NATO

ENERGY SECURITY

CENTRE OF EXCELLENCE

Connecting production facilities and transport infrastructure for creating robust and carbon-neutral sector-integrated energy systems

By Dr. Jutta Lauf and Dr. Reiner Zimmermann

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Introduction

Energy security of nations is a precondition for developing economic wealth and maintaining political power. As a means of international politics it is becoming increasingly important. Also, there is a growing political consensus that humanity must steer towards a carbon neutral future by shifting from fossil carbon-based fuels to renewable sources of energy. However, the pathways for such a transition are highly debated. An often overlooked problem in this global transformation process is the need to create completely new infrastructures, not only for renewable power generation, but for energy storage, transport and distribution beyond national boundaries and continents. Such new structures will dramatically re-arrange the political and economic importance of many nations, as well as their ability to generate revenues from energy production.

The three largest energy consuming sectors are power generation, transportation and heating/cooling. Currently the sectors are mostly separated, resulting in higher costs and pollution. For example the heat from electricity production is seldom used for district heating systems. Enhancing the transfer of energy and energy related by-products within these sectors is called “sector integration” and is widely discussed as one of the solutions to the climate crisis. This article discusses new components and interconnections of energy consuming and producing sectors to create primarily a robust energy system. Its security and resilience will be increased by multiple and technologically different production processes.

All this will come with higher energy costs, as economies of scales are missing or starting with a time lag, especially in the early stages of the transition. The measures to be taken will take decades and require huge financial investments. However, the environmental and human costs of the climate crisis with all its consequence are expected to be higher than that. A new energy system should be robust in term of disruptions of any kind, renewable in terms of not emitting CO_2 and sector integrated in terms of using synergy effects across all possible applications. Implemented wisely, this new energy system may contribute to a more equal global distribution of wealth and, therefore, may stabilise societies globally.

Perception changes in energy security

The security of an uninterrupted and affordable energy supply was for a long time taken for granted by industrialized nations. The first concerns regarding the availability of - at that time almost exclusively fossil - energy were caused by the international oil shortages in 1973 and 1979/80 when geopolitical disruptions resulted in supply problems and two global oil price shocks.[1] Surprisingly, in the aftermath of these events most industrial nations did not take any serious actions to reduce the dependency from fossil fuels, especially for their transportation and heating sectors. Energy security as a means of international politics was “off the radar” because strategic alliances with oil producing countries were well established and the shale oil boom and new fracking technologies in North America led to lower oil prices. Since then, the political situation for Western nations changed dramatically due increasing conflicts in many oil producing regions of the Middle East and North Africa, rising tensions with Russia and the disruptive politics of the new economic powerhouse of the People’s Republic of China.

Growing environmental concerns

In addition, growing political concern among parts of the general public in North America, Europe as well as a number of Asian countries have increasingly pressured governments to address the environmental and climate problems caused by the burning of fossil fuels. Rapid reduction of global carbon emissions is not only demanded by organisations like *Fridays for Future* or *Greenpeace*, but also by most political and economic stakeholders of industrial nations.[2] This resulted in the United Nations’ effort in 2015 for a legally binding international treaty on climate change. The treaty was adopted by 196 countries at the COP 21 conference in Paris in 2015 and entered into force on the 4th of November 2016. Its goal of the treaty is to limit global warming to well below 2.0 and preferably to 1.5 degrees Celsius, compared to pre-industrial levels, primarily by significantly reducing fossil carbon emissions. Ambitious goals for carbon emission reduction were declared by individual nations of the Western world, most notably by the European Union members, who unveiled the “Green Deal” package. This policy plan provided a comprehensive and detailed action plan how the EU can become fully carbon neutral by 2050.[3]

New energy infrastructures

Internationally the political consensus is growing that humanity must steer towards a carbon neutral future by shifting from fossil carbon-based fuels to renewable and whenever possible even carbon free energies. However, the technological pathways and ecologically sound solutions for such a transition, as well as the type of renewable energy resources used to achieve a carbon neutral energy sector, are highly debated. Focussing on more wind-, solar- and geothermal energy resources will inevitably change the geopolitical and economic significance of many nations. An often overlooked problem in this debate is the need to create completely new infrastructures, not only for renewable power generation, but for storage, transport and distribution of energy beyond national boundaries and continents. Such new structures will dramatically re-arrange the relative geostrategic importance of many nations and will impact their ability for generating revenues from energy production and transport. Thus, over the coming years, it will become a crucial task for industrialized nations to invest in new technologies and infrastructure projects in order to become reliable energy producing partners.

