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WORKING PAPER

Electrification and sustainable fuels: Competing for wind and sun (complement to the Policy brief)

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Working paper containing calculations and assumptions in support of the accompanying Policy brief with the same title

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Abstract

This study seeks to answer a simple question: will we have enough renewable electricity to meet all of the EU's decarbonisation objectives, and, if not, what should be the priorities and how to address the remaining needs for energy towards carbon neutrality? Indeed, if not, the policy push for green hydrogen would not be covered by enough green electricity to match the “energy efficiency and electrification first” approach outlined in the system integration communication, and a prioritization of green electricity uses complemented by other solutions (import of green electricity or sustainable fuels, CCS...) would be advisable [1]. On one hand, we show that the principle “Energy efficiency and electrification first” results in an electricity demand which will be very difficult to satisfy domestically with renewable energy. On the other hand, green hydrogen and other sustainable fuels will be needed for a carbon neutral industry, for the replacement of the fuel for aviation and navigation, and as strategic green energy reserves. The detailed modelling of these interactions is challenging, given the large uncertainties on technology and infrastructure development. Therefore, we offer a “15 minutes” decarbonization scenario based on general and transparent technical considerations and very straightforward “back-of-envelope” calculations. This working paper contains the calculations and assumptions in support of the accompanying policy brief with the same title, which focuses instead on the main take-aways.

Keywords

Sustainable fuels, electrification, decarbonisation, EU Green Deal, Fit for 55 package.

1. Introduction*

As part of the Green Deal[1] Europe wishes to reach full climate neutrality by 2050. As an intermediate step, a reduction in greenhouse gases of 55% by 2030 has been put forward as a target.

It is a challenging goal, compared, say, to the 20% set for 2020. The ETS was the major instrument deployed to reach this [2]. As complementary paths, renewable energy resources were introduced into the system (20% renewables in final energy use), particularly in the power system and for energy efficiency a target of -20% compared to business as usual was put forward. The so-called 20-20-20 targets by 2020 were the overaching story line.

As reductions become harder to reach in the approach towards full carbon neutrality, a set of policy measures have been launched in the last months.

When looking at the energy system, the basis of the overall approach is found in COM(2020) 299 "Energy system integration strategy" [1], a coherent approach, based on engineering fundamentals [3]:

Energy efficiency first, including the use of waste heat;

Then the electrification of those applications where this is credible in terms of cost-efficiency and technology;

If the first and the second approach prove unfeasible, sustainable fuels will have to be used (including hydrogen).

This approach leads to a sustainable energy system based on renewable resources that predominantly deliver electric energy as output: wind, solar and the more traditional hydro and some geothermal generation. The basic laws of thermodynamics, the physical laws that rule energy systems, are clear: every time the energy is changed from one vector into another (electricity into hydrogen, for example) a significant amount of the original energy is lost. Therefore, as (renewable) electricity may be considered to be the 'highest quality of energy' in the context of a decarbonising system, wherever possible it should not be changed "on route" towards its final use. In other words: if the energy service can be delivered electrically, it should be done in that way. Applications that can not be addressed by electricity are called "hard to abate" applications as they require alternative solutions.

Therefore, a smart transition, that is cost-effective, should try to deliver the energy for the services needed using a minimum amount of energy, which is guaranteed by electrifying the energy supplied a much as possible. Where this is not possible, the most efficient and effective sustainable fuel must be used. There are a number of options here, both low carbon (decarbonising industry using CCS/CCU and low-carbon hydrogen during a transition period) and zero-carbon hydrogen produced using electrolysis and maybe pyrolysis using renewable electricity. The potential of these alternatives has to be verified with further studies and some of them are still at lower TRL's (Technology Readiness Level) and therefore may require demonstration pilots. Given the basic laws of thermodynamics, using sustainable fuels based on green electricity for applications that can be supplied directly by electricity is always inefficient and leads to higher investments in required wind and PV resources and conversion systems (electricity to sustainable fuels and to final energy service).

* The authors would like to thank Prof. Jean-Michel Glachant (FSR), Andris Piebalgs (FSR) and Christopher Jones (FSR) for reviewing this piece and giving valuable inputs.

1 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2019:640:FIN

Energy targets, both at the supply and demand (energy services) side are also addressed in the legislative train [4] that accompanied the green deal [5]. Both energy supply side, which has to be carbon neutral by 2050, and energy use in energy services are dealt with there. Attention is also given to grids (pipelines and electricity grids). The relevant texts sometimes describe, in great detail, the steps to reach specific targets. Detailed modelling may be the basis of decisions that have to be made in the years to come. For other future developments, a more general analysis may be used. Overall, there is an impressive amount of legislation envisaged for the years to come.

However, it seems that a cross check of the interacting files is missing.

For instance, is the input of green electric energy envisaged by 2030, in the NECPs, sufficient to decarbonize around 65% or more of present electricity use by 2030 towards the -55% GHG emissions reduction target of the EU Green Deal? [6] How does the extra demand for the electrification of transport or the heating of buildings affect electricity demand? Can the policy push for green hydrogen [7] be covered by enough green electricity in order to be coherent with the “energy efficiency and electrification first” approach envisaged in the system integration communication?

There are comparisons of detailed modelling exercises, for instance in a recent JRC technical report [8]. The results of these kinds of exercises depend on the assumptions made, the model calculation and the parameters and data adopted. For the sake of transparency, we offer a “15 min” decarbonization scenario based on general and transparent technical considerations and very straightforward “back-of-envelope” calculations.

A simple three steps methodology is followed. The starting point for any discussion is the energy use and flow data as provided by Eurostat for 2019[2]. Then we estimate the share of the future energy services that can be supplied by electrification, taking due account of the improvement in energy efficiency that results from using electricity for transport and heating compared to using fossil fuels. Finally, we assess how much renewable electricity will be needed to do so, accounting for the policies set forward by the EU and other reference modelling works (IEA, IRENA, EU EC …).

In preparing this analysis, at every point where the option presented itself, we have taken a 'conservative' approach to demand and supply. We therefore assume that ambitious predictions/estimates regarding renewable electricity production will be met, and that energy demand will be reduced or constrained based on the achievement of even more ambitious energy efficiency objectives (that would require a step-change compared to current success in this area). Energy services that cannot be electrified need to be fueled by sustainable fuels. Sustainable fuels may be biofuels, low carbon or carbon neutral hydrogen (blue or turquoise) as well as e-fuels based on green hydrogen. E-fuels require a rough estimate of the electricity needed for their production. We should keep in mind that each energy transformation leads to reduced energy efficiency all the way down the energy chain. Also, when looking at sustainable fuels, another greenhouse gas – methane – has to be carefully considered. It constitutes the major part of natural gas and it is at the centre of the so-called “methane strategy” published on 14 October 2020.

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[2] Source: https://ec.europa.eu/eurostat/cache/sankey/energy/sankey.html?geos=EU27_2020&year=2019&unit=KTOE&fuels=TOTAL&highlight=_&nodeDisagg=0101000000000&flowDisagg=false&translateX=0&translateY=0&scale=1&language=EN

2. Energy supplied to present energy services

Energy services are key for society. They can, of course, be delivered by different energy sources. Let us go back 150 years. At that time almost all energy services were delivered to society through coal:

- House heating (exception: wood and peat)
- Transport (major exception: horses)
- Industry, e.g. steam engines

New energy carriers were introduced over time as they could provide for the increasing demand for energy services in a more diversified, convenient and comfortable way:

- Petroleum/oil
- Electricity
- Gas

Not all energy sources directly deliver energy services. They often come to the final user *via* another energy carrier, often electricity (e.g. nuclear, hydropower).

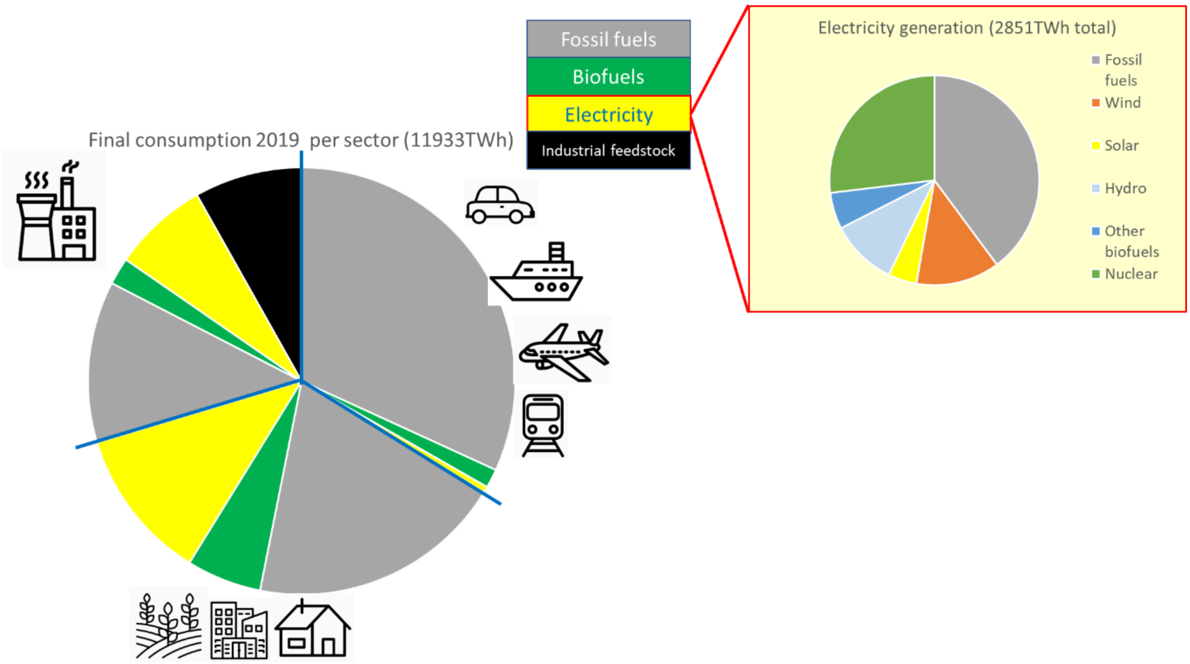
The energy transition that we are seeing now, is triggered by the aim of limiting global warming by making the supply of energy services carbon neutral. The comfort level will likely increase in parallel with decarbonization, but this is not the focus of the present paper.

