ENVT-3065 sustainability and challenges

Renewable energy systems

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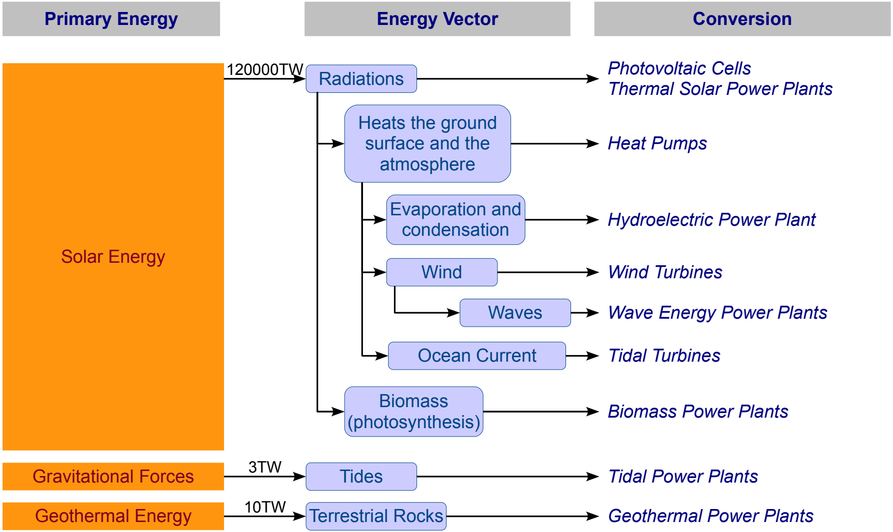
Adapted from: Sylvain Quoilin, *Duurzame energiesystemen* (B-KUL-ZA0039), Lecture Slides, KU Leuven, 2020

Renewable Energy Systems

Renewable Energy in the EU

Overview of Renewable Energy sources



Question

A flat surface perpendicular to the sunlight and located at the limit of the terrestrial atmosphere receives, on average:

$$C^* = 1366\,\mathrm{W\,m^{-2}} \pm 3\,\%$$

According to the IEA, the yearly world primary energy supply was 14 282 Mtoe (= 166099 TWh) in 2018. Calculate how long it takes for the earth to receive this amount of energy from the sun.

Renewable share in the EU energy system

Offshore/Onshore Wind

Solar PV

Hydro

Biomass & Waste

Concentrating solar

Solar thermal

Ocean

Geothermal

Biogas

Biofuels

Renewable share in the EU energy system

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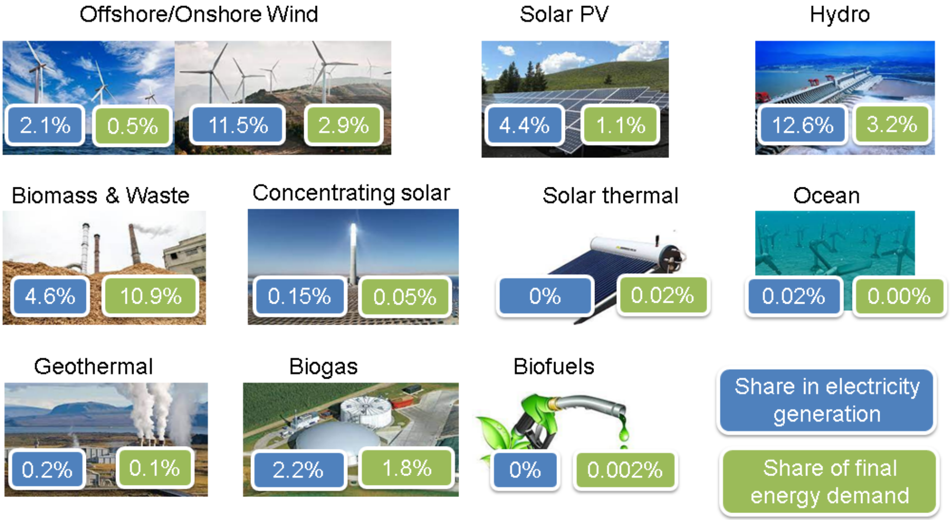
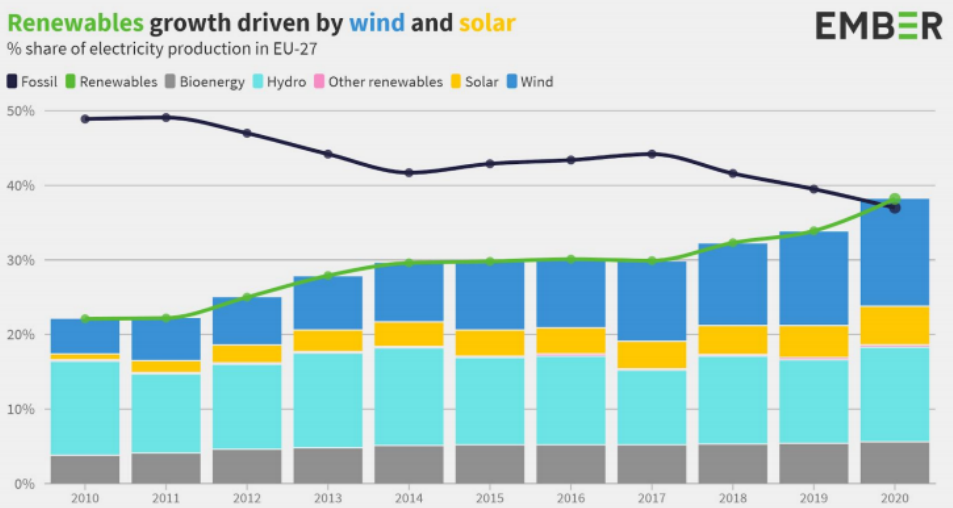
Share in electricity generation

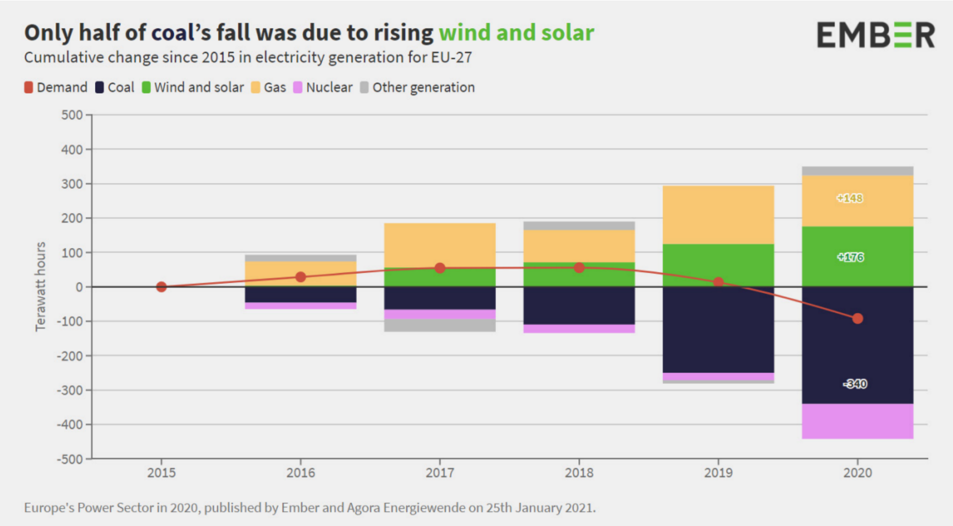
Renewable share in the EU energy system



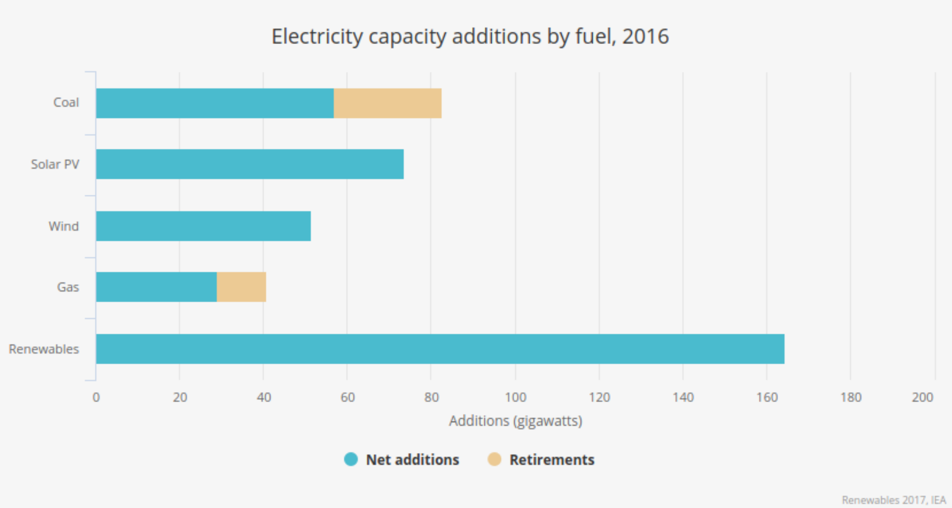
Renewables overtook fossil fuels as EU's main power source in 2020



EU electricity capacity addition

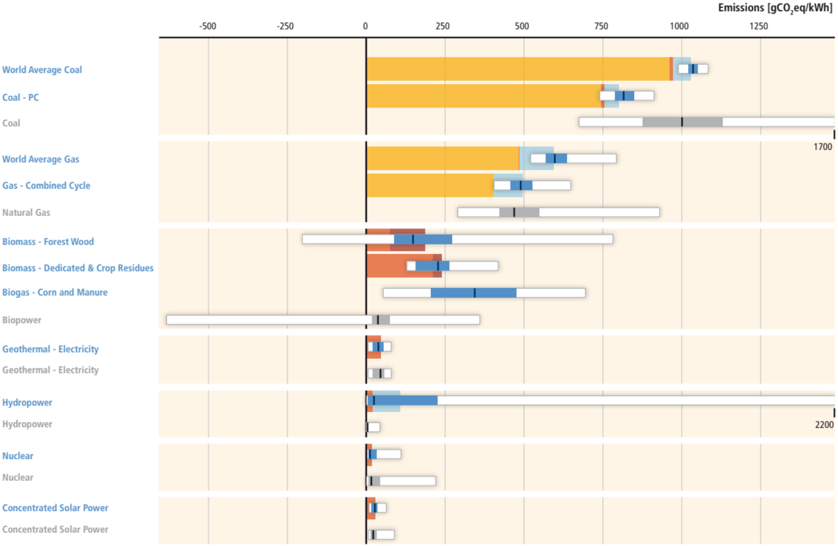


Global electricity capacity addition



Benefits and disadvantages of renewables

Benefits of renewables (1): Carbon Footprint



Benefits of renewables (1): Carbon Footprint

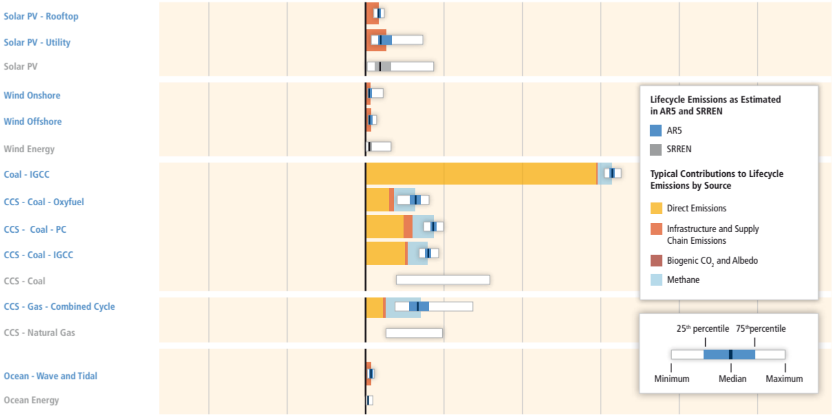


Figure: Lifecycle greenhouse gas emissions (source: IPCC AR5 WG3, 2018)

Question

If the life cycle emission combined cycle gas turbine are $500 kg_{CO2}/MWh$ and those of coal power plant are $1000 kg_{CO2}/MWh$ (cfr previous slides), which percentage of gas leakage would bring the carbon footprint of the gas power plant to the level of the coal power plant?
NB: to simplify, we can assume that natural gas is composed exclusively of methane. The 20-years Global Warming Potential of methane is given in the table below.