Integrating the energy sectors

Globally, the three largest energy consuming sectors are power generation, transportation and heating/cooling, which usually depend on often very long energy and material supply routes (pipelines, shipping, trucking). The three sectors still heavily rely on fossil fuels and only on rare occasions exchange energy with each other. The enhancement of the transfer of energy and energy related by-products within these sectors is called “sector integration”. It is widely considered as one of the solutions to the climate crisis, as sector integration has the potential to (1) reduce greenhouse gas (GHG) emissions, (2) reduce long term energy costs and (3) increase energy supply security. For example, in a combined electric power and heat generation plant, the fuel is used for both producing electric power for the grid and heat for district heating systems.

The usage of surplus electricity from renewable power plants is regarded as a key element for sector integration and for the creation of an energy supply completely fed by renewable power plants. Surplus electricity occurs when renewable power plants produce electricity, which is neither instantly demanded nor stored. In windfarms this leads to intentional idling of wind generators and in solar parks to intentional shorting of the arrays, both resulting in a reduction of the economic (reduced working hours) and ecological gains (fossil powered plants will produce cover the demand). However, such excess power could be used in district heating systems.[4] Other options include the conversion of electric energy into storable hydrogen by electrolysis of water or into ammonia (NH_3) by using N_2 and the Haber-Bosch process.[5] Yet another alternative could be the production of carbon based synthetic fuels from H_2 and a carbon source.[6] The potential for pumped storage in hydro power stations is limited and further expansion generally meets strong opposition from environmentalists and the society at large.[7] Overviews of renewable energy technologies and challenges involved can be found in recent issues of “Energy Highlights” for H_2 producing technologies, carbon based synthetic fuels and nitrogen based fuels.[8]

Creating robust sector-integrated renewable energy systems

This article will provide an overview of the infrastructure demands for creating a robust sector integrated renewable energy system and the expected costs. The energy source of this system is electric power generated from renewable sources. The system analysis includes the costs of raw materials, production sites, and transmission of electricity and transport of energy products such as ammonia, methane and synthetic carbon-based fuels. We will look at alternative fuels as means of renewable energy conversion and storage in the form of hydrogen (H_2), ammonia (NH_3) or synthetic carbon-based fuels (synfuels). As a caveat, it has to be stated that all alternative fuels are currently much more expensive than fossil fuels. This is a major obstacle in convincing less technologically and financially endowed nations, as well as most producers of fossil fuels, to switch to carbon neutral or even carbon free technologies. In this paper we will use geographical Europe as a case study, because it is an industrial powerhouse with many components of a future energy system already existing or being planned. Other aspects like technological safety as well as physical security (e.g. kinetic attacks) and cyber security (e.g. hybrid warfare) are also important, but will not be part of the discussion in this article.

Building blocks of a future sector integrated energy system

A robust electricity system depends on a reliable and flexible energy supply, preferably from multiple and – if possible - technologically different sources. The necessary energy generation resilience requires also some degree of robustness and redundancy of production sites, intermediate storage and transmission/transport options. This inevitably increases the costs. Besides reliability and flexibility, carbon neutrality is a new and integral requirement for future sustainable energy generation from renewable sources. This can only be achieved if technologies for carbon capture are fully integrated into carbon-based energy generation processes or completely carbon free energy systems are installed. Carbon capture, as an integral part of the energy production process, will be discussed more in detail in the next chapter of this article.