In the figure below, an overview is given of the 2019 demand for energy carriers and industrial feedstock in the different sectors, and of the relative shares of electricity generation by energy source according to Eurostat[3.] Final energy and feedstock consumption is roughly 12.000 TWh, of which electricity is only 21% (2485 TWh)[4.] 37% of the gross electricity production is supplied from renewable resources (953 TWh: wind 367 TWh, hydro 293 TWh, solar 126 TWh, geothermal 7 TWh, bioenergy 160 TWh).

[3] Source: https://ec.europa.eu/eurostat/cache/sankey/energy/sankey.html?geos=EU27_2020&year=2019&unit=KTOE&fuels=TOTAL&highlight=_&nodeDisagg=0101000000000&flowDisagg=true&translateX=0&translateY=0&scale=1&language=EN

[4] In EU-27 in 2019 an overall amount of final energy of 10.881 TWh was supplied, in addition to 1052 TWh equivalent of industrial feedstock (“non-energy”).

Figure 1



Currently only a small amount of sustainable energy sources or “renewable energy” are in the mix: most are biofuels as other renewable energy sources like wind, solar and hydro are largely “hidden” behind “electricity” (see the tables below).

International transport (marine bunkers 507 TWh and international aviation 485 TWh) are not included in energy use by Eurostat, but are added in the values above and in the table below for the sake of completeness. Adding these leads to an overall energy supply of 11.933 TWh. The additional 992 TWh of international transport are supplied by oil and petroleum products, increasing the overall input from these sources to 5012 TWh from 4020 TWh.

Figure 2

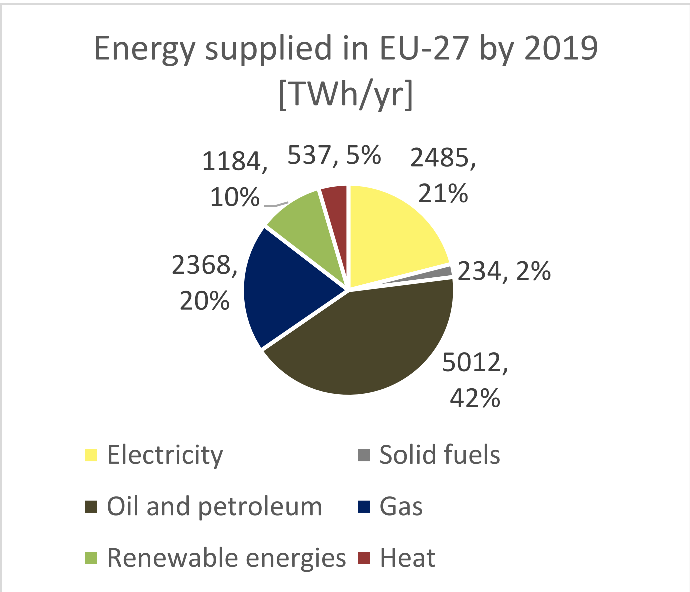


Table 1

Item	Energy use per year [TWh/yr]
Overall	10881
Electricity	2485
Solid fuels	234
Oil and petroleum	4020
Gas	2368
Renewable energies	1184
Heat	537
International aviation	*485*
Marine bunkers	*507*

Table 2

Item	Electricity gross production in 2019 [TWh/yr]
Overall (excl. 52 TWh pumped hydro)	2851
Renewables (wind, solar, hydro, geothermal)	953 (37%)
• Wind	367
• Solar (incl. 6 TWh solar thermal)	126
• Hydro (excl. 52 TWh pumped hydro)	293
• Geothermal	7
• Bioenergy	160
Fossil fuels	1133
Nuclear	765

Note: 52 TWh/yr of pumped hydro were not reported, in line with the assumptions used latter on for 2030 electricity generation. The shares of renewables including pumped hydro is 35% (1005 TWh/yr). The electricity use in 2019 (2485 TWh) differs from the overall gross electricity production (2851 TWh), because of intermediary losses and self-consumption.

The present final energy consumption is split into three major groups:

- Transport
- Other sectors (mostly services and buildings)
- Industry

2.1 Transport

In transport, oil products dominate. All other energy vectors are marginal except for electricity in railway transport.

Figure 3

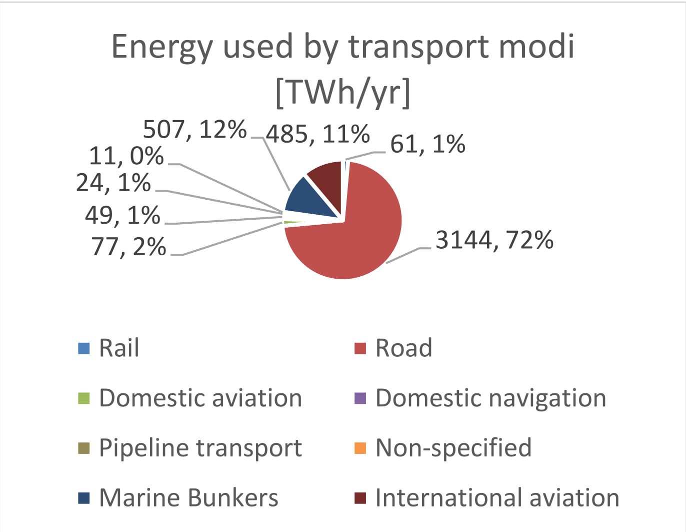


Table 3

	Energy [TWh/yr]	Of which electricity [TWh/yr]
Total	4358	59
Rail	61	47
Road	3144	3
Domestic aviation	77	0
Domestic navigation	49	0
Pipeline transport	24	2
Non-specified	11	0
Marine Bunkers	507	0
International aviation	485	0

2.2 Other sectors (services and buildings)

Electricity supplies roughly a third of energy to buildings (services and households), another third comes from natural gas. The remainder is supplied by petroleum products, biomass and other products.

Figure 4

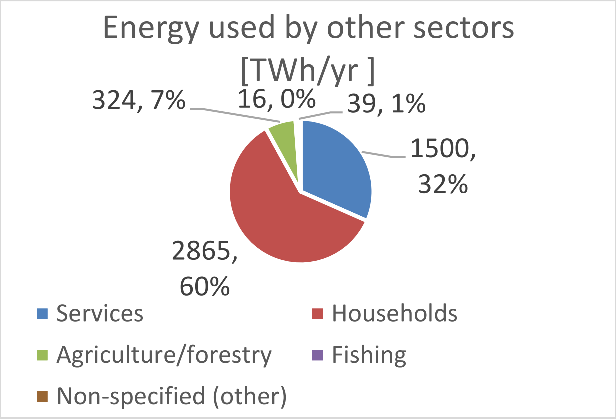


Table 4

	Energy [TWh/yr]	Of which electricity [TWh/yr]
Total	4745	1493
Services	1500	729
Households	2865	706
Agriculture/forestry	324	53
Fishing	16	1
Non-specified (other)	39	3

2.3 Industry

The industrial demand is split by Eurostat into thirteen groups. Roughly a third of current demand is covered by electricity. Some sectors have a very specific energy input, eg “paper, pulp and print” use 156 TWh renewables, almost totally biomass.