Name	Formula	Lifetime (yr)	Radiative efficiency (W m^{-2} ppb^{-1})	AGWP 20 (pW m^{-2} yr kg^{-1})	GWP 20	AGWP 100 (pW m^{-2} yr kg^{-1})	GWP 100	AGWP 500 (pW m^{-2} yr kg^{-1})	GWP 500	AGTP 50 (pW m^{-2} yr kg^{-1})	GTP 50	AGTP 100 (pW m^{-2} yr kg^{-1})	GTP 100
Major Greenhouse Gases													
Carbon dioxide	CO_2		1.33×10^{-5}	0.0243	1	0.0895	1	0.314	1	0.000428	1	0.000395	1
Methane	CH_4	11.8	0.000388	1.98	81.2	2.49	27.9	2.5	7.95	0.00473	11	0.00212	5.38
Nitrous oxide	N_2O	109	0.0032	6.65	273	24.5	273	40.7	130	0.124	290	0.0919	233

Figure: Tables of greenhouse gas metrics (source: IPCC AR6 Table 7 SM7, 2021)

Current debate on leakage rates

Jamie Henn @jamieclimate · Oct 20, 2020

If 3.2% of methane leaks during production, it makes **gas** worse than coal for the climate.

A study found the **leakage rate** in the Permian Basin, the largest oil & **gas** field in the US, is 3.7%.

Gas is a bridge...to hell.

insideclimatenews.org

Super-Polluting Methane Emissions Twice Federal Estimates in Permia...

Methane emissions from the Permian basin of West Texas and southeastern New Mexico, one of the largest oil-producing regions in ...

Matt McCarville @Matt_McCarville · Oct 15, 2019

The overall U.S. methane leakage rate, from shale gas, which includes leaks from drilling and from pipe transmission and distribution to electric power plants, industrial facilities, homes, and other buildings, may be ~3.5% (@howarth_cornell, 2019). 3/11

1 1

Kees van der Leun @Sustainable2050 · Jun 21, 2018

Since methane is a much stronger greenhouse **gas** than CO2, such a 2.3% **leakage rate** would mean natural **gas** loses roughly half of its greenhouse **gas** advantage over coal.

Jilles van den Beukel @JillesAppelscha · Jun 21, 2018

New study published in Science estimates methane emissions from the U.S. oil and gas supply chain at 2.3% of US gas production (about 60% higher than estimated by the EPA). science.sciencemag.org/content/early/...

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Benefits of renewables (2): Worldwide potential

World primary energy consumption: 500 EJ

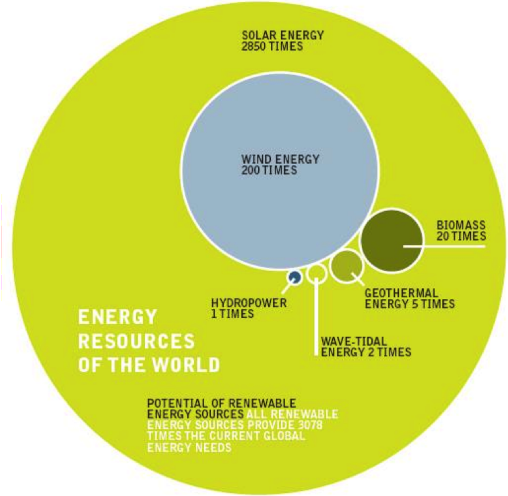
Published estimates for RE global technical potential.

Study and year of estimate	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Electricity	Heat
Hafele (1981) ('*realizable*' *potential*)	NA	95 (*32*)	33 (*16*)	95 (*47*)	189 (*161*)	3.2 (*3.2*)	47 (*16*)
Lightfoot/Green (2002) (*range of values*)	163 (*118–206*)	72 (*48–72*)	0 (*1.8–3.6*)	19 (*16–19*)	539 (*373–772*)	1.5 (*1.5*)	NA (*NA*)
Gross et al. (2003)	43–144	72–144[a]	7–14[b]	NA	29–90	NA	14–144[c]
Sims et al. (2007)	1650	600	7	62	250	NA	5000[c]
Field et al. (2008)	NA	NA	NA	NA	27	NA	NA
Resch et al. (2008)	1600	600	NA	50	250	NA	5000[c]
Klimenko et al. (2009) ('*economic*' *potential*)	2592 (*19*)	191 (*8.6*)	22 (*2.2*)	54 (*29*)	NA (*NA*)	22 (*3.6*)	NA (*NA*)
Cho (2010)	>1577	631	NA	50	284	NA	120
Tomabechi (2010)[d]	1600	700	11	59	200	NA	310,000[c]
WEC (2010)	NA	NA	7.6[b]	57.4	50–1500	1.1–4.4	140
All studies range	118–2592	48–600	1.8–33	50–95	27–1500	1.1–22	14–310,000
Earth energy flows	3,900,000	28,400	700	130–160	3000	1300	

Source: [14,18,25–33].
NA: not available.
[a] Onshore only.
[b] Wave only.
[c] Includes both electricity and direct heat.
[d] 'Usable maximum'.

Figure: Worldwide renewable potential studies (in EJ)

Benefits of renewables (2): Worldwide potential



source WBGU

THE AMOUNT OF POWER THAT CAN BE ACCESSED WITH CURRENT TECHNOLOGIES SUPPLIES A TOTAL OF 5.9 TIMES THE GLOBAL DEMAND FOR POWER

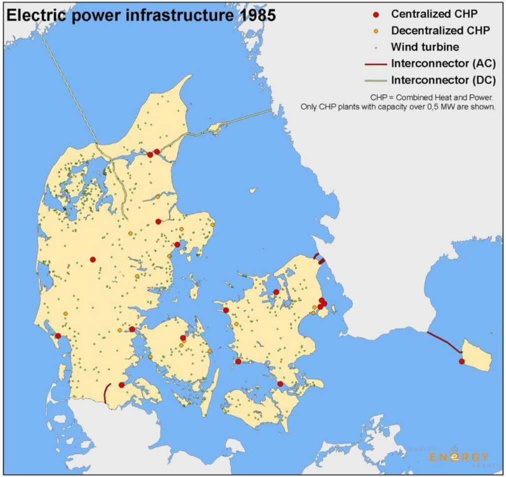
Sun	3.8 times
Geothermal heat	1 time
Wind	0.5 times
Biomass	0.4 times
Hydrodynamic power	0.15 times
Ocean power	0.05 times

source DR. JOACHIM NITSCH

Benefits of renewables (2): Worldwide potential

- Careful with potentials! They are only estimates and are hard to evaluate.
- Example of the 2009 influential book "Energy without the hot air" by David MacKay:
  - The book uses an estimate of 53 PTWh for the wind potential
  - The solar PV potential is discarded because of its excessive price
  - The book concludes that the renewable potential is insufficient for a "post-European consumption" of 80 kWh/pers/day.
- However:
  - Only 8 years later, NREL re-assessed the global wind potential and obtained a number of 875 PWh, 16 times higher than MacKay's estimate. (source: NREL, *An improved global wind resource estimate for integrated assessment models*, 2017)
  - The potential for solar is known to be orders of magnitude higher than the demand
  - These difference are explained by technical progress, more refined estimates, costs declines, ...
  - They completely invalidate the 2009 conclusions

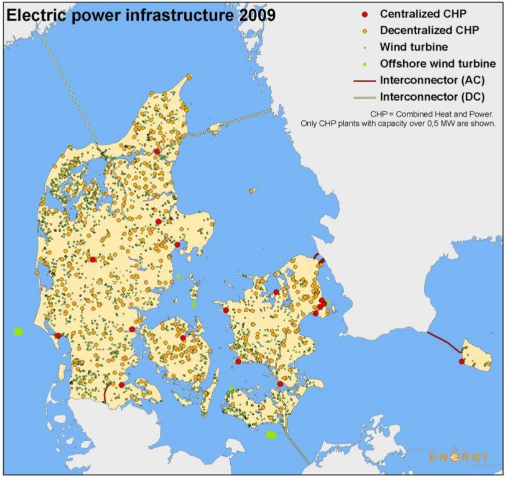
Benefits of renewables (3): Diversification



Denmark: -20% CO_2 emissions thanks to District heating and CHP

- Insulation
- CHP (now 53% of the electricity)
- Wind power

Benefits of renewables (3): Diversification



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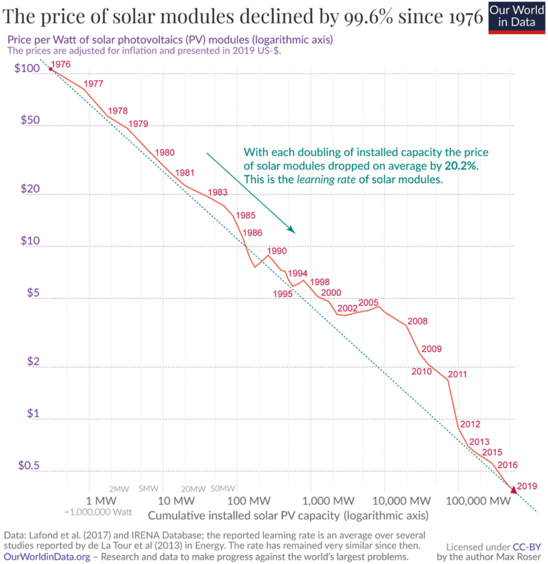
Benefits of renewables (4): Learning curve



Benefits of renewables (4): Learning curve

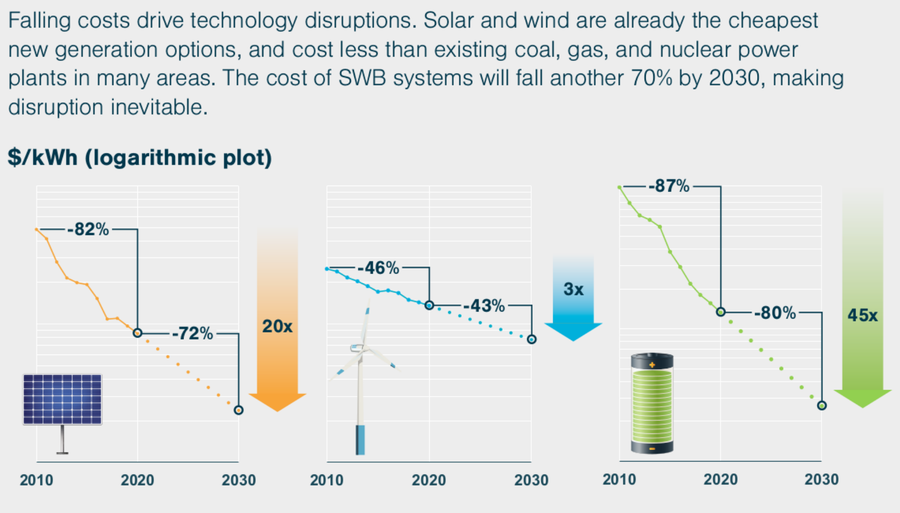


Figure: Source: RethinkX (2020), Rethinking Energy 2020-2030

Benefits of renewables (5): Jobs and macroeconomic insulation

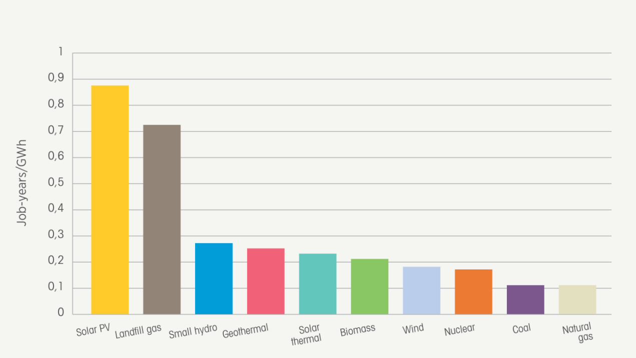


Figure: Renewables are more work-intensive than conventional generation technologies