Electricity has to be supplied to electric grids in real-time synchronisation with the demand. Any significant fluctuations in energy production lead to blackouts. While any intermediate storage of electricity is costly, various storage technologies are available: (1) electrically - in batteries, (2) physically - in pumped hydropower dams or kinetic flywheels, (3) chemically - in energy rich compounds e.g. in synthetic fuels. Hybrid systems like Redox flow-batteries are also available.[9] Due to its low energy storage/weight ratio, energy storage in batteries is limited in capacity as well as in spatial and temporal reach. Batteries are expensive in production, maintenance and recycling and require intensive use of rare earth metals. Only a few large battery arrays have been built so far in Australia and Japan.[10] A major battery storage project associated with a 215 turbine wind farm is to be built in Scotland by 2021. The battery storage site would have the size of half a football pitch.[11] Batteries are typically used for small-scale solutions *i.e.* for private households or small businesses. Physical storage can reproduce electricity on demand with minor energy losses. Pumped hydropower dams have the potential for long term storage but are only possible in a very limited set of geographic conditions. The construction of hydro dams has decreased in recent years because of the social and environmental damages they inflict. Flywheel storage is used to stabilise the power supply fluctuations from renewable power plants in time scales of hours, but long term storage has not yet been achieved.[12]

Currently, the most promising solution for large scale energy storage is chemical storage, which is possible by generating H_2, NH_3 or carbon-based synthetic fuels (though other options also exist). The electricity demand for the production of these fuels increases from H_2 and NH_3 to carbon-based gases and liquid fuels. An additional advantage of such synthetic fuels is the relative ease of adapting existing and proven technologies for their transport, storage and use.[13] Nevertheless, all alternative fuels are currently significantly more expensive than fossil energy. This remains the major economical obstacle for implementing non-fossil carbon neutral and carbon free technologies.

The usage of electricity in a future sector integrated energy system should follow the principle of highest energy efficiency. A possible pathway is illustrated in Figure 1. Electricity from renewable power plants and CO_2 capture from secondary sources are the two resources. Electricity should be used directly throughout the sectors in order to obtain the best energy efficiency. The capture of CO_2, which is essential for obtaining carbon neutrality of all processes involving the production of carbon based synfuels-, is an energy intensive process.

It should be primarily done by using highly enriched industrial sources (e.g. cement production, biogas plants, bioethanol production) and as a second option only from ambient air by direct air capture (DAC).[14] In the context of synfuel production carbon capture technology temporarily recycles CO_2, but does not remove it permanently from the atmosphere as it is released again by the combustion of the synfuel. In the context of sector coupling and energy production, any CO_2 capture is for the atmosphere a carbon neutral process only. CO_2 capture from fossil fuel burning plants is not discussed in this article, because fossil burning will be phased out in the coming decades in most industrialized countries. Some countries may lag behind this process because of the great abundance of cheap fossil fuels and the lack of funds for building up new plants.

Hydrogen is the least energy intensive product when converting electric power into an alternative fuel. It is also the chemical base compound for producing other alternative fuels. Hydrogen gas is produced by electrolysis of pure water and can be used in heating, mobility and power production.[15] Hydrogen and N_2 from ambient air are needed in NH_3 production in Haber-Bosch-plants.[16] Hydrogen and CO_2 is needed to produce carbon-based synfuels such as methanol (CH_3OH), methane (CH_4) and liquid fuels for internal combustion and jet engines like non-fossil diesel or aviation fuel types. All the fuels discussed - alternative as well as fossil based - are often difficult to handle and safety precautions have to be established. Hydrogen, methane, alcohols, and all fossil fuels are flammable or even explosive. While ammonia is not flammable it is still a potentially harmful substance. Base materials for production like carbon dioxide and nitrogen are chemically inert. However, carbon dioxide in higher concentrations is suffocating to humans.