Figure 5

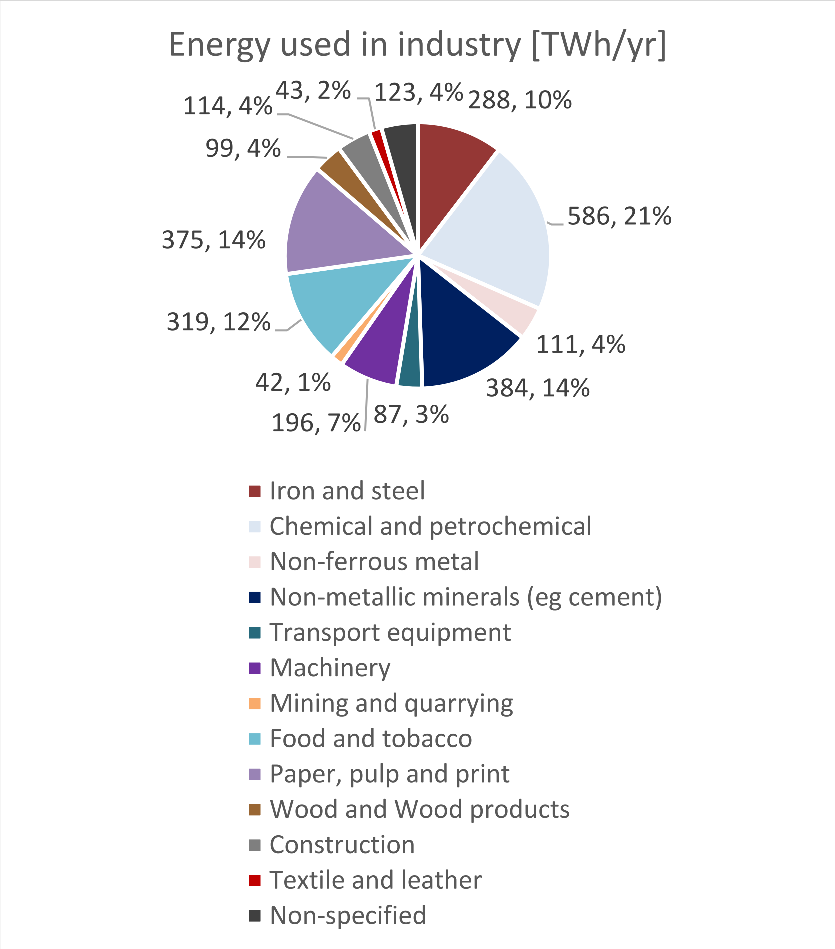


Table 5

	Energy [TWh/yr]	Of which electricity [TWh/yr]
Total	2770	933
Iron and steel	288	108
Chemical and petrochemical	586	166
Non-ferrous metal	111	61
Non-metallic minerals (eg cement)	384	64
Transport equipment	87	49
Machinery	196	111
Mining and quarrying	42	19
Food and tobacco	319	112
Paper, pulp and print	375	104
Wood and Wood products	99	26
Construction	114	25
Textile and leather	43	18
Non-specified	123	72

2.4 Overview of energy used

From this overview we can start the analysis of a very rough overall route to -55% carbon reduction by 2030 and carbon neutrality by 2050. We will break down the analysis into four groups, where the timing and technologies differ:

- existing electricity demand
- additional electricity demand for the electrification of transport
- additional electricity demand for the electrification of other sectors (services & buildings)
- additional electricity demand for the electrification of industry.

3. Decarbonizing existing electricity demand

3.1 First step: Green electricity by 2030

The first step towards decarbonization is to cover existing electricity demand by carbon neutral resources. To decarbonise around 65% or more of the present EU-27 electricity use by 2030 – an estimated, reasonable contribution to reach the -55% GHG emissions reduction target of the EU Green Deal[5] -, 1615 TWh of green electricity supply will be needed. This step would require the installation of enough technological capacity for the generation of sufficient green electricity. On the basis of existing EU Member States targets/commitments, assuming that they are met, this gives the following:

i. Onshore + offshore wind: In the EU-27 national energy and climate plans (NECPs) by 2030, excluding the UK6, a total of 340 GW of on- and offshore wind turbines are envisaged compared to the current 168 GW. This leads, in 2030, to a wind energy output of 817 TWh, compared to 367 TWh in 2019.

ii. Solar PV: The overall energy output of PV by 2030 in the NECPs can be estimated at between 328 and 369 TWh (≈ 349 TWh)7, and capacity stands at 341 GW, compared to the current 120 TWh and 132 GW8.

iii. Others (hydro, geothermal …): in order to get a full picture of all renewable energy sources, we add the output of hydropower (293 TWh, excluding 52 TWh of pumped hydro) and geothermal (7 TWh). We assume that both are constant over time till 2030 and beyond. Biomass to power (160 TWh in 2019) is not taken into account.

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5 This estimate is also in agreement with the EU-27 ambition level set for the renewable share in the supply-side towards the achievement of the EU Green Deal targets. COM(2020)562 [9]: "By 2030, the share of EU renewable electricity production is set to at least double from today's levels of 32% of renewable electricity to around 65% or more."

6 A total of 397 GW of windturbines are envisaged (on- and offshore) with a 953 TWh of energy output. These figures include the UK which is 57 GW (mostly offshore). Even if we calculate the energy output proportionally – in a conservative fashion since the majority is offshore and offshore energy output per unit power is higher than average, this is 136 TWh [10]. This leads to a wind energy output in 2030 of 817 TWh in EU 27, with respect to 363 TWh in 2019 (https://ec.europa.eu/eurostat/statistics-explained/images/3/32/Electricity_Statistics%2C_EU-27_and_EA-19%2C_2017-2019_%28GWh%29.png) .

7 For the remainder of this paper and for the following figures, we will consider 349 TWh.

8 Total PV by 2030 would correspond to 341 GW, or circa 369 TWh. As the present PV power installed is 132 GW, the extra PV capacity to add by 2030 is 209 GW (http://taiyangnews.info/markets/209-gw-solar-pv-capacity-in-europe-by-2030/) or with 1000 to 1200 h this is 209 to 250 TWh w,rt, . 119 TWh (Eurelectric), so 901 h, in 2019 https://ec.europa.eu/eurostat/statistics-explained/images/3/32/Electricity_Statistics%2C_EU-27_and_EA-19%2C_2017-2019_%28GWh%29.png).

On the one hand, biomass is a limited resource; and, on the other, biomass and biofuels might be better used to fullfill the needs of hard to abate applications and may also be used as feedstock for biobased chemistry bringing more added value. If biomass quality is too low to be further processed and to be used as a basic material, employing it as electric energy source may be envisaged.

Figure 6

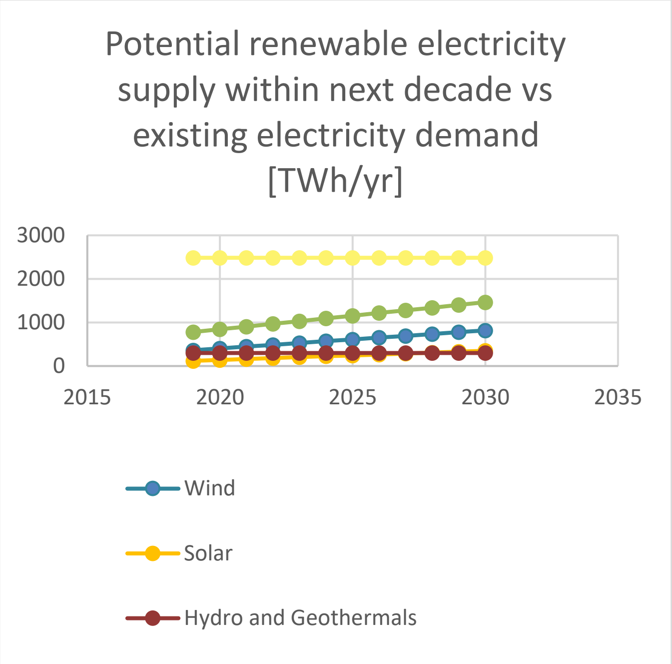


Table 6

[TWh/yr]	2019	2030 - NECPs	2030 – SWD176(2020) MIX scenario
Wind	367	817	1076
Solar PV	120	328/369	429
Hydro (excl. pumped hydro)	293	293	599
Geothermal	7	7	
Bioenergy	160	-	
Total	953	1477	2105
% of current electricity supply (2851 TWh)	33%	52%	74%

On this basis, we can estimate the EU-27 output of wind and PV by 2030 at around 1150 TWh per year compared to the present 487 TWh, an addition of 663 TWh. If we add hydro and geothermal, we get 1477 TWh. This estimate may be viewed as reasonable in the light of comparative studies. A study by FSR on the decarbonization costs [11] estimates a potential, by 2030, of 1361-1367 TWh for solar and off/onshore wind together. EU EC SWD(176) MIX scenario suggests there is a potential of 1505 TWh for the same technologies by 2030, and of 2104 TWh including other renewables (hydro, biomass …). However, the link is to be made with demand for sustainable fuels and feedstock for biobased chemistry. The capacities reported in the FSR study are also comparable with the numbers included in this paper (340 GW of wind, 341 GW of solar PV) and reported in the MIX scenario, except for the MIX estimates for wind (439 GW of wind, 370 GW of solar).

Table 7

Renewable capacity estimated	Wind	PV
Today	168 GW	117 GW
This paper – NECPs – 2030	340 GW	341 GW
IEA – 2030	336 GW	391 GW
IRENA – 2030	319 GW	284 GW
EU EC - SWD176(2020) – MIX scenario	439 GW	370 GW

In conclusion, based on the NECPs, and assuming that Member States meet their objectives, supplying around 65% of current electricity demand (1615 TWh) with renewable electricity by 2030 may be considered to be ambitious, but technically feasible.