Benefits of renewables (5): Jobs

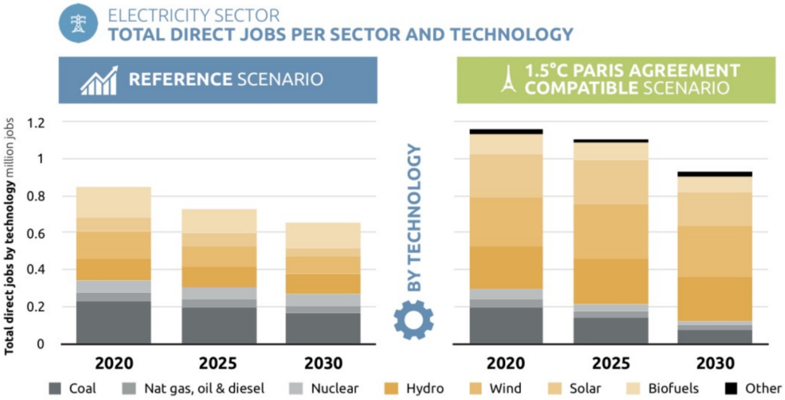
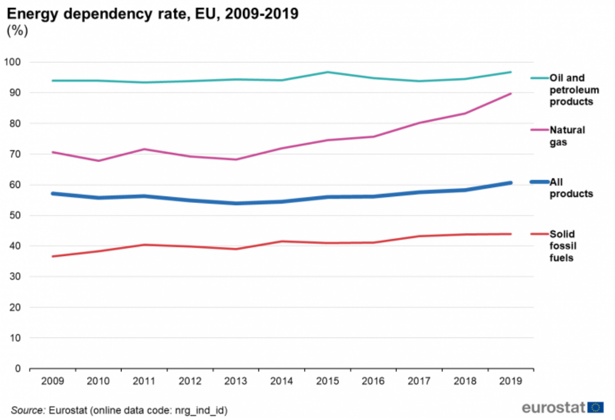


Figure: Total direct jobs per employment sector and total direct jobs per generation technology for the reference scenario (graphs on left) and the 1.5°C Paris Agreement compatible scenario (graphs on right) for the EU electricity supply sector. Note: ‘other’ comprises geothermal, marine and waste. Source: Climate Action Tracker, 2018

Benefits of renewables (5): Macroeconomic insulation

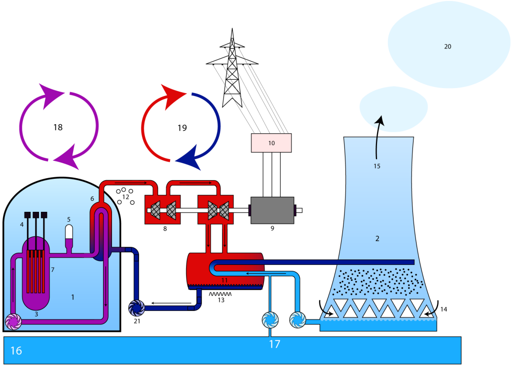
EU is highly dependent on foreign countries in the energy sector



- More than half (60.7 %) of the EU's gross available energy in 2019 came from imported fossil fuel sources.
- EU's energy import bill reached €331 billion EUR in 2018, more than 2% of EU GDP

Benefits of renewables (6): Water

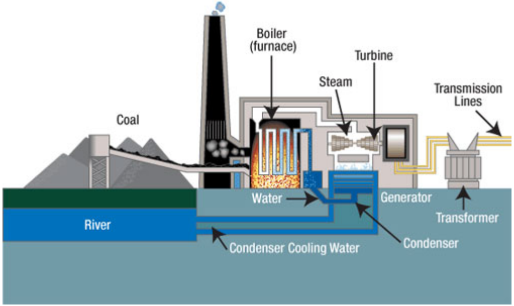
First possibility: indirect, wet power plant cooling



- Significant water consumption (withdrawal)
- Evaporated in the cooling tower

Benefits of renewables (6): Water

Second possibility: direct power plant cooling



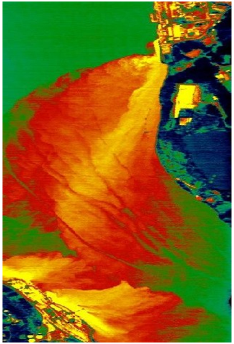
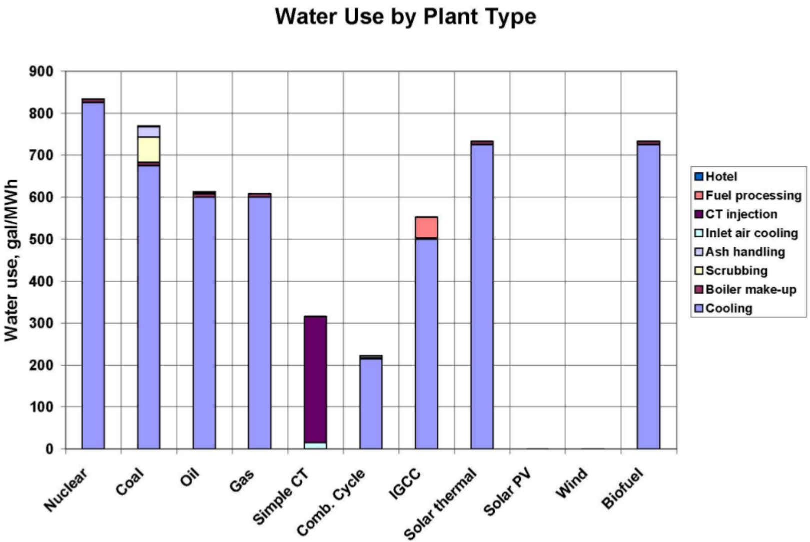


Figure: Thermal pollution in the Hudson River downstream of the Indian Point nuclear power plant, New York

- High thermal pollution
- High water withdrawal
- But no water consumption

Benefits of renewables (6): Water



Benefits of renewables (7): Accidents

- Large-scale technologies can cause huge and widespread damages
- Ex:
  - Chernobyl
  - Fukushima
  - BP spill in the gulf of Mexico
- Small scale often means less impact if something goes wrong

Benefits of renewables (8): Cost?

In the past, renewables have been heavily subsidized. However, due to the rapidly falling prices of wind turbines and PV, some technologies are now more cost-effective than fossil-fuel or nuclear generation.

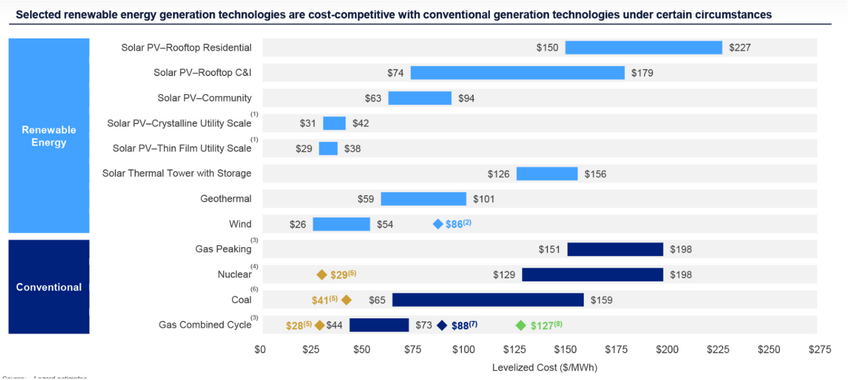


Figure: Unsubsidized Levelized Cost of Energy Comparison (Lazard's estimates for 2020)

BENEFITS OF RENEWABLES (8): EXTERNAL COSTS

In addition, the LCOE does not incorporate the externalities. Externalities are "hidden costs", consequence of the considered activity. They include for example the damages to the environment or the adverse health effects for nearby residents. It is not easy to quantify them, but they are obviously much lower for renewable technologies. The table below provides a summary of different estimations.

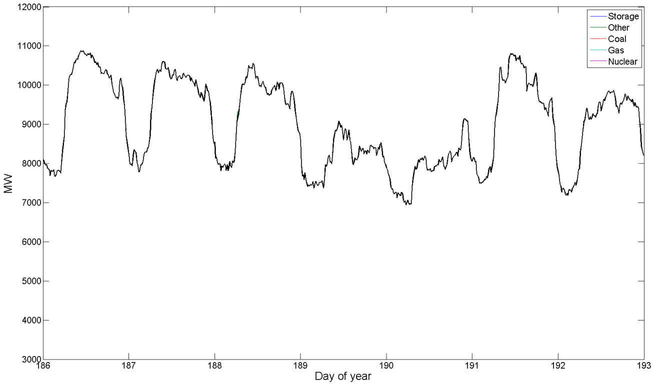
Table B. Summary of 63 External Cost Estimates from the Literature

Cents/kWh	Coal	Oil	Nat. Gas	Nuclear	Hydro	Wind	Solar	Biomass
No. estimates	36	20	31	21	16	18	11	22
Min	0.01	0.04	<0.01	<0.01	0	0	0.00	0
Max	90.61	53.43	17.69	86.23	35.14	1.18	2.94	29.56
Mean	18.75	16.48	6.17	9.53	4.50	0.41	1.12	6.62
Median	8.54	12.19	3.51	1.08	0.43	0.43	1.02	3.59

Source: Sundqvist and Soderholm 2002.