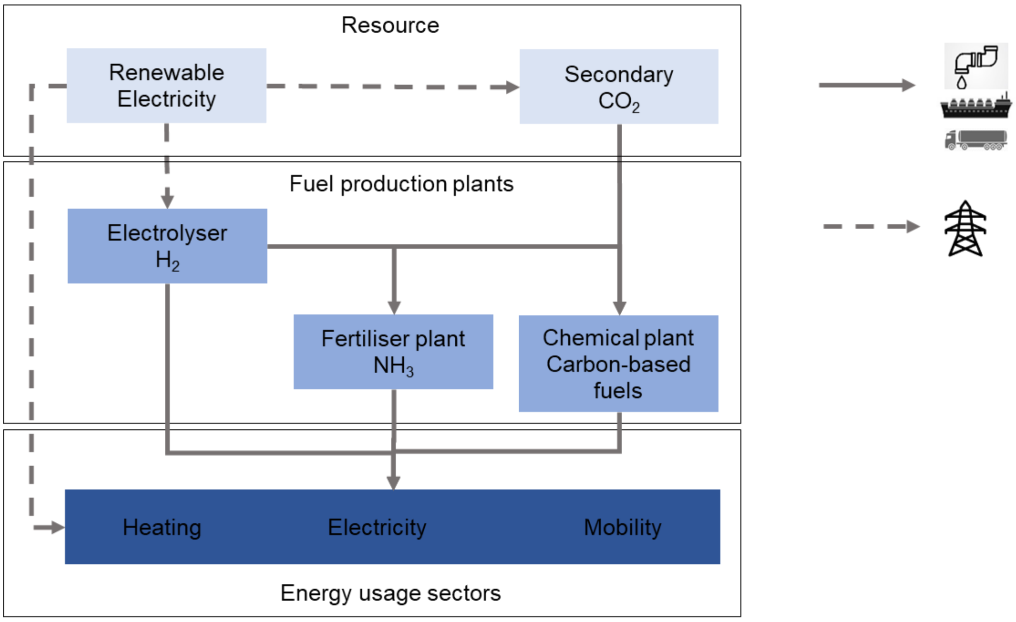


Figure 1: Components and possible pathways of a sector integrated renewable energy system for production of alternative fuels. Resources are electricity from renewable power plants and secondary CO_2. Fuel production plants are production facilities for H_2, NH_3 and synthetic carbon-based fuels (synfuels). Energy usage sectors include heating, electricity and mobility. Solid arrows = liquid or gaseous transport by pipeline, ship or truck. Dotted arrows = electric transmission lines.

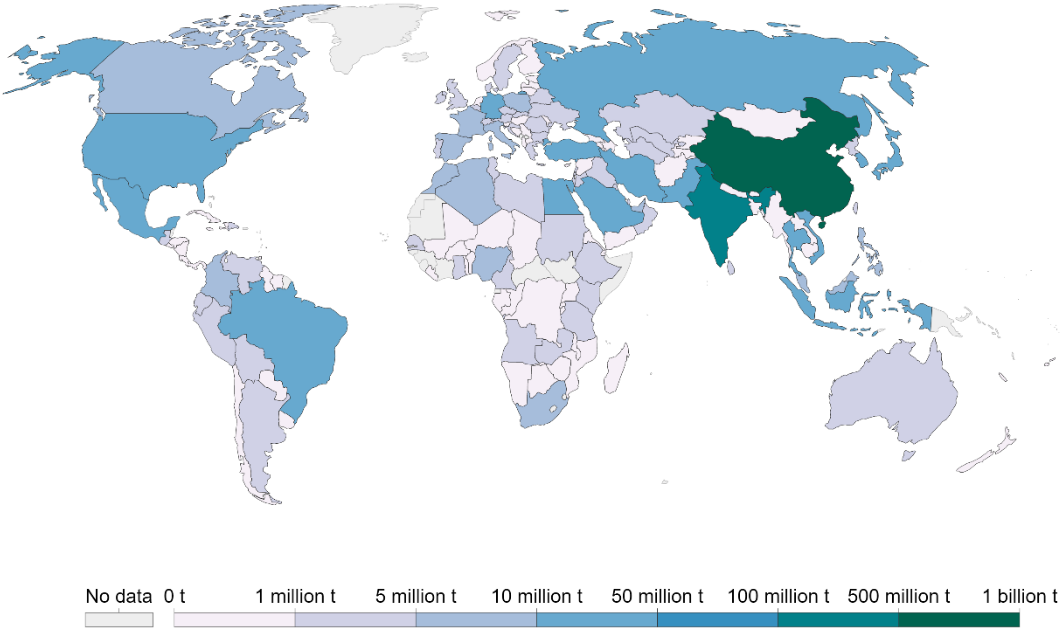
A key element of a robust future sector integrated renewable energy system is an efficient and frictionless transport of energy from and to power productions sites, alternative fuel production plants, industrial customers and industrial as well as private customer fuel distribution networks. In the following chapter we will discuss several important resources and production plant options with respect to their main productions processes and the site selection of the plants. In the last chapter, we will present and discuss the construction and maintenance costs of power transmission facilities and alternative fuel transport infrastructure.