This does not, however, take into account the additional expected demand for renewable electricity from electrification in other sectors. Equally, we will need to factor in the electricity system changes that will result from such rapid renewable electricity growth, notably given the intermittent nature of the power. Additional investments in grid and storage will be required to enable these levels of renewable electricity to be achieved.

3.2 Second step: Green electricity beyond 2030

Inevitably, predicting potential or economically efficient electricity demand and the ability of renewable electricity supply to meet it is more difficult with greater levels of uncertainty. This is the case, for example, by 2050. It is clear that any number beyond 2030 is more uncertain as grid developments, storage deployment and active balancing demand and supply will have significantly advanced to accommodate renewable shares.

However, we have reviewed available estimations for solar PV, on- and offshore wind on the basis of models from IEA, IRENA, EU EC, and the aforementioned FSR study, and of other relevant sources.

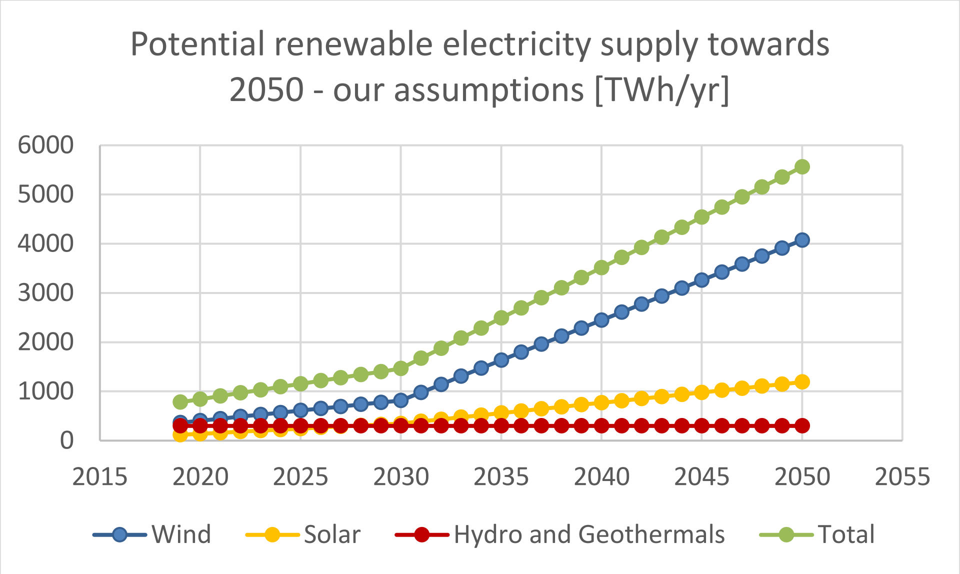
In its offshore communication the EU [12] states that offshore renewable energy has, among renewable technologies, perhaps the greatest potential to scale up. The objective is to have an installed capacity of 300 GW by 2050. There is talk, in the report, of 40 GW of ocean energy. Ocean energy is still at lower TRL levels, and, therefore, will not be included in this paper. The capacity factor for offshore wind is estimated at 55% as Europe has in the North Sea very good offshore wind conditions. IRENA indicates capacity factors of between 43% and 60% in 2050, in agreement with our assumption [13]. Using 55% leads to an annual energy output of 1445 TWh.

In its November 2020 policy recommendation, the European wind energy sector puts forward an onshore wind capacity of 750 GW by 2050 [14]. For onshore wind IRENA reports a wider range of capacity factors, probably due to very good wind conditions in specific parts of the world ranging from 32% to 58%. 40% would mean an annual energy output of 2628 TWh.

For solar PV developments, no numbers were found that are compatible with grid developments. There are huge numbers for solar deployment in the south. The only report is from Solar Power [15]: reporting a power level of 8 TW of PV and 1.7 TW of wind energy. These numbers are, however, not coherent at all with the Eurostat numbers as the geography is larger than the EU 27 countries. In order to get a feeling for PV impact, we doubled PV growth from now (i.e., 42 TWh, or around 40 GW per year). This leads to 1189 TWh and 1.1 TW by 2050.

Below we report the result from these assumptions.

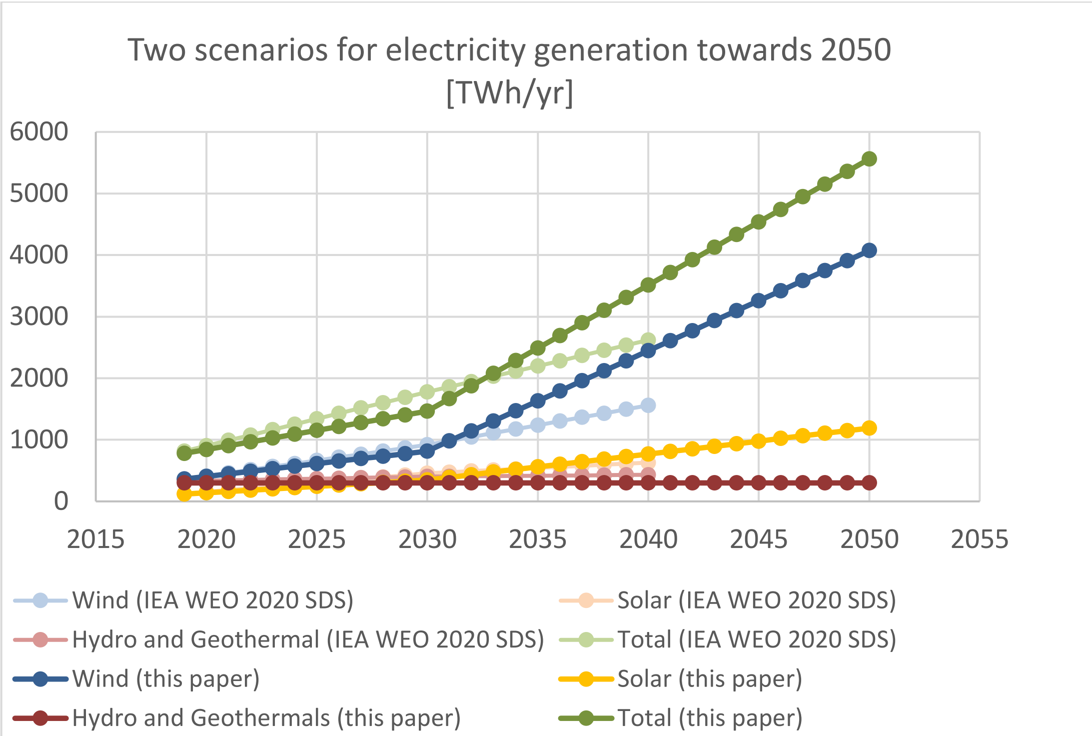
Figure 7



Below we list some reference scenarios supported by detailed modelling and with different results:

- The assumptions by the latest MIX decarbonization scenario of the EU [16] are interesting in this respect. The MIX scenario assumes 2304 GW of renewable electricity capacity: 290 GW from offshore wind; 963 GW from onshore wind; and 1051 GW from solar PV. Data for renewable electricity generation by 2050 is also disclosed: 1155 TWh from offshore wind; 2259 TWh from onshore wind; and 1315 TWh from solar PV.
- The IRENA "Global Renewables Outlook: Energy Transformation 2050" TES scenario assumes 1405 GW of variable renewable electricity by 2050: of which 621 GW from wind and 784 GW from solar PV. Data on renewable electricity generation in EU-27 is not disclosed.
- In the figure below we report the values for IEA WEO 2020.

Figure 8



Note: the plot above does not include the renewable electricity supply from Marine (IEA; 2030: 5 TWh), nor bioenergy (IEA; 2030: 257 TWh). The renewable electricity supply from CSP (IEA; 2030: 13 TWh) was included within the values for "Solar".

- For instance in its refence scenario for renewable technical potential including GIS-based land-restriction constraints, JRC [17] suggests 220.6 GW[9] for offshore wind (excluding floating wind), with an average capacity factor of 43.85% and a production of 860 TWh. The 220.6 GW is below the 300 GW mentioned above. For onshore wind, 1847 GW is given with an average capacity factor of 30% [18] (compared to 750 GW). The setback distances of onshore wind turbines from housing are studied in detail, together with high resolution geo-spatial wind speed data. This leads to a very high potential of 5003 TWh, which may prove difficult, though, in terms of social acceptance. Indeed, social acceptance is an important factor within assessments of potential renewable electricity production. Detailed modelling and assumptions are also used to assess the potential from solar PV, distinguishing for example between solar PV installed on residential, industrial or natural areas and between different irradiation scenarios. By assuming 3% of the non-artificial areas as available and a range of irradiation values from 85 MW/km^2 to 300 MW/km^2 [10], while disconsidering the potential from CSP, the JRC study suggests an upper bound for potential electricity production from solar PV ranging between 4.7 TW / 5041 TWh (85 MW/km^2) and 15.5 TW / 16421 TWh (300 MW/km^2). These numbers can be regarded as the upper bound for renewable energy levels by 2050.