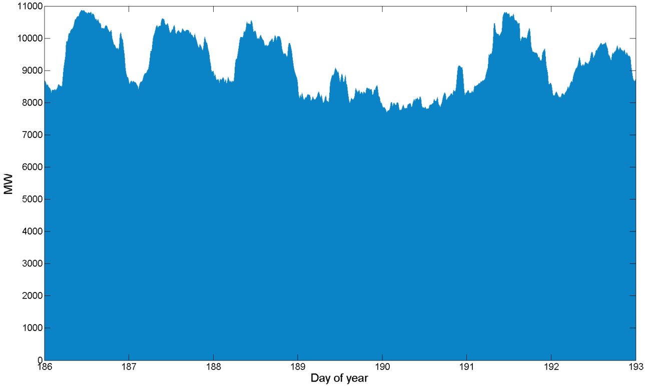
Disadvantages of renewables (1): Variability

Example: The Belgian demand and generation from July 6th to 12th, 2011:



Disadvantages of renewables (1): Variability

If renewables are increased, the variability of the residual load increases:



Wind: 1 GW

PV: 1.6 GW

Disadvantages of renewables (1): Variability

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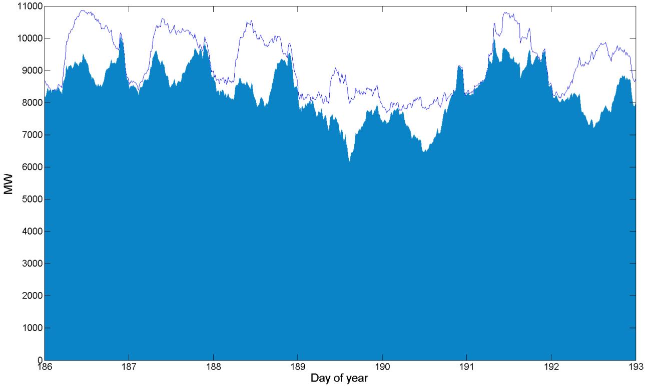
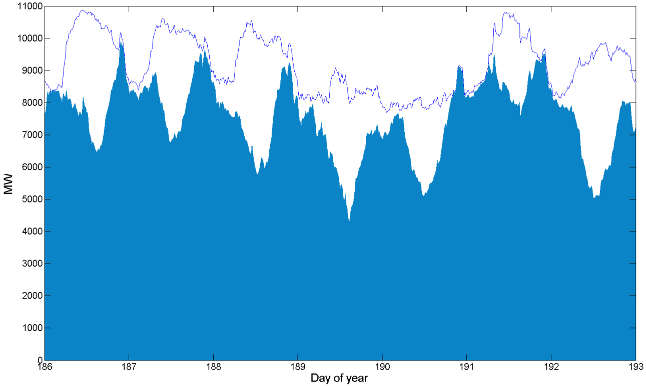


Wind: 2 GW

PV: 3.2 GW

Disadvantages of renewables (1): Variability

If renewables are increased, the variability of the residual load increases:

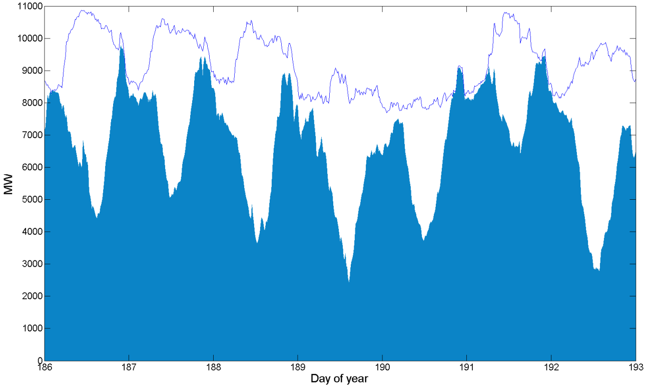


Wind: 3 GW

PV: 4.8 GW

Disadvantages of renewables (1): Variability

If renewables are increased, the variability of the residual load increases:

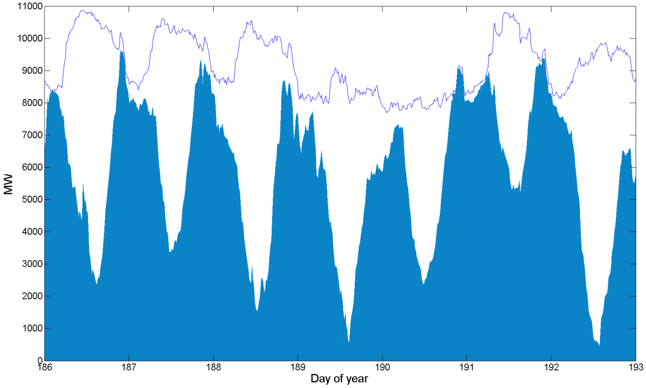


Wind: 4 GW

PV: 6.4 GW

Disadvantages of renewables (1): Variability

If renewables are increased, the variability of the residual load increases:



Wind: 5 GW

PV: 8 GW

DISADVANTAGES OF RENEWABLES (2): EMBEDDED ENERGY

We will consider two concepts/metrics to evaluate the amount of energy required for the production of the renewable technologies themselves (e.g. the wind turbine)

- **Energy return on investment** (EROI, or energy return on energy invested, EROEI) is the ratio of energy returned from energy extraction and production activities compared to the energy invested in those energy gathering processes.

$$EROI = \frac{\text{lifetime energy output}}{\text{Embedded energy}}$$

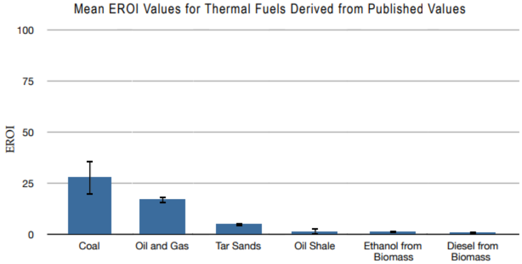
- **Energy Payback Time** (EPBT) is the time it takes for the system to generate the amount of energy equivalent to the primary energy or kWh equivalent that was used to produce the system itself.

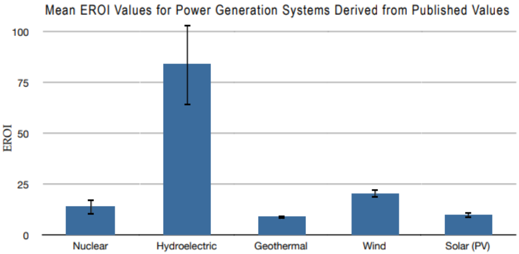
$$EPTB = \frac{\text{Embedded energy}}{\text{Annual energy generated}} = \frac{\text{lifetime}}{\text{EROI}}$$

Disadvantages of renewables (2): Embedded energy

Energy Return on Investment:

- EROI is generally high for renewables.
- For biofuels, there are some cases in which it is lower than one! This bias can be created by poorly designed subsidiation schemes and is obviously problematic.





Source: Lambert et al, EROI of Global Energy Resources Preliminary Status and Trends, 2012

Disadvantages of renewables (2): Embedded energy

Energy Payback Time: example for solar PV

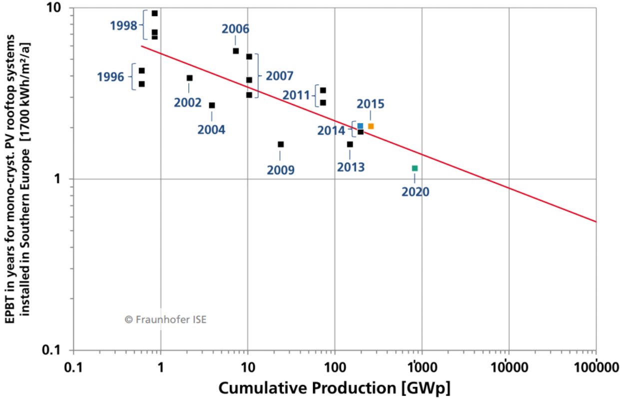


Figure: Fraunhofer Institute for Solar Energy Systems, ISE, PV Report, 2021

Disadvantages of renewables (2): Embedded energy

Energy payback time:

- Highly variable depending on the technology, the location, etc.
- Rule of thumb: 0.5 year for wind, 1 to 1.5 years for PV

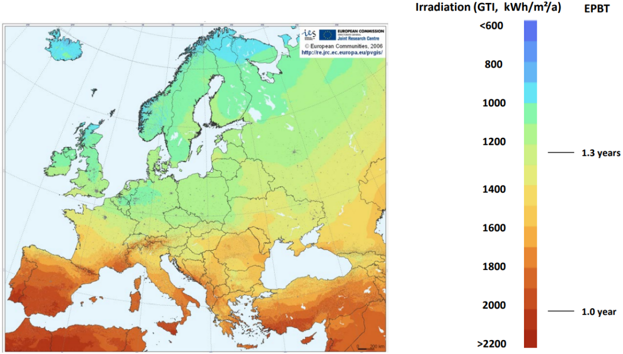
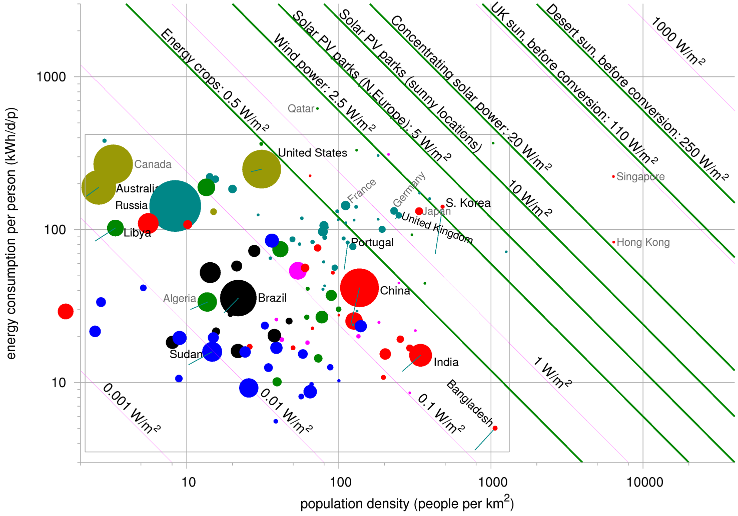


Figure: Fraunhofer Institute for Solar Energy Systems, ISE, PV Report, 2021

Disadvantages of renewables (3): Land use

- Most renewable energy sources "consume" a significant amount of land.
- Exceptions: geothermal, hydro run-of-river
- Expansion potentials are limited by land usage, living areas, conservation areas; potential yearly energy yield at each site is also limited by weather conditions
- A good metrics for land usage is the power density. The **peak power density** (in Wp/m^2) should not be confused with the **average power density** (in W/m^2). The ratio between both is the **Capacity Factor** (CF)
- Land usage should also be considered at the light of alternative activities. For example, agriculture is compatible with wind turbines, and new concepts of agriculture with PV ("agrivoltaics") are appearing.

Disadvantages of renewables (3): Land use



Source: David J C MacKay (2013) Solar energy in the context of energy use, energy transportation and energy storage. Phil Trans R Soc A 371

Disadvantages of renewables (4): Critical materials

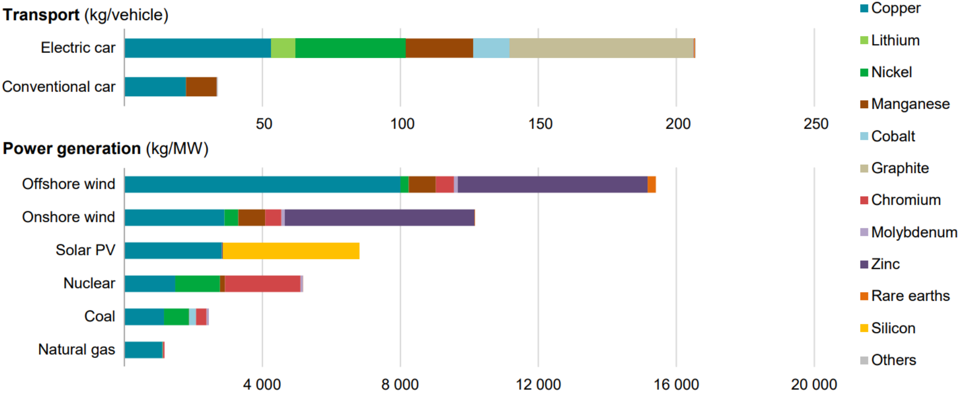


Figure: Minerals used in selected clean energy technologies (Source: IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021)

The rare earth debate

Novethic

"La transition énergétique est la plus fantastique opération de greenwashing de l'Histoire", selon Guillaume Pitron

"La transition énergétique est la plus fantastique opération de greenwashing de l'Histoire", selon Guillaume Pitron. C'est un livre choc sur la...

