time period between 2010 and 2050. REmap allows for assessment of the accelerated potential of low-carbon technologies, and their subsequent effects on costs, externalities (human health and climate change), investments, and the emissions of CO_2 and air pollutants.

The REmap analyses assume two trajectories of energy system development:

- The Reference Case is based on national energy plans. It represents the energy use developments based on policies in place or under consideration. The Reference Case also includes any expected developments in energy efficiency improvement. The availability of country data for national energy plans varies, so data gaps are filled

based on similar reputable sources that forecast expected developments for the energy demand for a country, and IRENA worked with the national experts of countries in developing a Reference Case. Any missing datasets, for instance for end-use sector demand, has been completed with information from literature and commercial databases.
- The REmap Case is a decarbonisation scenario based on the REmap technology options assessment approach. The REmap Case explores low-carbon technology pathways to achieve a carbon budget in line with the Paris Agreement to limit the global average surface temperature increase to below 2 °C with a 66% probability.

The standard IRENA REmap analysis is for the year 2030. In developing the 2030 country analyses, IRENA engages nominated experts from each country who review and provide feedback on the analysis and findings. As of early 2017, these analyses cover 70 countries, representing 90% of global energy use. For the purpose of the decarbonisation analysis, IRENA has expanded the assessment to the year 2050.

The bottom-up country and sectoral analysis is carried out based on the REmap tool that was internally developed by the IRENA. This is a relatively simple accounting framework. The aim of this tool is not to apply complex models or sophisticated tools to assess the potential, but to facilitate an open framework with countries to aggregate the national renewable energy plans to develop the Reference Case and the REmap Case. However, this tool does not explicitly take into account the inter-temporal dynamics and inertia that determine deployment, system constraints, path dependencies, competition for resources, etc.

The bottom-up approach is complemented with a top-down global demand assessment done at the sectoral and sub-sectoral level for end uses with high technology resolution. For the top-down analysis, activity-level growth rates were estimated for the period between 2015 and 2050. Each end-use sector is divided into the main energy-consuming applications – for example, steel production. For energy efficiency and materials efficiency, the analysis combines this with technology options to reduce energy use for a given level of production. The technology potential of renewable energy also is analysed at the sub-sectoral level – for example, the potential of a renewable energy technology to provide water heating in the building sector. This potential of the relevant low-carbon technologies for each application was estimated based on market growth rates, resource availability and other constraints. A combination of both an iterative bottom-up country approach and a top-down sectoral approach allows for better representation of country plans in energy use forecasts, but also for a more cohesive global set of technology development assumptions and costs relating to decarbonisation technologies.

The REmap Case gives preference to renewable energy and energy efficiency, technologies and sector-coupling solutions, such as EVs, district heating and cooling, heat pumps, etc., ahead of other low-carbon technology options such as CCS and nuclear energy. Technologies that were considered in the REmap Case include the following:

- Renewable energy technologies for energy
- Renewable energy feedstocks for production of chemicals and polymers
- Energy efficiency measures, including electrification
- Material efficiency technologies such as recycling
- CCS for industry

More information about IRENA's REmap data and methodology can be found at: www.irena.org/remap.

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