Overall, we see the potential for a three to four times increase in renewable electricity generation compared to 2030 within the EU. While the renewable electricity capacity of onshore wind and solar PV are assumed to increase by a factor of between two to three, the renewable electricity capacity of offshore wind is assumed to grow from 88.4 GW to either 290

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[9] 324.2 GW offshore, if the 103.6 GW in the UK are included.

[10] 85 MW/km^2 = 85 W/m^2; likewise 300 MW/km^2 = 300 W/m^2

GW or to 300 GW (by a factor of almost four). Again, this is ambitious, will require huge investments and continued (or even increased) public acceptance on funding and planning, but is technically possible.

In the table below, we summarise the estimates on potential of renewable electricity generation by 2050 according to the sources mentioned above:

Table 8

2050 (*except for IEA's numbers which go only until 2040)	Our assumptions	IEA WEO 2020 SDS scenario [19]*	IRENA Global Renewables Outlook TES scenario [20]	EU EC SWD176 (2020) [16]
Solar PV	1100 GW 1189 TWh/yr	500 GW* 596 TWh/yr*	784 GW †	1051 GW 1315 TWh/yr
Onshore wind	750 GW 2628 TWh/yr	476 GW (on- and offshore) * 1559 TWh/yr*	621 GW (on- and offshore) †	963 GW 2259 TWh/yr
Offshore wind	300 GW 1445 TWh/yr			290 GW 1155 TWh/yr
Total	2150 GW 5262 TWh/yr	976 GW* 2155 TWh/yr*	1405 GW †	2304 GW 4729 TWh/yr

*Notes: † Generation data by 2050 was not disclosed in publicly available documentation relative to this scenario. * IEA WEO 2020 SDS scenario does not disclose its results relative to 2050. Therefore, the data reported is relative to 2040.*

What about nuclear? In order to have a full overview of carbon neutral technologies, nuclear power needs to be taken into account. In 2019 in EU-27 106 nuclear reactors with an overall power of 104 GW delivered 765 TWh, or 26 % of all electricity supplied [21]. Four reactors with an overall power output of 4.3 GW are under construction: in Finland, France and the Czech Republic. Additionally, seven reactors are planned with a total power of 7.29 GW. However the future of nuclear power is unclear. The present power plants are ageing, and most of them will be out of service by 2050. It is still unclear when the third generation power plants under construction (Flamanville, Oikilotto, Hinkley Point) will finally come online and at what cost. Given the price of the energy produced, new nuclear power is not competitive with renewable sources. We may still see nuclear power in the mix by 2050, but probably less than today. Indeed, the EU EC SWD(176) MIX scenario (2020) calculates 89 GW of nuclear by 2050, and IEA WEO 2020 95 GW by 2040, compared to 104 GW by 2019.

4. Decarbonizing existing and future electricity demand

The next step of this 'availability analysis' is to consider the questions: how much renewable electricity will the EU need, for which uses, and by when to meet its GHG objectives and associated targets?

Again, for 2050, such an analysis is of course difficult; it depends on many factors including technological development and policy choices. However, we have undertaken a high-level sector-based analysis of expected additional electricity demand, based on -55 % carbon reduction by 2030 and carbon neutrality by 2050. Sometimes there may be a need for intermediate steps in the analysis. For instance, five years may be needed, to clarify matters. In particular we have assessed the electricity needed to decarbonize the transport, buildings and service sectors, and finally for industry, on the basis of the end-uses that can be technically and cost-effectively electrified. If a service is provided, for example, using green hydrogen whenever electrification would be possible instead, the total electricity necessary from renewable resources will be higher and this will have to be accounted for in the planning. Indeed, hydrogen produced from electricity induces substantial losses in the overall chain.

We assume that the demand for energy services - i.e. the amount of km that people will wish to travel or of industrial products required - does not change[11], but we have factored in energy efficiency improvements that result from changes in energy vectors (electric cars and heat pumps are far more efficient, for example, than combustion engine's and oil boilers). This (largely reasonable) assumption reflects that this is not a detailed energy modelling exercise, but rather a trend analysis.

4.1 Decarbonizing Transport

The EU puts forward a “sustainable and Smart Mobility Strategy – putting Europe on track for the future” on 9 December 2020 [22]. The strategy provides a link with the green deal: “The success of the European Green Deal[1] depends on our ability to make the transport system as a whole sustainable.” However, the emission reduction put forward in transport by 2050 is only 90%, something incompatible with the carbon neutrality of the green deal. The only concrete number given is the estimate/aim that by 2030 at least 30 million zero-emission vehicles will be in operation on European roads. This is not a particularly impressive number as some 243 million passenger cars operate on European roads [23], while the definition of “vehicle” in the EU is much wider (including, among others, cars, lorries, buses, coaches, light vehicles, trains, aircraft, ships, boats, ferries, etc.). In practice this would imply that only 10% (maximum 12.5%) of vehicles would be zero-emission by 2030. This number is totally incompatible with the 55% greenhouse gas reduction by 2030 put forward in the Green Deal.

Ten flagship projects are defined in the mobility strategy. In flagship 1 “Boosting the uptake of zero-emission vehicles, renewable & low-carbon fuels and related infrastructure” no figures are given. Classic instruments are repeated and other linked strategies are mentioned, amongst others: CO_2 standards; air pollutant emissions standards; batteries; 2zero; hydrogen; and high performance tyres. No numbers on vehicles are given at all. The other nine flagship projects do not provide any further elements on the timetable for reaching carbon neutrality in transport.

Therefore, we look at the data available in Eurostat to find a hypothetical path towards transport decarbonization by 2050, with an intermediate target in 2030. Transport overall requires 4.357 TWh[12], and is, according to Eurostat, composed of three parts:

- i. Transport as defined by Eurostat 3.365 TWh
- ii. Bunker fuels for international navigation 507 TWh
- iii. Fuel for international aviation 485 TWh

11 Mobility in persons.km or ton.km remain the same as are the transport modi. The temperature and comfort in the houses remain the same.

12 Source:
https://ec.europa.eu/eurostat/cache/sankey/energy/sankey.html?geos=EU27_2020&year=2018&unit=GWh&fuels=TOTAL&highlight=_&nodeDisagg=0101111111000&flowDisagg=true&translateX=-3806.753595830847&translateY=-617.7487735928504&scale=2.512716829970907&language=EN

Table 9: Eurostat data on transport demand in 2019

Transport	Energy use per year [TWh/yr]
i. Transport Eurostat	3365
➢ Electricity	59
➢ Oil and petroleum	3080
➢ Gas	43
➢ Renewables (biofuels)	183
ii.International aviation	485
iii.Marine bunker	507
Total Transport	4357

Apart from a few vehicles currently using electricity and gas, the energy for the transport sector is currently mostly supplied by liquid fuels (3263 TWh): most of it being fossil fuels (3080 TWh), and the remaining renewables (biofuels) (183 TWh) blended with fossil fuels.

4.1.1 Decarbonizing road and rail transport

Road transport uses 3144 TWh of fossil fuels and biofuels. If we include rail transport – with a 14 TWh oil and petroleum demand - we derive a very good estimate of overall liquid fuels consumption by internal combustion engines (3158 TWh). In principle, with present technology, it is possible to electrify this demand for energy services through batteries supplying electric drives.

The individual transport of persons is transitioning to electricity. Electric cars have, on average, an electric energy demand of 20-25 kWh/100 km [24,25]. For smaller cars, the electric energy demand is lower than 20 kWh/100 km. The average fuel demand of the current ICE fleet is 7.2 l/100 km [26]. For Europe a number of 5.1 l/100 km is given, with a disclaimer that the number of SUVs is growing fast. With a weighted average of 46% petrol and 54% diesel passenger cars [27], this leads to an average of 73.2 kWh/100 km with a minimum of 52 kWh/l for the lowest European figure: overall, electric cars consume 2.5 to 3 times less energy than ICE cars.