05 Mar 2018

Libération

Présidentielle Politique International CheckNews Culture Idées et Débats So

Accueil / International

Interview

Métaux rares : «Un véhicule électrique génère presque autant de carbone qu'un diesel»

Dans son dernier ouvrage, «La Guerre des métaux rares», Guillaume Pitron dénonce «la face cachée de la transition énergétique et numérique». Pour le journaliste, éoliennes, panneaux solaires et voitures électriques se contentent de déplacer la pollution à l'autre bout du monde.

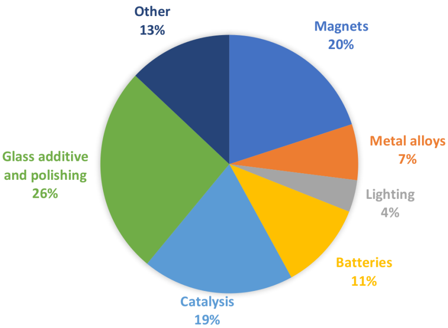
Révolution Énergétique

La transition énergétique va-t-elle manquer de matières ...

Par comparaison, la consommation de terres rares (qui, rappelons-le ne ... Guillaume Pitron, affirment l'impossibilité de la transition.

17 May 2021

Rare earth are not rare!



Source: https://lelementarium.fr/product/terres-rares/

- Rare earth elements are essentially used in two renewable energy technologies containing permanent magnet motors:
  - Wind turbines
  - Electric vehicles
- Demand side management (DSM) relies on the Internet or Things (IoT), which requires components such as indium
- There are no rare earths in Li-Ion batteries!
- The vast majority of PV modules do not contain rare earths

Disadvantages of renewables (4): Critical materials

- For wind turbines, rare earths intensive technologies can be substituted:
  - DFIG (double-fed induction generators) account for more than 70% of the onshore wind market
  - DD-PMSG (direct-drive permanentmagnet synchronous generator) account for 60% of the offshore market

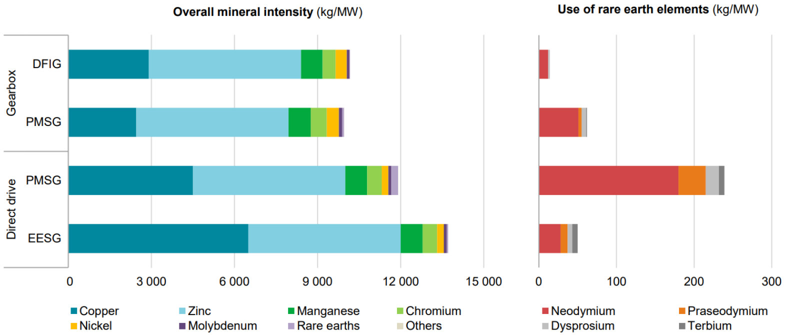
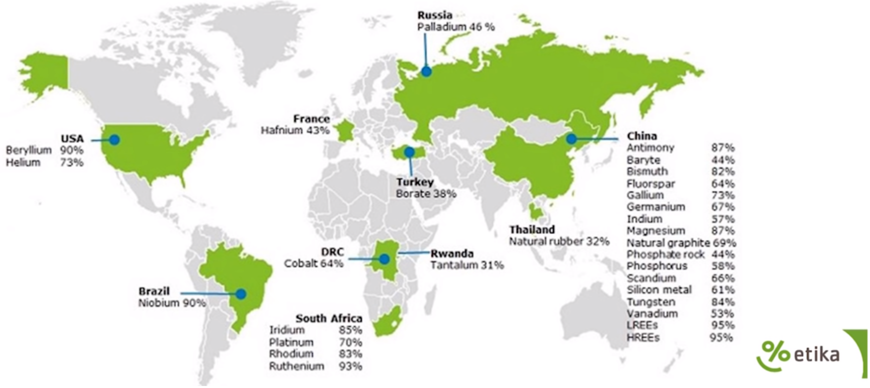


Figure: Mineral intensity for wind power by turbine type (Source: IEA, The Role of Critical Minerals in Clean Energy Transitions, 2021))

Disadvantages of renewables (4): Critical materials

The origin of rare earth materials is tightly linked to geo-strategic concerns:



Disadvantages of renewables (4): Critical materials

Rare-earth mining in China comes at a heavy cost for local villages

Pollution is poisoning the farms and villages of the region that processes the precious minerals

Health hazard ... pipes coming from a rare-earth smelting plant spew into a tailings dam on the outskirts of Baotou in China's Inner Mongolia autonomous region. Photograph: David Gray/Reuters

Source: http://theguardian.com

- The exploitation of rare earths in China has catastrophic environmental consequence
- China extracts 60% of rare earths in the world, but still has 90% of the refinery capacities
- However, a cleaner exploitation is possible, as indicated by Marx et al. (*Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits*, 2018)

Disadvantages of renewables (4): Critical materials

- Many new technologies rely on rare earth materials. These (17) elements present similar physical properties are available in very low concentration in the earth crust and generate high geopolitical and environmental issues for their extraction.
- However, their current consumption is more associated with traditional activities (petroleum refinery, catalytic filters in diesel cars, ...) than with emerging renewable energy technologies.
- Recycling of these materials is currently almost inexistent.
- Other ("critical") materials must also be considered and might have some scarcities. For example
  - Modern batteries technolgies require Cobalt, with little substitution materials currently available. Cobalt consumption grows by 14% per year and is expected to boom with the penetration of electric vehicles.
  - Rare earth can be avoided in wind turbines, but are substituted by other materials (e.g. copper), which also have environmental impacts!
- **Substitution** is key! Alternatives to rare earths exist but also have environmental impact.

Support Mechanisms

Support Policies to Renewable Energy

Feed-in tariffs where the energy from renewable sources is purchased by the system operator (or a supplier) at a fixed price (suppliers are obliged to take that output).

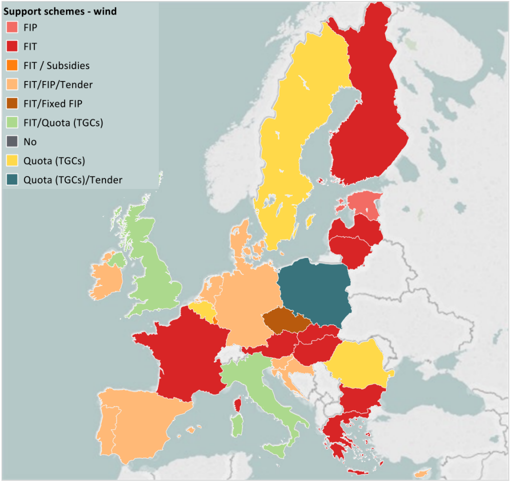
Auctions which are a variation of feed-in-tariffs, in which an auction is organized by the government for a certain capacity of renewables. The winning companies are the ones bidding for the lowest tariff (i.e. accepting the lowest remuneration for their production)

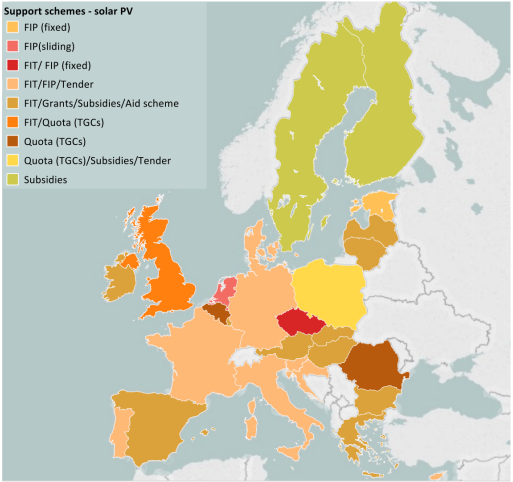
Quotas system where the suppliers are obliged to source a minimum fraction of their electricity from renewable sources.If the supplier cannot comply, obligations (penalities) can be bought for the shortfall. This system is often associated to Green Certificates.

The Carbon Tax that penalizes the carbon emissions and, indirectly, favours the renewable sources.

Tax Discount that have the effect to decrease the investment cost.

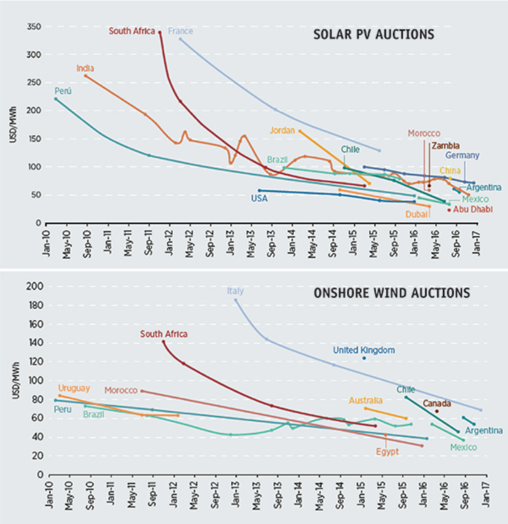
Different Systems in Europe





Support schemes for wind in EU countries (Source: JRC, Renewables in the EU: the support framework towards a single energy market, 2017)

Support Policies: auction mechanisms



The real cost of electricity can be revealed through the results of "Renewables Auctions":

- Companies compete to build new renewable capacities with the lowest possible guaranteed tariff
- The price/kWh of the winning projects has been falling quickly in the last years

Support Policies: auction mechanisms

Climatehope @Climatehope2 · Dec 22, 2020
"Indian **PV auction** delivers final **record** low price of $0.0269/kWh." With solar prices this low, coal will wither away.

pv-magazine.com
Indian PV auction delivers final record low price of ...
The solar electricity price in India has dipped further to an all-time low of INR 1.99 ($0.0269)/kWh in a ...

1 · 3

Terje Osmundsen @OsmundsenTerje · Sep 11, 2018
Jordan Round 3 **PV auction** attracts **record** low bids pv-magazine.com/2018/09/10/jor...
What a revolution! In 2014 we signed one of the first contracts for solar in Jordan, with the FiT $0,16/kWh. Four years later: $0.02488/kWh!

7 · 4

Tim Buckley @TimBuckleyIEEFA · Feb 24, 2017
Indian electricity transformation: 1,000MW **wind auction** sets **record** low US5.2c/kWh Carmichael stranded @mattjcan 2/2

energy.economictimes.indiatimes.com
Wind power tariff falls to record low of Rs 3.46 a u...
Mytrah Energy (India) Private Ltd, Green Infra Wind Energy Ltd, Inox Wind Infrastructure Services Ltd ...

2 · 38 · 25

BalkanGreEnNews @BalkanGreEnNews · May 31, 2020
At the country's 🇦🇱 second **#auction** for utility-scale #photovoltaics **#PV**, @VoltaliaSA offered to sell #electricity for just EUR 24.89 per MWh, a regional **record**.

balkangreenenergynews.com
Albania secures lowest solar power price in Balkan...
Albania said it would agree to the fixed price for half of the 140 MW solar power plant in Karavasta for 1...

6 · 7

Alejandro Nuñez Jimenez @anunezjimenez · Jul 30, 2019
Portugal #solar **PV** prices shatter previous **record** with 14.76€/MWh contract (~16.44USD/MWh) to be built within 36 months in Southernmost part of country

With average price 20€/MWh, Portugal's **auction** demonstrates what spectacular developments await for South EU in coming years!