Resources and production of alternative fuels

The production of most carbon neutral fuels from renewable energy as well as carbon capture technologies requires a carbon source of high purity and concentration. In a robust future energy system industrial sites may function as a source (by supplying CO_2 or energy) as well as a consumer (by using H_2 for heating purposes or as a feedstock for chemical synthesis). In this chapter three examples of renewable energy and raw material sector coupling are presented. First, the cement industry is globally a huge carbon emitter and may become a CO_2 source for the production of carbon-based synthetic fuels and a H_2 consumer for heating purposes. Second, the fertilizer industry uses large amounts of H_2 for the production of ammonia. In the case of a downstream urea production plant, carbon dioxide is needed and can be supplied from secondary sources. Fertilizer plants could increase their production of NH_3, which will be used as a carbon free fuel. Third, conventional oil refineries may become important facilities for the future purification of the mixtures of organic components retrieved from Fischer-Tropsch-Synthesis of carbon-based synfuels.

Cement industry as base material provider for synfuel production

The magnitude of global cement production and associated CO_2 emissions is enormous: if the global cement industry would be concentrated in one single country, it would be the third largest CO_2 emitter worldwide.[17] Cement producing plants are located on all continents (Figure 2) and the amount of the emissions is closely related to construction activities. Hardened cement contains 58–66 % of calcium hydroxide ($Ca(OH)_2$) and is obtained from heating limestone ($CaCO_3$) at high temperature (>1000 °C) while releasing large amounts of CO_2. The heat is normally provided by fossil fuels and therefore additional CO_2 is emitted during cement production.[18]



Source: Global Carbon Project; Carbon Dioxide Information Analysis Center (CDIAC)
OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Figure 2: Global CO_2 emissions from cement production in 2018.[19]

The limestone needed for cement production is mined in quarries. Therefore, cement producing plants are generally located in close proximity to these deposits to reduce the transportation costs of the bulky and heavy raw material.[20] This is shown in Figure 3 using Germany as an example.[21]