Heavy-duty vehicles, lorries, buses and coaches are responsible for about 25% of CO_2 emissions from road transport in the EU [28]. Therefore, we estimate that roughly 75% of the energy for road transport is going to cars and 25% to heavy transport:

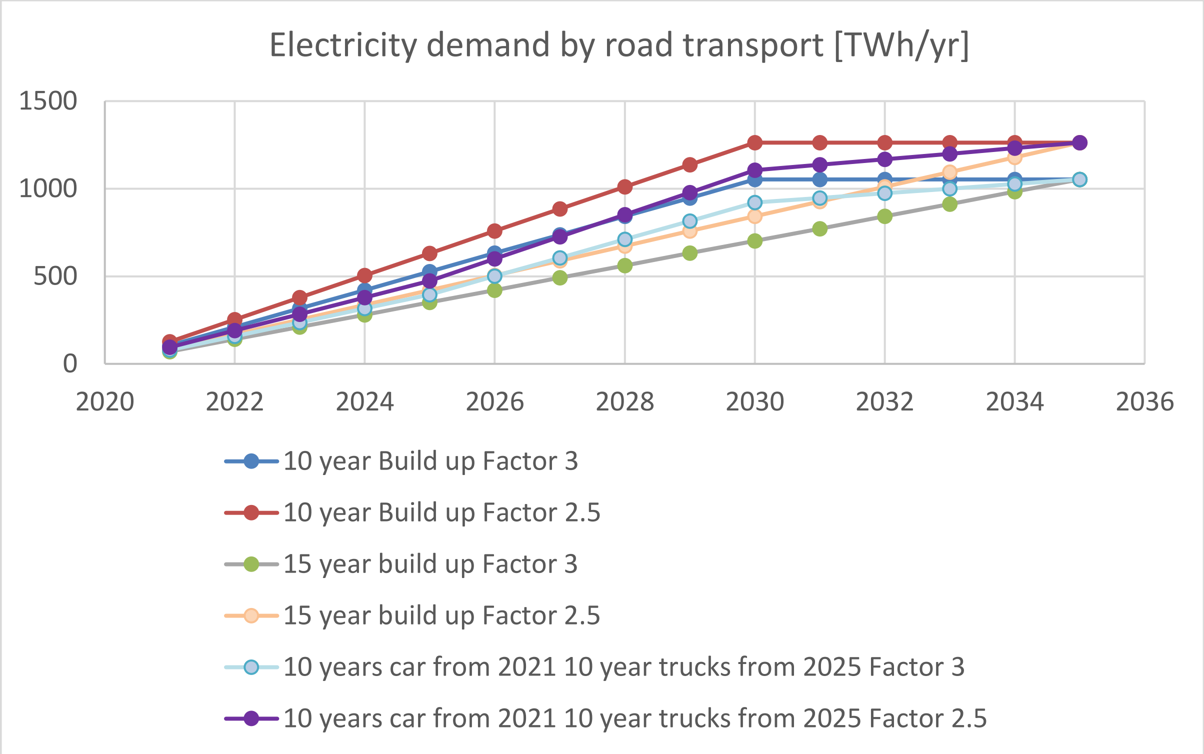
- Local buses can be cost-effectively electrified, given that trajectory and charging times can be planned;
- The electrification of trucks is more difficult but seems to be taking off [29]. As the efficiency of large diesel engines, for instance, in trucks and diesel trains, is higher than the average car, the energy gain when electrifying these engines will be lower.

Let us assume, for the purpose of this exercise, that all applications of road and rail internal combustion engines can eventually be electrified and that there is constant mobility demand.

In order to get a feeling for the amount of electricity needed for transport electrification, we put forward six ambitious scenarios. The extra renewable electricity to be supplied, taking account of ICE vehicle efficiency assumptions, amounts to 1053 TWh (factor 3) to 1263 TWh (factor 2.5). The electrification of road transport implies an enormous gain in energy efficiency. In the figure below we assume the following ambitious electrification routes:

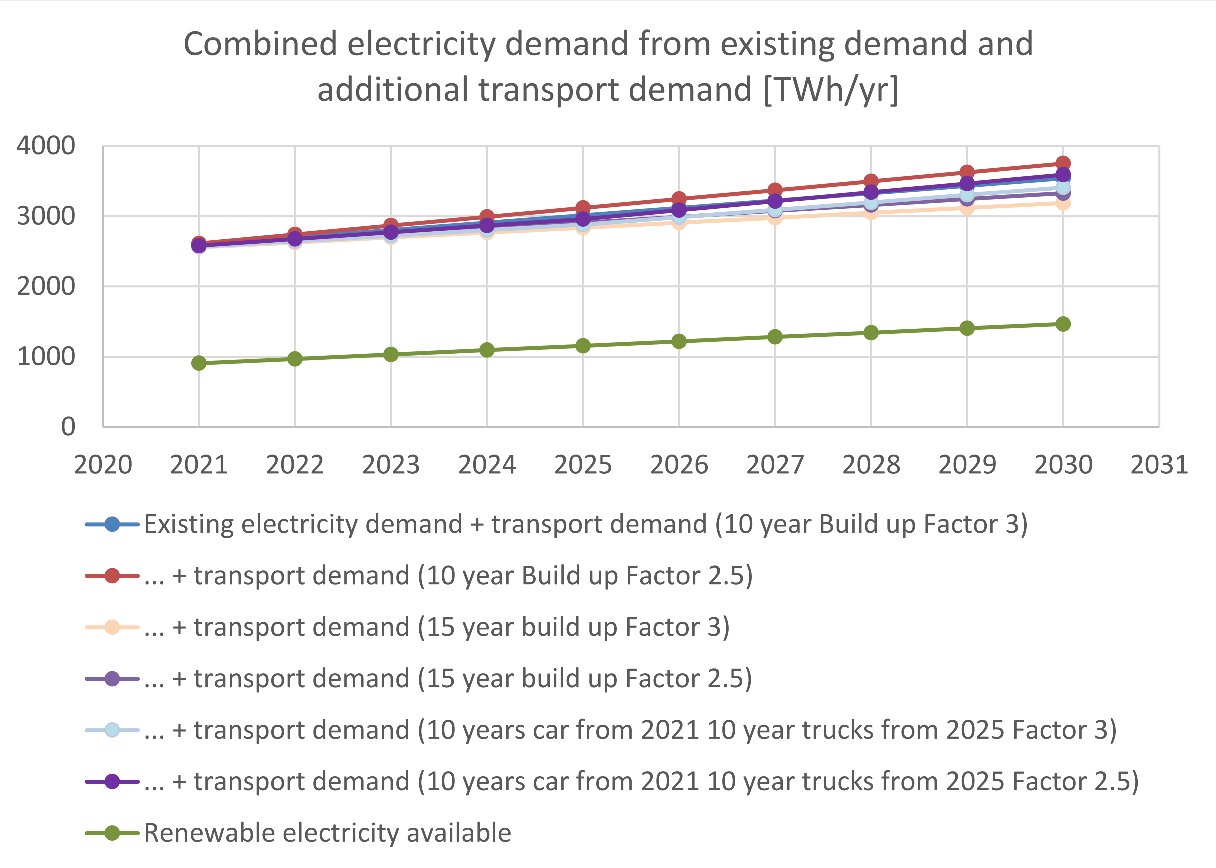
- Electrification of road transport by 2030 (factor 3)
- Electrification of road transport by 2030 (factor 2.5)
- Electrification of road transport by 2035 (factor 3)
- Electrification of road transport by 2035 (factor 2.5)
- Electrification of cars from today until 2030 and of heavy traffic between 2025 and 2035 (factor 3)
- Electrification of cars from today until 2030 and of heavy traffic between 2025 and 2035 (factor 2.5)

Figure 9



The next figure compares the combined demand for electricity (present-day electricity demand and electricity demand for transport) up to 2030. It is clear that the projected increase in renewable generation (1615 TWh) will not be able to cover the increase in road transport electricity demand in addition to existing electricity demand.

Figure 10



Let's assume that the same percentage would be aimed at as the renewable portion of the electricity supplied for road transport as with existing electricity demand (65%). In that case the deployment of renewables would need to be increased with respect to our assumptions (1615 TWh) by a minimum of 57% (fifteen-year build up, factor 3) and a maximum of 102% (ten-year build up, factor 2.5) in the next decade.

The decarbonization of road transport as described above may seem too ambitious. It assumes that all land transport is electrified by latest 2035, and that 65% of the present electricity demand is decarbonised. Therefore, we designed a seventh "retarded electrification of transport" scenario, whose relative percentages for demand uses covered by renewables are reported in the table below, and the relative amount of renewable electricity demand beyond 2035, going towards 2050, in the figure below.

Figure 11

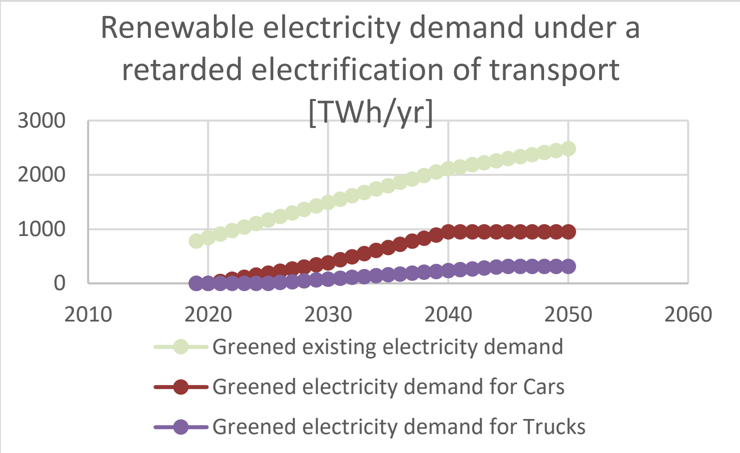


Table 10

% covered by renewables	2030	2040	2050
Existing electricity demand	60	85	100
Cars energy demand	40	100	100
Trucks energy demand	40	80	100

Of course, electrification can be slowed down, at the cost however of not reaching the target of carbon neutrality. The authors' believe that biofuels cannot substitute electrification to a substantial extent within a carbon neutrality pathway.