Support Policies: auction mechanisms

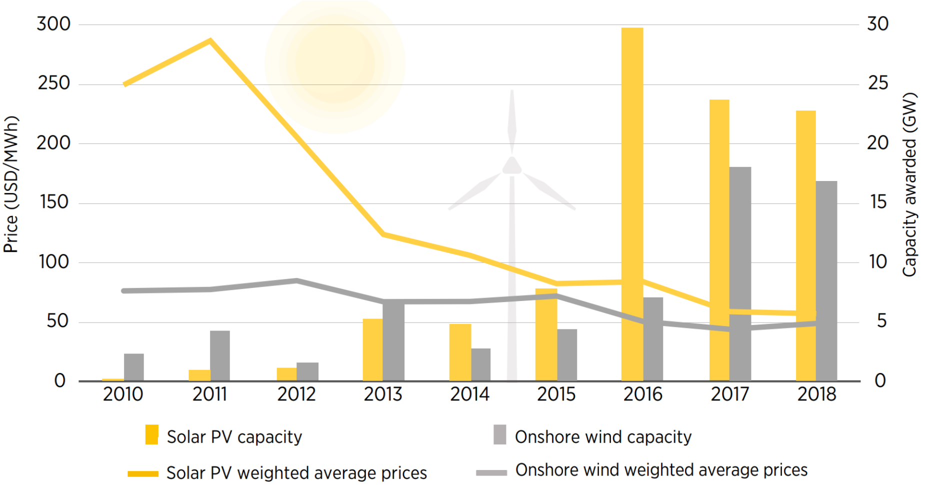


Figure: Global weighted average prices resulting from auctions, 2010-2018, and capacity awarded each year (Source: IRENA)

Support Policies: auctions for offshore wind

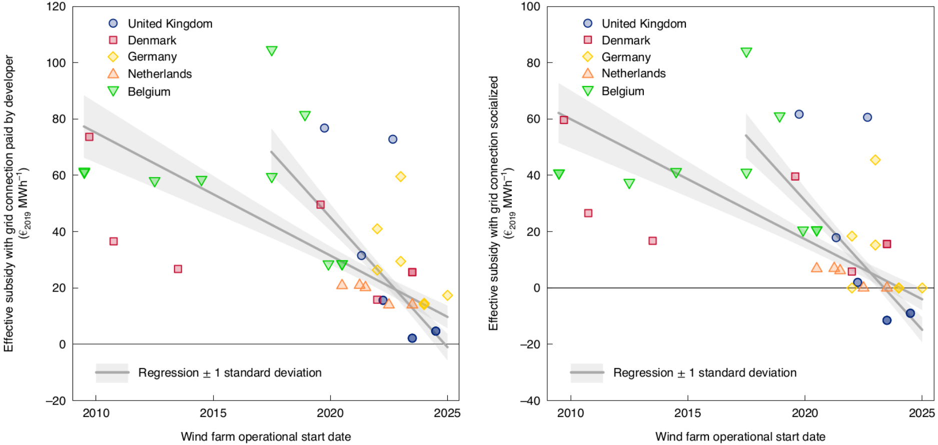
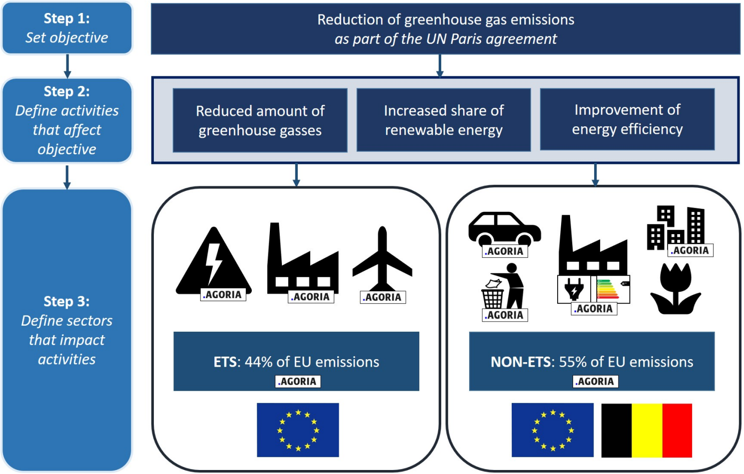


Figure: Effective subsidy for each offshore wind farm auctioned in Europe

Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. Nature Energy.

The European Emission Trading System (ETS)



Schematic representation of the design of the European climate legislation (Source: C.J. van der Veer - Agoria)

ETS Description

The ETS is a quotas (or cap and trade) system on CO_2 emissions set up in the European Union. It limits the total amount of CO2 that can be emitted, and creates a market where emission allowances can be traded.

- The first (pilot) phase (2005-2007) restricted to large plants over 20MW such as steel industries, paper mills, cement industries,... The cost reached €30 in 2006.
- The second phase (2008-2012) consisted in lowering the quotas and include a broader range of installations. The cost of carbon increased towards €20 to decrease back down to €6.
- Third phase (2013-2020): the total volume of emission allowances is determined at the EU level (it was previously decentralized). The share of freely allocated allowances is progressively reduced.
- In the fourth phase (2021-2030), number of emission allowances declines at an annual rate of 2.2% (compared to 1.74% previously). The goal is -43% by 2030 compared to 2005.

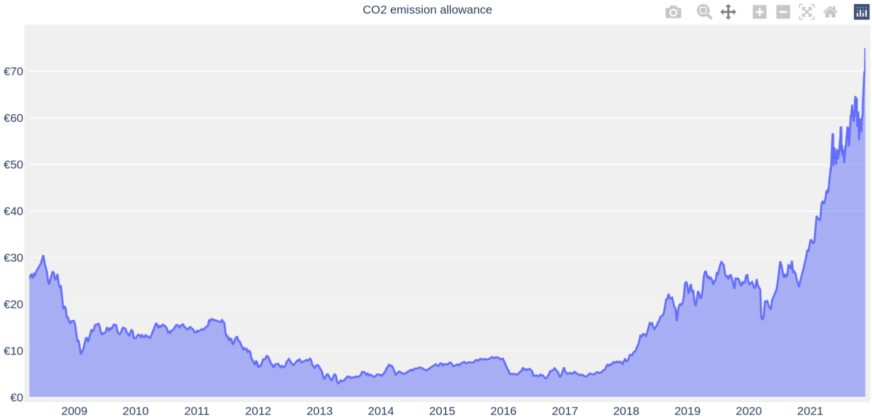
ETS Description

- Because of an oversupply of ETS (due to various reasons such as an excess free allowances allocated to some industries, to the economic downturn, etc), the price for one ton of CO2 has remained very low (a few euros) $\Rightarrow$ the influence of ETS on energy markets is negligible.
- However, since 2017-2018, prices have gone up, which is due to diverse reasons such as the reduction of the oversupply (back-loading) or the economic recovery.
- To prevent **carbon leakage**, i.e. the risk of relocating the production of certain sectors outside of the EU, free allowances are given to industrial installations belonging to a sector deemed at risk of carbon leakage. This system is expected to last at least until 2030.
- The EU ETS was directly connected to the Kyoto system: regulated installations were allowed to use Certified Emissions Reductions (CERs) obtained in other countries to offset their EU emissions. The system is abandoned in Phase 4.

ETS evolution

EUA and CER prices, 2005-2019 (source: https://fsr.eui.eu/eu-emission-trading-system-eu-ets/)

ETS evolution



Source:sandbag.be

Renewable energy systems: challenges and modeling

Influence of Renewables on Energy Systems

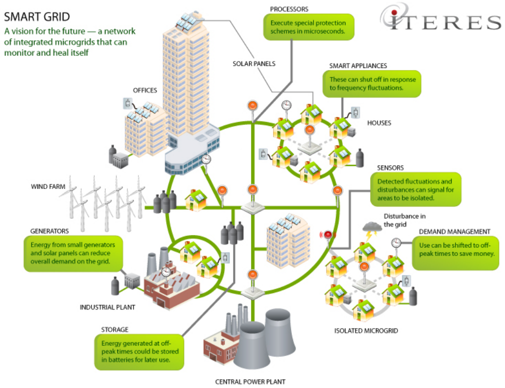


Figure: Smart grid with cross-sectoral interactions

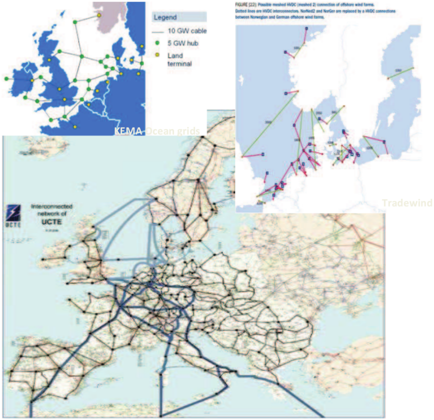
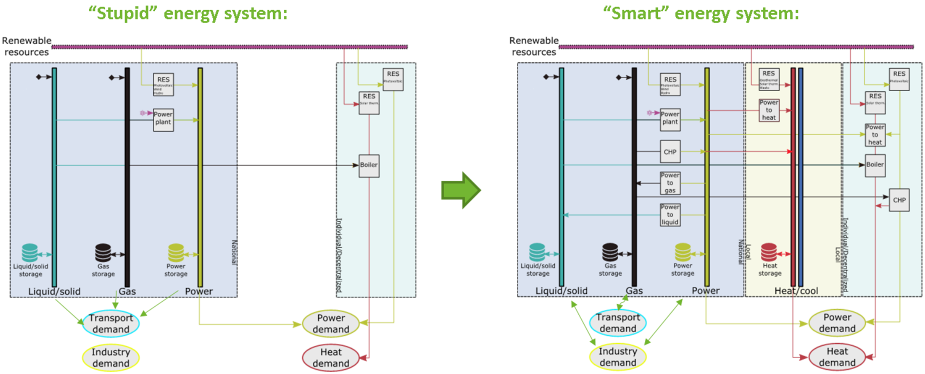
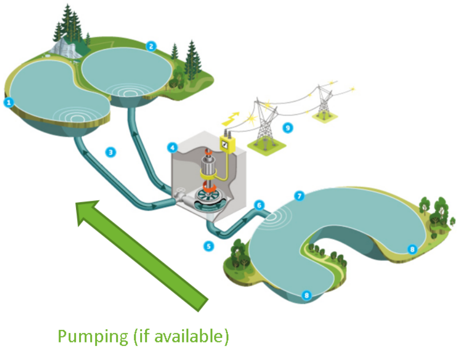


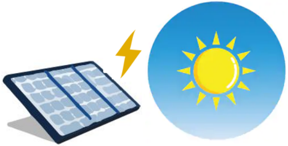
Figure: Supergrid, with long-distance HVDC lines

Smart Energy Systems

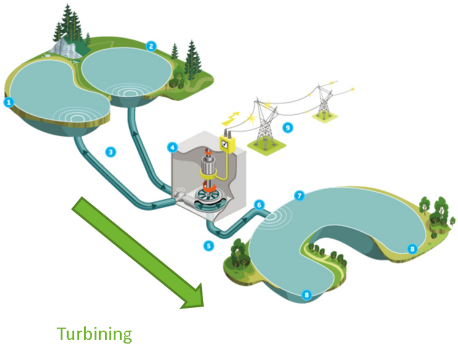


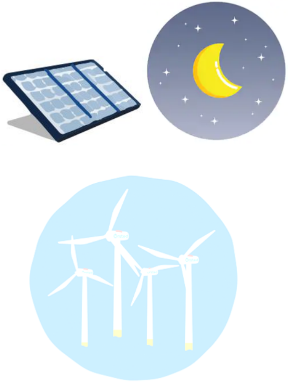
Smart Energy Systems: flexibility from hydro





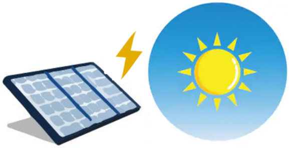
Smart Energy Systems: flexibility from hydro