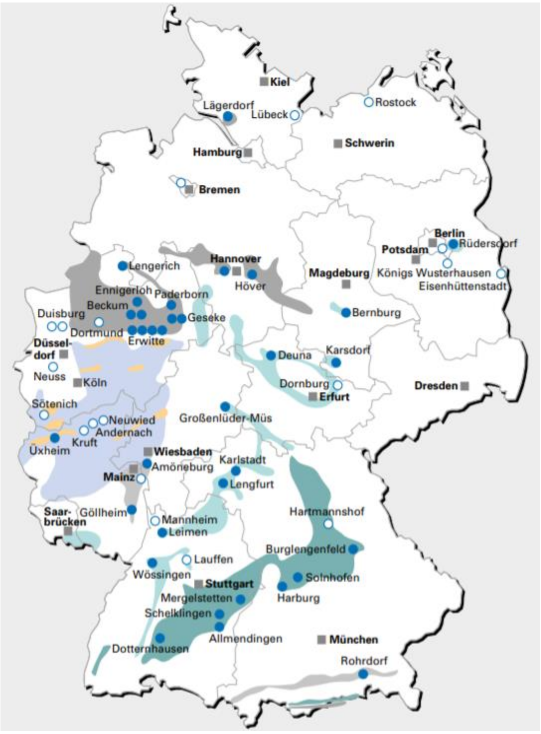


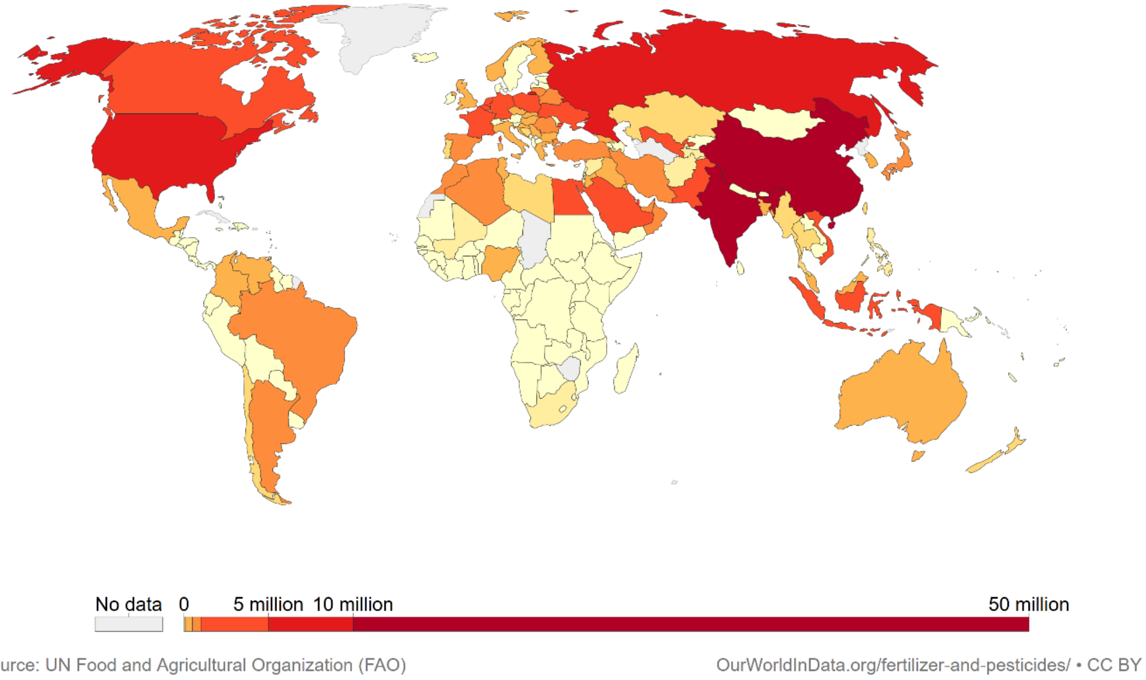
Figure 3: Location of raw material deposits and cement plants in Germany. Deposits are marked in areas of light grey = Tertiary, dark grey = Cretaceous, dark blue = Jurassic, middle blue = Middle Trias, light blue = Devonian, light yellow = compact limestone. Cement plants are marked in blue dots = plant with cement clinker production

and withe dots = plants without cement clinker production. Cement clinker is a limestone based stone while bricks are clay based stones.[22]

Several pilot projects have been started to capture the CO_2 emissions from the production process as well as using H_2 as a heating material. Cement plants supply cheap CO_2, as it is highly enriched in the waste gas. Usable industrial waste heat is not produced, as it is already used for the pre-heating of the raw material.[23]

Fertilizer industry and N-fuel production

Ammonia is a globally used commodity in agriculture, the chemical and the cooling industry.[24] The global fertilizer production in 2014 was approx. 113 x 10^6 tonnes. The production, transportation and distribution capacities and handling know-how exists on all continents (Figure 4).[25] Countries with large agricultural sectors typically have high levels of production.