4.1.2 Decarbonizing aviation and shipping transport

The EU-27 demand for liquid oil and petroleum products for aviation and shipping (passenger and freight transport, including marine bunkers and international aviation) is estimated in 2019 at 1118 TWh. In Eurostat, the fuel for international navigation and aviation is not included in energy for transport.

With the exception of a small share of domestic navigation, the potential for direct electrification is limited and hydrogen or synthetic fuels/biofuels will be required. Therefore, we estimate the renewable electricity demand by 2050 for decarbonizing aviation and shipping at 1490 TWh. In order to do so, we assumed that aviation and navigation can be performed using hydrogen - and not other hydrogen-derived fuels - and that the efficiency of electrolysers will improve to around 75%. This latter assumption means that at least 33%[13] more of renewable electricity will be required in order to consume 1 kWh of hydrogen, compared to using directly 1 kWh of electricity. If more appropriate fuels (ammonia, methanol, methane, e-diesel, e-kerosine) are used, the overall conversion efficiency will be lower and the amount of renewable electricity required will be higher.

4.2 Decarbonising buildings and services sector

On 14 October 2020 the European Commission published its "Renovation Wave Strategy", which aims to at least double renovation rates in the next ten years and to make sure that these renovations lead to higher energy and resource efficiency. In her 2020 State of the Union address, Commission President Ursula von der Leyen indicated that the renovation "wave" would be a core feature of the Next Generation EU economic recovery plan. Indeed, the Commission envisages that by 2030 up to 35 million buildings could be renovated [30], but so far only 1% of buildings in the EU are renovated each year. Based on existing experience, the aforementioned goal is extremely ambitious, but nonetheless we base our calculations on the

[13] To deliver 1 kWh of energy as H2 rather than electricity, at a power-to-H2 conversion efficiency of 75%, there would then be a need for 1/0.75 = 1.33 kWh of electricity.

assumptions that it will be achieved. Buildings are responsible for 40% of the EU's energy consumption and 36% of its greenhouse gas emissions, so this is an important assumption.

2019 EU-27 energy consumption in residential (2865 TWh) and commercial buildings (1500 TWh) was 4365 TWh. The non-electrical part (67%; 2914 TWh) of the energy supply is dedicated to space heating, hot water, and cooking. Out of this non-electrical part, all fossil-based heating (oil, petroleum, gas, solid fuels) currently provides around 1887 TWh[14].

Let's assume that, and in order to stay in line with EU ambitions [31], circa three quarters of non-electrical energy demand are saved through renovation (2196 TWh). Additionally, part of the remaining energy demand might continue to be supplied through the present sources (heat networks, renewables). We assumed, for our purposes, that heat networks will be supplied by renewable resources or waste heat from industry or similar resources, in addition to green electricity (e.g., heat pumps). The fossil-based portion which will remain after deep renovation should be decarbonised using heat pumps. These will demand some 755 TWh of heat. The amount of electricity to be supplied depends on the COP (coefficient of performance) of the heat pump.[15] Therefore, we usefully assumed an average COP of 3.5. This leads to an additional electricity demand of 216 TWh [32]. Indeed, electrification combined with renovation implies real gains in energy efficiency and we can also notice that this amount of extra electricity is low compared to the values found for the electrification of road transport.

The above-mentioned 75% energy efficiency assumption is highly ambitious given existing renovation rates and levels (few renovations today provide the savings needed to meet these objectives). Nonetheless, in line with the conservative approach taken in this analysis, we have calculated expected future renewable electricity demand for 2050 assuming they are met.

Neither hydrogen nor synthetic fuels are needed, at least, in theory, though it is conceivable that fuels will be used, say, rurally where there are weak electricity grids, or where customers prefer to heat using molecules (and regulation currently permits this). It is evident that substituting the heat pump/renewable electricity combination with a boiler employing sustainable fuels is not as efficient, and requires vastly more renewable electricity for supplying the electrolysers producing the hydrogen at the basis for sustainable fuels.

Additionally, we need to include in commercial buildings the additional electricity demand from data centres. JRC [33] estimated the total EU data centres electricity demand at 104 TWh by 2020 – be it for operational activities or for cooling. By 2030, this demand is expected to increase to 160 TWh.

4.3 Decarbonising Industry

To a significant extent, regarding heating applications within industrial processes, fossil fuels could theoretically be substituted by direct electrification. For temperatures of up to around 1000°C, direct electrification technologies are available [34]. Especially for low-temperature processes (<100-200^{0}C), heat pumps often prove an efficient solution.

For very high temperature heating industrial processes electrification is currently not an option, and sustainable fuels - molecules will be necessary. The need for molecules as feedstock has to be added. However, the amount is far from clear as a lot of the future technological zero-GHG processes are themselves not yet clear. Investment cycles are typically of five to seven years and sometimes even longer. In fact, between now and 2030, we could expect only one major investment wave for industrial processes particularly with large

[14] natural gas (1345 TWh) and petroleum/solid fuels (542 TWh)

[15] For a heat pump with air as heat source the COP is lower than in a water or geothermal sourced systems.

industrial plants (e.g., iron & steel, chemistry, cement). Therefore, the introduction of new technologies fully based on electrification or hydrogen is going to be very limited within the next ten years, and may expect to be concentrated between 2035 and 2050. It remains to be seen how this will develop, and one constraining factor may indeed be the physical unavailability of renewable electricity in the EU for all potential uses, and notably industry for direct and indirect (hydrogen) uses. In such circumstances CCS can be added to existing installations - we have 30 years of technological development to possibly bring CCS/CCU and other low-carbon technologies to very close to zero-, if not zero-, carbon.

If we focus on the industrial processes where fossil fuel input is both part of the material and the energy flow (iron and steel, chemical and petrochemical, non-metallic minerals), fossil fuel consumption for these applications currently stands at 912 TWh. By 2050, if we assume – as a minimum – that half of it will be replaced by electricity, an additional 456 TWh of annual electricity consumption will be created by 2050. Below we explain how:

- The iron and steel industry in Europe will require 400 TWh of electricity, i.e. 292 TWh more than today [35]. Part of it (234 TWh) is needed for producing hydrogen, sometimes at a different place, sometimes integrated within the steel plant [36]. If production is in-house, electricity has to be added to the EU's renewable electricity demand. Even without accounting for the electricity used for hydrogen production integrated in steel plants, the additional electricity demand will stand at about 56 TWh.
- The chemical and petrochemical industry will see a lot of important changes in the flow of molecules and the demand for additional electricity demand is difficult to predict. The installation of electric crackers has already been announced. This will add a large amount of electricity demand.
- The same holds for the cement industry. However, predicting additional electricity demand will be difficult.

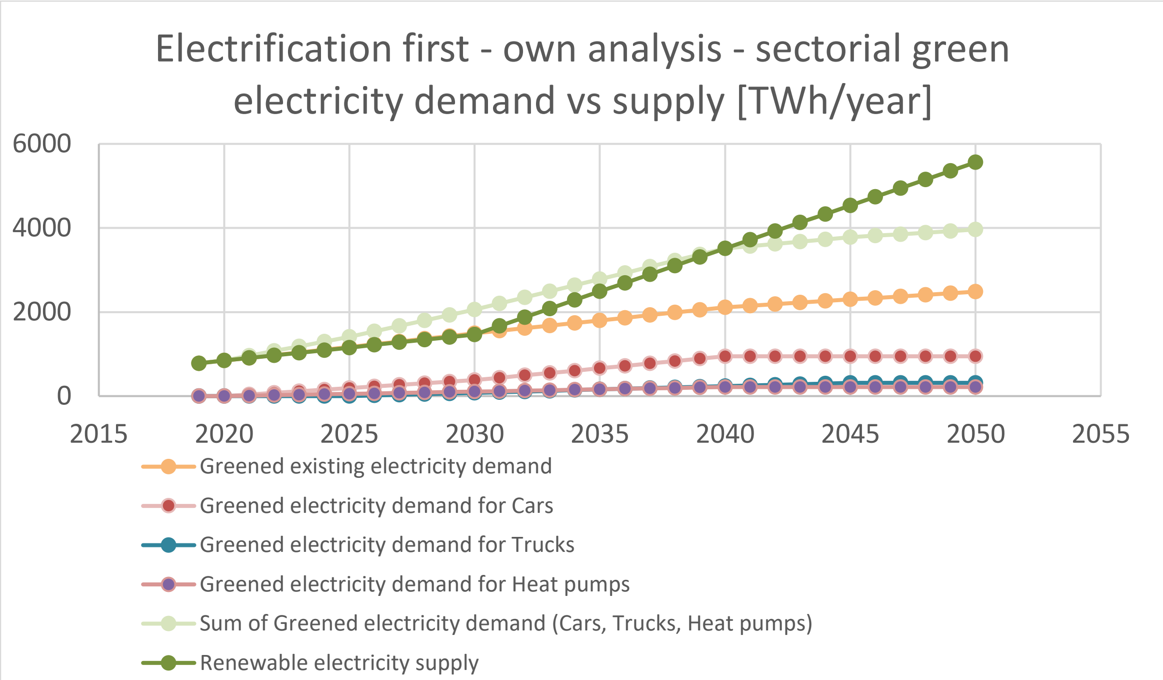
Overall industrial electricity demand is therefore going to increase substantially, with a minimum of 500 TWh, but very possibly double this amongst other as the above discussion does only cover part of the industrial demand.