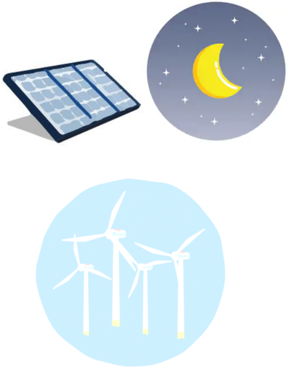


Smart Energy Systems: flexibility from electric vehicles

A fraction of the electric vehicle capacity
Is reserved to provide services to the grid



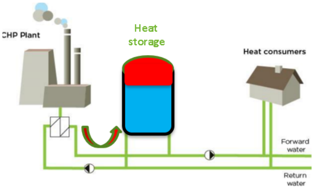
Smart Energy Systems: flexibility from electric vehicles



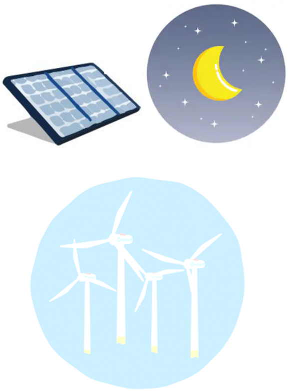
A fraction of the electric vehicle capacity
Is reserved to provide services to the grid

Charging stations could allow energy flows
from the vehicle to the grid (vehicle 2 grid)

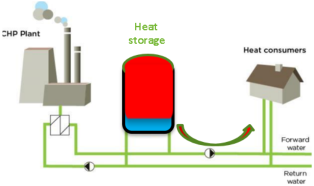
Smart Energy Systems: flexibility from the heating sector



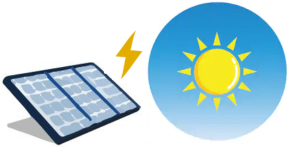
Fynsværket power plant, Denmark (Anders Dyrelund, 4th Generation District Energy, 2017)



Smart Energy Systems: flexibility from the heating sector



Fynsværket power plant, Denmark (Anders Dyrelund, 4th Generation District Energy, 2017)



Smart Energy Systems: benefit of sector coupling

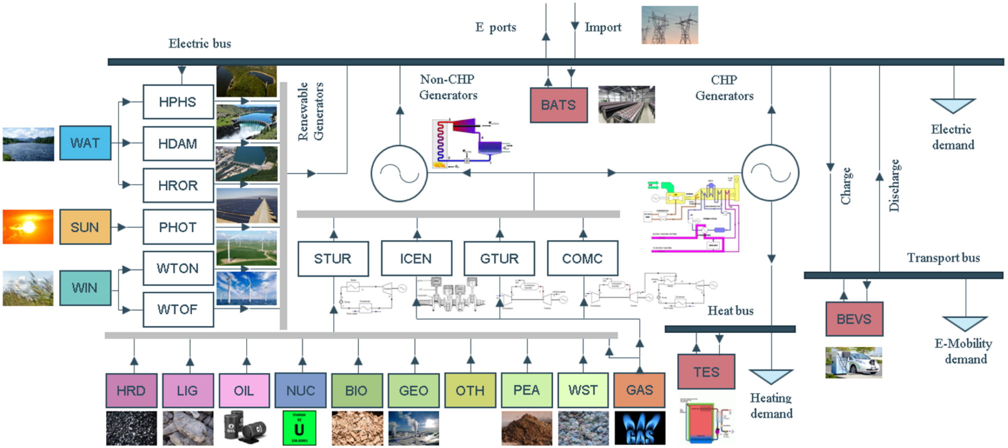
Battery storage: 176-270 USD/kWh
(sources: Bloomberg, 2018; DOE, 2019)

Pumped hydro: 165 USD/kWh
(Source: DOE, 2019)

Thermal storage (sensible): 7.5 €/kWh
(Data and photo from Heat plant Reick)

Underground gas storage:
0.005-0.03 €/kWh
(Sources: EU Commission, 2015; FERC, 2004)

Smart Energy Systems: Modeling



Pavičević, M., Mangipinto, A., Nijs, W., Lombardi, F., Kavvadias, K., Navarro], J. P. J., Colombo, E., & Quoilin, S. (2020). The potential of sector coupling in future European energy systems: Soft linking between the Dispa-SET and JRC-EU-TIMES models. Applied Energy, 267, 115100.

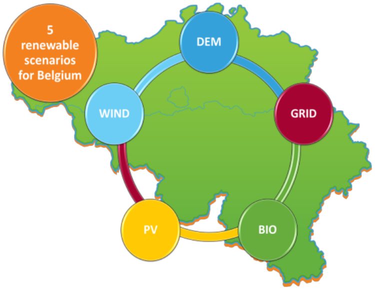
Future energy systems with (almost) 100% renewables

- Many studies are now being published showing that a decarbonized energy system is feasible
- It is important to distinguish between:
  - Going to 100% renewable sources
  - Going to near zero emissions
  - In the second case, technologies such as nuclear or carbon capture and storage (CCS) can be accepted and become significant part of the simulated energy mix.
- We will consider as example two studies with different geographical scales (Belgium, EU):
  - Wouter Nijs, Jan Duerinck, Danielle Devogelaer, Dominique Gusbin, Yves Marenne, Marco Orsini, A 100% Renewable Energy System In Belgium by 2050, 2013
  - Brown et al., Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy, 2018

100% Renewable Energy System in Belgium

Definitions of scenarios

REF Fossil Benchmark scenario



DEM

Limited RES potentials in DEM Scenario

- Wind
  - 8 GW offshore on the Belgian EEZ
  - 13 GW offshore on other EEZ's
  - 9 GW onshore
- Solar (PV)
  - 50 GW on Belgian soil
- Biomass
  - 100 PJ domestic production
  - 200 PJ import
- Geothermal
  - 4 GW domestic
- Electricity import 5.8 TWh
- Hydro 120 MW

End use of energy: Buildings – heating and appliances, Industry, Transport, Agriculture

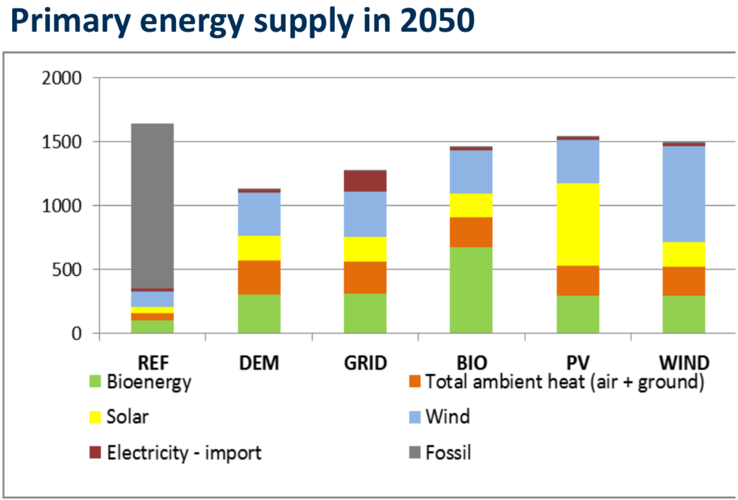
GRID Allows more Elec import → in 2050, 44 TWh is being imported

BIO Allows more biomass import → in 2050, 570 PJ is being imported

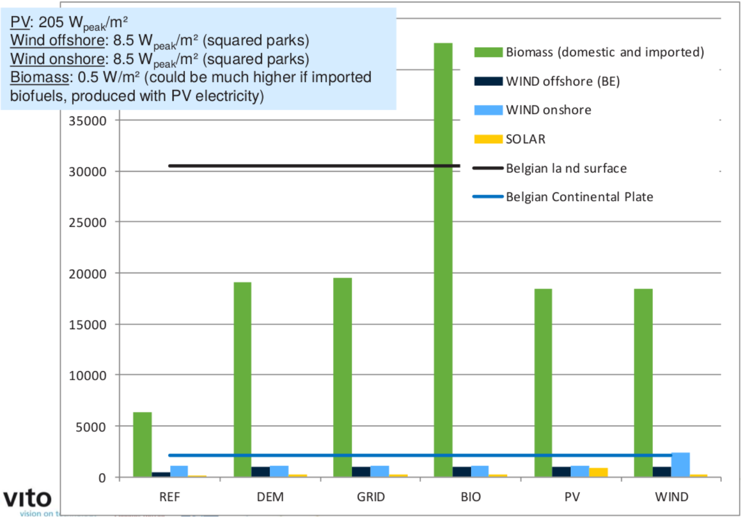
PV Allows more PV → in 2050, 170 GW is being installed

WIND Allows more wind → in 2050, onshore: 20 GW offshore: 47 GW

100% Renewable Energy System in Belgium

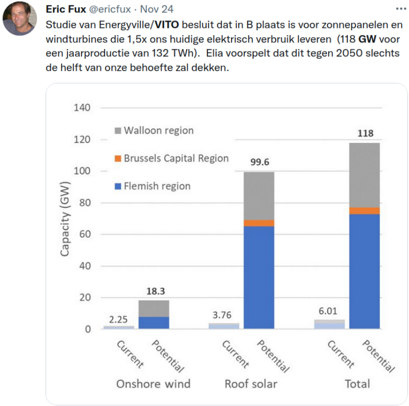


100% Renewable Energy System in Belgium



100% Renewable Energy System in Belgium

A more recent (November 2021) analysis reveals that the renewable potentials are actually higher than the initial hypotheses.

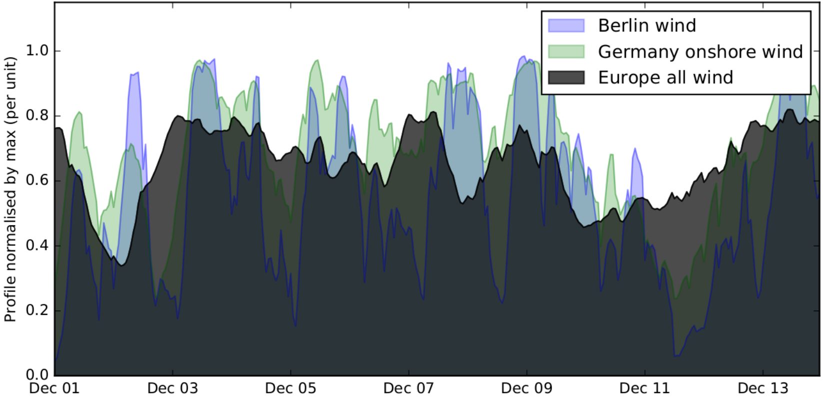


High decarbonisation of European power, heating and transport systems

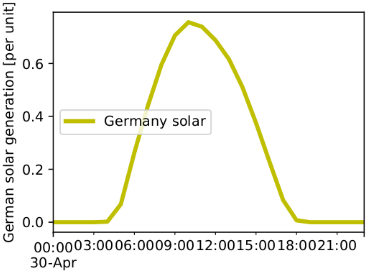
- Exchanges between countries (through interconnections) are important since they can help balance the variability of renewable generation (cfr wind example on the next slide)
- The model should have high time resolution (one hour) to allow considering daily variations
- main conclusions obtained with the PyPSA model from Brown et al.:
  - Electrification of other energy sectors like heating and transport is important, since wind and solar will dominate low-carbon primary energy provision
  - Grid helps to make CO2 reduction easier = cheaper
  - Cross-sectoral approaches are important to reduce CO2 emissions and for flexibility

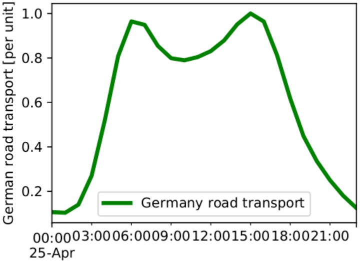
Importance of interconnections

When larger geographical areas are interconnected, the resulting wind generation profile is much smoother!