Source: UN Food and Agricultural Organization (FAO)

OurWorldInData.org/fertilizer-and-pesticides/ • CC BY

Figure 4: Global nitrogen fertilizer production in 2014 by countries. A total of 113.31 * 10^6 tonnes was produced worldwide.[26]

The production of NH_3 via the Haber-Bosch process requires H_2 and N_2.[27] Industrial ammonia production plants may use compressed ambient air (78% N_2 content) or for generating high purity N_2 via air separation technology.[28] For H_2 as source material several options are available: (1) Typically H_2 is produced by steam reforming of fossil fuels at Haber-Bosch plants, releasing huge amounts of CO_2. However, only when the NH_3 is further processed into urea, the CO_2 is used in the production process.[29] (2) H_2 production from the electrolysis of water is currently used in countries with large amounts of cheap electricity.[30] However, both production pathways mentioned above are very cost intensive. A third and promising option might be (3), the usage of waste H_2 from industrial chemical production. In the Netherlands waste H_2 from a "Dow Benelux" production plant is transported to the fertiliser production plant of "Yara" because "Dow Benelux" has no usage for the waste H_2.[31]

All major European countries produce nitrogen-containing fertilisers.[32] The required increase of nitrogen output for alternative fuel production should be easily manageable, as existing plants may simply increase their production capacity and no limitations with respect to availability of the raw materials, technological know-how and trained personnel exist globally.

Oil refineries for purifying synthetic carbon-based fuel mixtures

Crude oil has to be processed and upgraded in refineries in order to be used as base material or energy source. Refineries are normally located in close proximity to the oil fields or along transport routes like pipelines or shipping terminals. Separate pipelines, ships and shipping terminals for crude and refined products are also in use. A good example of a refined product transport structure is the Central European Pipeline System (CEPS), which is operated by NATO in Europe.[33] While crude oil and its refined products for energy generation will be eventually replaced by renewable energies, the fossil carbon itself may remain an important base material for the chemical industry for quite some time. It is important to note that the entire existing refinery infrastructure can be easily used or modified to accommodate non-fossil based processes and constitutes an important asset in future efforts for sector coupling.

Chemical syntheses – such as the Fischer-Tropsch synthesis for producing synfuels – produce a mixture of components. Generally, these mixtures are not fit for further use and have to be purified. In the case of synfuels the required process is a fractionated distillation similar to the one performed for crude oil. Existing crude oil refineries are huge industrial complexes (Figure 5). The main and also the largest components are the towers for fractionated distillation. Depending on the boiling point, several fractions are differentiated: at ambient air pressure these are (1) liquefied petroleum gas (<20 ºC, ambient air temperature), (2) petrol (20 - 150 ºC), (3) Kerosene (150 - 200 ºC), (4) Diesel (200 - 300 ºC), (5) fuel oil (300 - 370 ºC) and (6) residues containing lubricant oil, paraffin wax and asphalt (370 - 400 ºC). All fractions are mixtures of several chemical components, which are determined by the origin of the oil. The main components are: (1) aliphatic saturated hydrocarbon (alkane), (2) cyclic saturated hydrocarbons (naphthene) and (3) cyclic unsaturated hydrocarbons (aromatic hydrocarbons). Since chemically homogeneous products are needed for further use e.g. as petrol fuel, these are obtained by cracking (breaking down of longer chain alkanes to lower chain alkanes) and reforming (cyclising, dehydration and isomerisation of alkanes to naphthene and aromatic hydrocarbons).[31] Oil refineries often host both crackers and reformers. By the end of 2020, ninety oil refineries were operational in Europe with a capacity of 665 x 10^6 t per year.[31] Retrofitting these refineries for processing synfuels is possible.

The global oil company BP (formerly British Petroleum) announced in its recent mission statement the goal to transform itself into a green-energy supplier.[34] It can be assumed, that other oil companies will follow the lead of BP in the coming years and that the existing infrastructure of pipelines, ships and refineries may be re-fitted for synfuel refining and transportation.