5. Green electrons will be scarce and should be considered valuable

The following graph illustrates our findings, illustrating how much renewable electricity production may be expected on the assumption that the EU installs the equivalent of 65% of its current electricity demand by renewable by 2030 and then exploits the potential set out in previous sections. It plots also the expected demand from electricity ('regular'), transport and buildings.

We do not, at this stage add industry. For the moment there are GHG's emissions options available, though some of them are still at a lower TRL level, to get to high and potentially very high carbon neutrality levels (CCS, turquoise) that require no or far direct, local electrification. Together with potential import of sustainable molecules, this makes the situation in the longer run less evident than for transport and heating of buildings.

Figure 12



Note: This is a simplified analysis, and a complete assessment of supply and demand would require inputting the numbers for industry, data centres, other electrified transport means and for sustainable fuels production. However, "the bucket is already empty" without accounting for those. We report here the seventh transport decarbonization scenario, which we called "retarded electrification of transport" scenario. The conclusions drawn from this figure do not change if we substitute the numbers for future renewable electricity supply with those of other scenarios we analysed (e.g., IEA).

The required renewable electrical energy shown in the figure above– and the relative scenario - is an estimation of the minimum need to deliver the energy for decarbonizing present-day electricity demand, all road transport and building heating/cooling. It does not include the electricity needed to make industry carbon neutral. At least 500 TWh of electricity, but most probably double this amount, will be needed for industrial carbon neutrality. Another relatively large future energy service – not included in the figure above - has also to be considered: data centers. In its study JRC estimates that 160 TWh [33] will be needed; up from the 104 TWh required today. Nor does this scenario account for the renewable electricity needed to produce e-fuels for decarbonized industry, for the replacement of the fuel for aviation and navigation, and as strategic green energy reserves. Additionally, if part of the decarbonization of road transport or building heating were to be done by sustainable fuel (based on green hydrogen), the overall need for renewable electricity for the same energy services would be considerably higher. By then, "the bucket would already be empty".

In a well designed electricity system, with digitalization to control demand and storage with respect to production patterns towards a consequent optimized grid use, together with increased and well-managed cross-border capacity, there will be a limited amount of curtailment. This is not necessarily a problem. Demand may even be somewhat larger than using the electricity directly at the moment it is produced, as part of the demand can be satisfied through electricity temporarily stored in batteries (e.g. home batteries, day-night cycle) with a roundabout efficiency of around 85 %, which is far better than the roundabout efficiency of, for instance, storage via hydrogen (around 35 % [37]). Other storage means could also be considered. But by 2030 producing sustainable fuels through electrolysers supplied by electricity from the grid would increase electricity demand. It would require the use of fossil-based generation technologies, given the insufficiency of the renewable energy supply. If natural gas power plants are used, and assuming a 400 kg CO_2/MWh, then one MWh of hydrogen produced would generate 533 kg of CO_2[16].

Now a summary:

- The electrification of road transport leads to a massive improvement in energy efficiency. Electric drives supplied through batteries (instead of the internal combustion engine) reduce energy demand by a factor 2.5 to 3. If this substitution could be made for the entire fleet, the present 3154 TWh of fossil-based energy become between 1053 to 1263 TWh of renewable electricity by 2050. The exact number depends on the average energy efficiency of the ICE used (better for large lorry motors and diesel engine cars). By 2030, assuming a "retarded electrification of transport" with a 40% share of electric vehicles and 20% of electric trucks, the additional renewable electricity demand is estimated at 458 TWh.
- Buildings will require far less energy for space heating after renovation. The 1887 TWh of fossil-based heat can be reduced to 755 TWh by deep renovation. Supplying this heat by heat pumps requires 216 TWh of electric energy, further reducing energy demand.

How can the carbon content of energy services be most effectively reduced? It would be necessary to electrify heat demand and road transport from renewable resources, in addition to present-day electricity demand. This would yield 3769 to 3979 TWh of renewable electricity directly supplied to the final energy service. By doing this, supplying further energy services in industry with renewable electricity is going to be very difficult. In fact, we should also plan for other potential renewable electricity uses towards carbon neutrality:

- Extra renewable electricity will be needed in the decarbonization of industry. A reasonable amount may be estimated to be 1000 TWh in the longer run. Which part already would be needed by 2030, is unclear, while potentially small.
- A further large electric energy demand by 2030 will come from increasing digitalization. But that is hard to assess. JRC has estimated that the energy demand from EU data centres will increase by 56 TWh in the next decade. But digitalization is not only about data centres.
- If 40 GW of electrolysers were installed by 2030 with an economically required number of operating hours at a minimum of 2000 hrs/year, this would require at least 80 TWh/year of additional electricity. Instead, if the Commission's 2030 target of substituting 8 MT of 'grey' hydrogen demand currently used as feedstock is to be achieved only through electrolysers, around 400 TWh/year of additional electricity demand would be needed.

Seen in this light, and again on the basis of a conservative analysis and an achievement of current targets set towards carbon neutrality, it becomes clear that there is little room by 2030 for supplying the additional renewable electricity demand due to the electrification of road transport (458 TWh for 40% electric vehicles and 20% trucks), the heating of buildings (108 TWh for 50% renovation and heating by heat pumps, ie half of the renovation wave, the lower hanging fruit, finished by 2030), not even including the electrification of industry and the electricity demand for producing synthetic fuels – including hydrogen.

6. Conclusions & policy recommendations

The green deal was put forward by the EU, with the aim of making Europe the first carbon neutral economy. Renewable energy resources that will be the key providers of electricity in

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[16] Considering an electrolyser efficiency of 75%, 1 MWh hydrogen would correspond to 1.25 MWh of fossil based generation, so to 1.25 * 400 = 533 kg of CO_2.

the sustainable future are wind (onshore and offshore) and solar (photovoltaic) power. Electric energy is the most effective form of energy (highest quality) and the relevant engineering principles are clear: every change in the form of energy means losses. Therefore, the most efficient way to use electricity is to feed it directly to the energy services needed by the user. The optimal use of the available renewable resources in the “efficiency and electrification first” approach towards carbon neutrality leads to a minimum cost in investments; to a minimum use of space (offshore and onshore); and to a minimal environmental and societal impact.

The first step towards carbon neutrality will be to decarbonize present-day electricity demand, some 2485 TWh. Reaching 65% renewable electricity supply by 2030 for present-day demand (≈1615 TWh) is almost feasible based on present policy input (e.g., NECPs). But if we combine the results discussed above, there is no flexibility by 2030 for supplying the extra electricity demand from industrial electrification and sustainable fuels production. This is due to the electrification of road transport (458 TWh for 40 % electric vehicles and 20 % trucks for a not so ambitious electrification strategy) and the heating of buildings (108 TWh for 50 % renovation and heating by heat pumps). Additional electricity demand due to the electrification of industry, to data centres (an additional 56 TWh according to JRC) and to the production of sustainable fuels (e.g., H_2) also has to be planned for. In other words, “green electrons will be scarce”.

Given the fact that green electrons will be scarce, they should therefore be considered valuable. Five main actions need to be considered by 2030 and 2050:

- A significant increase in ambition for renewable electricity supply is required. However, producing all of the above with renewable electric energy in the EU-27 will be very hard, and close cooperation with neighboring countries will be needed. For example, cooperation with the UK, Norway and Switzerland will be especially important: as will cooperation with countries to the east. Electric links might also be usefully established with North Africa.
- The use of renewable electricity has to be targeted following the energy system integration strategy. Applications where electrification brings an enormous gain in efficiency such as passenger transport or low-temperature heating both in building and industry should be prioritized.
- In terms of producing hydrogen, there is strong GHG value in achieving the Commission's target of substituting 'grey' hydrogen demand used as feedstock by 2030. Using renewable electricity to do so would add around 400 TWh p.a. to produce the 8 MT of grey hydrogen currently consumed in the EU. Using precious renewable electricity over the next decade to do so when the hydrogen can be very largely decarbonised using SMR/CCS, and almost certainly at far lower cost, appears illogical unless considerable very cheap renewable electricity can be produced in addition to needs for electricity supply, transport building and industry, which appears unlikely. Pyrolysis, producing potentially zero-carbon hydrogen using a fraction of the renewable electricity compared to electrolysis is a promising technology, that needs maturing.
- Reaching for full carbon neutrality by 2050, for the hard-to-abate sectors where sustainable fuels are likely needed as feedstock and/or energy source in high temperature applications in industry or for long-distance transport applications (aviation and navigation) or as green energy strategic reserves for periods with low wind and sun (including the shorter Dunkelflaute), the focus might usefully be put, in the next years, on technology development and demonstration.
- In addition to carbon neutral technologies, the import of both renewable electricity (requiring major new power lines to be constructed) and renewable energy based molecules from outside Europe should be assessed or rolled out.

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