DAILY VARIATIONS: CHALLENGES AND SOLUTIONS

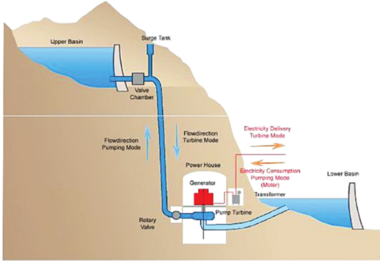




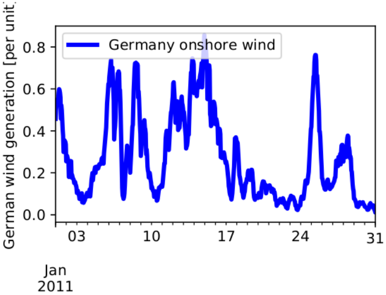
Daily variations in supply and demand can be balanced by

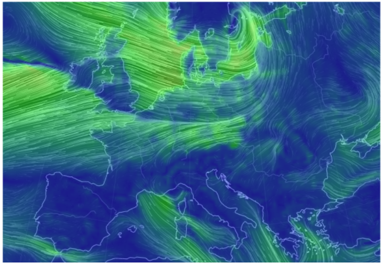
- short-term storage (e.g. batteries, pumped-hydro, small thermal storage)
- demand-side management (e.g. battery electric vehicles, industry)
- east-west grids over multiple time zones

Adapted from: Brown et al., 2018



Synoptic variations: challenges and solutions

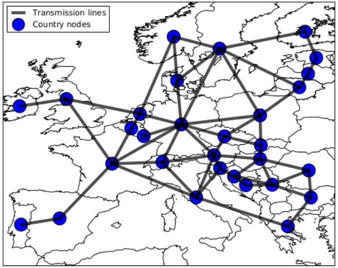




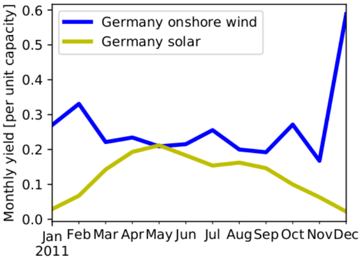
Synoptic variations in supply and demand can be balanced by

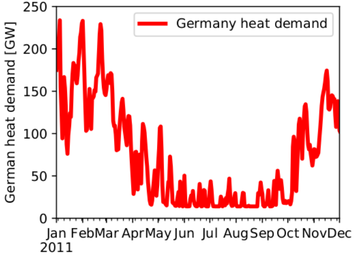
- medium-term storage (e.g. compressed air, chemically with hydrogen or methane, thermally, hydro reservoirs)
- continent-wide grids

Adapted from: Brown et al., 2018



Seasonal variations: challenges and solutions

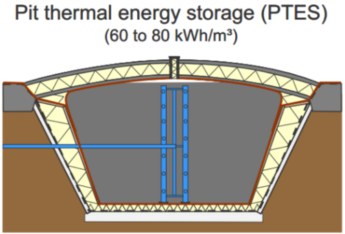




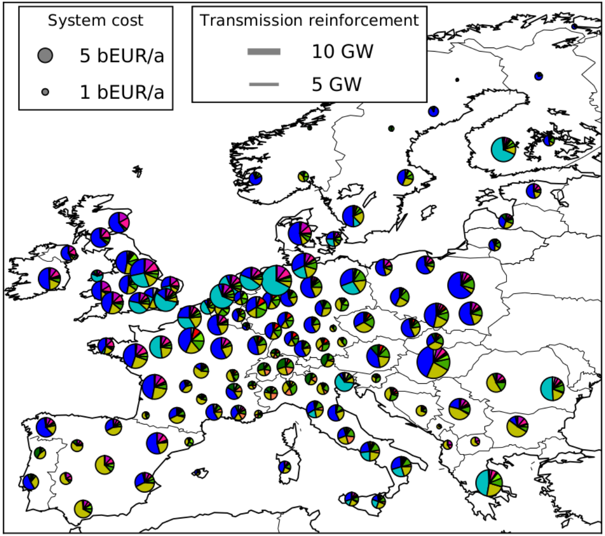
Seasonal variations in supply and demand can be balanced by

- long-term storage (e.g. chemically with hydrogen or methane storage, long-term thermal energy storage, hydro reservoirs)
- north-south grids over multiple latitudes

Adapted from: Brown et al., 2018



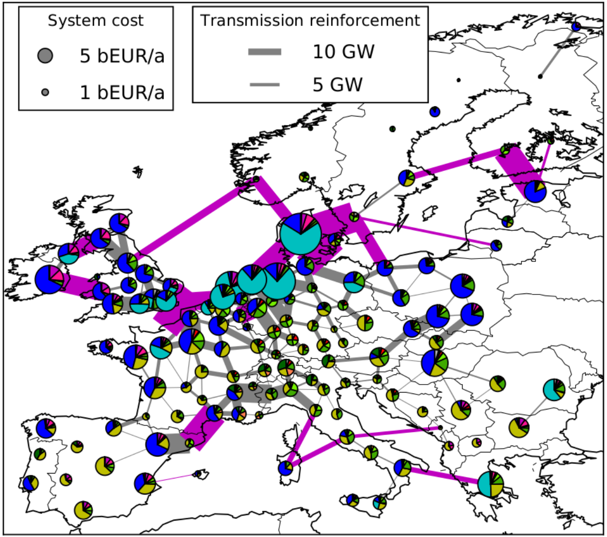
Distribution of technologies: No grid expansion



- Mix of solar and wind at almost all locations
- Capacities of offshore wind limited by grid restrictions
- Large share of power-to-gas paired with on- and offshore wind, particularly at periphery of network

Adapted from: Brown et al., 2018

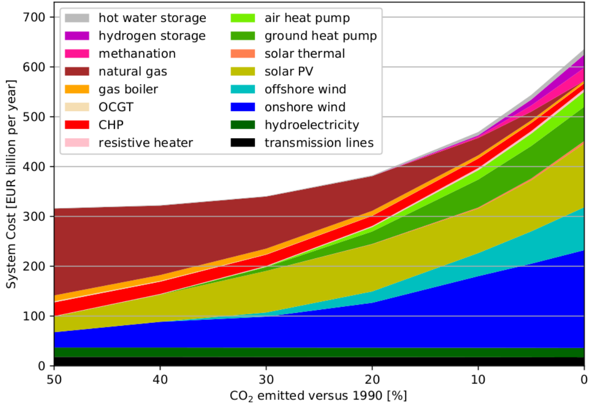
Distribution of technologies: 100% more grid volume



- Further expansion of off- and onshore wind in North
- Grid expansion focuses again on North and East-West axis

Adapted from: Brown et al., 2018

Pathway down to zero emissions in electricity, heating and transport

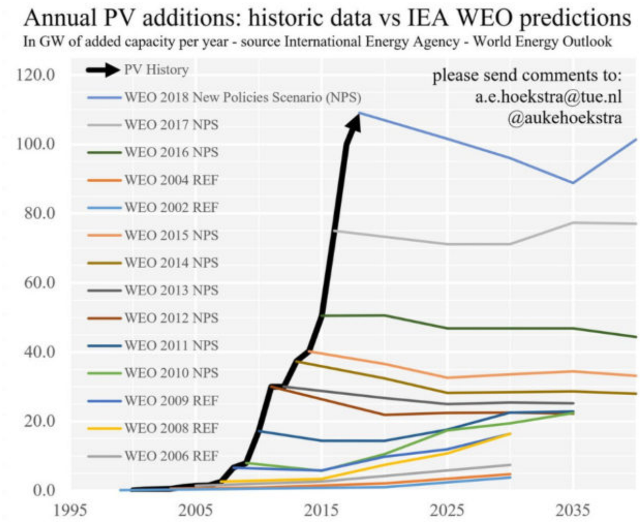


If we look at investments to eradicate CO2 emissions in electricity, heating and transport we see:

- Electricity and transport are decarbonised first
- Heating comes next with expansion of heat pumps below 30%
- Below 10%, power-to-gas solutions replace natural gas

Adapted from: Brown et al., 2018

Limitations of energy system models



Limitations of energy system models

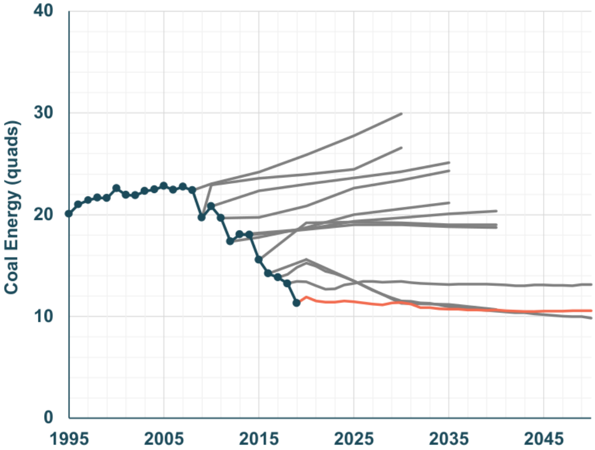
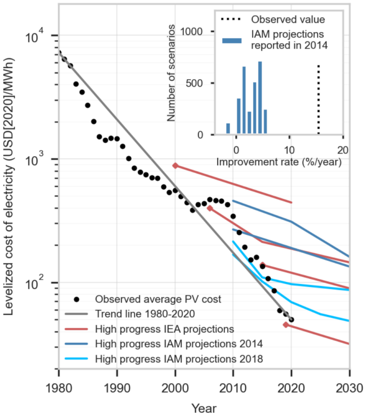
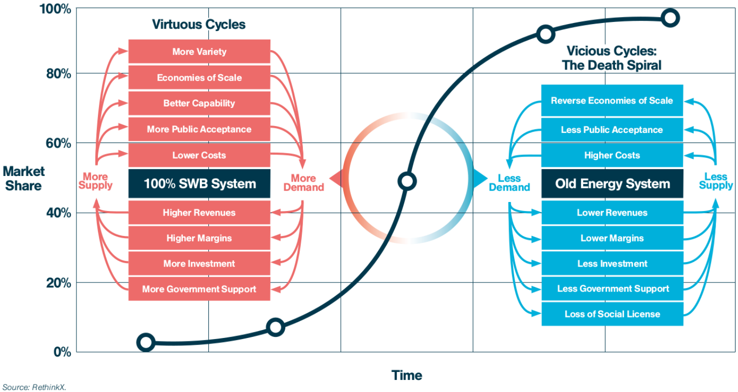


Figure: EIA Annual Energy Outlook annual coal generation forecast and historical data (Source: Rethinkx, 2020)

Limitation of energy system models



Historical PV cost forecasts and floor costs, Rupert Way et al, 2021



Source: RethinkX.

Traditional models have consistently failed to produce results in line with past trends. They are not designed to catch non-linear transitions (or disruptions).

CONCLUSIONS

- We are now at a critical period in which renewable energy is mature enough to replace fossil fuels for electricity generation
- Decarbonizing the other sectors is however more complex/costly and will require their electrification wherever possible
- Renewable energy source, as all energy activities, have an environmental impact. It must be taken into account and compared to that of the substituting technologies
- In a densely populated country like Belgium, it is difficult to cover 100% of the demands only with renewables
- At the EU level, multiple studies demonstrate that going to net zero carbon is feasible by 2050! It will require, among others, sector coupling and grid extension.
- Much progress is still required in the energy system models, e.g. to integrate the learning rates, to model all the sectors simultaneously, to increase the spatial and temporal granularity, ...