Figure 5: Chevron Burnaby oil refinery plant near Vancouver (Canada) (Resnick-Ault 2016).[35]

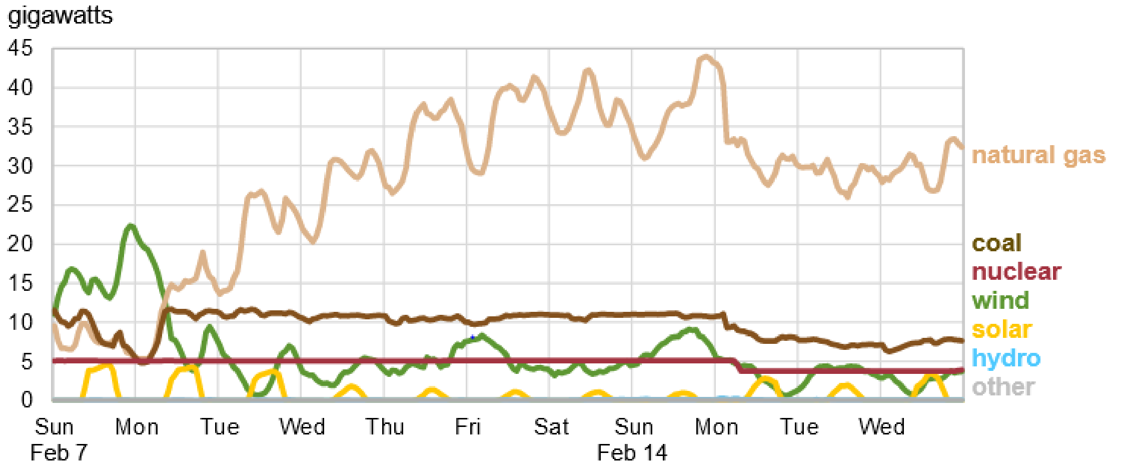
Electrolyser, synfuel plants and DAC productions sites are not discussed here, as they have no specific placement demands and have to be newly build anyways. Strategic transport considerations should define the decision process for their construction and location.

Sector integration

Sector integration is generally deemed essential for tackling the global climate crisis. In the energy systems to come, electricity will play a key role. The production costs of electricity from renewable power plants commissioned in 2018 are lower than from fossil or nuclear plant commissioned during the same period.[33] Considerable further reductions in production costs are predicted for the years and decades to come, with higher cost reduction effects for renewable technologies than for fossil and nuclear power plants.[36] Electricity will become a low price commodity, while the energy storage problem for providing a stable supply still needs to be solved. Long range transport and the production of alternative fuels may soon become economically feasible under these circumstances. A robust renewable energy system must have reserves in terms of capacity as well as various options for fuel usage and for long distance electricity and fuel transport.

Energy systems which are primarily based on electricity must be designed in a robust and resilient manner. A recent example for the failure of an energy system due to inappropriate design assumptions was a large scale power outage in February 2021 in Texas, USA. It caused the largest insurance damage in the history of Texas, even larger than the damages caused by hurricane Harvey in 2017 and even 47 fatalities. An unusual cold and long lasting weather situation caused not only renewable but also fossil and nuclear power production facilities to fail (Figure 6). At the same time about 16 GW of electricity could not be covered by renewable power plants (mainly wind turbines). Texas covers about 20 % of its power demand from renewable sources, mainly wind. Wind turbines in cold regions are self-defrosting. The power providers in Texas however, had decided not to install such safeguard mechanisms to keep costs low. 30 GW power production capacity from fossil and nuclear plants were also lost, mostly because of frozen pipelines and valves in the natural gas and water system. One block of the South Texas Nuclear Power Station had to be shut down because of failing water supply for cooling. While energy production dropped dramatically, consumers demanded more power than usual for heating, which could not be provided within the closed power grid of

Texas. To prevent the power grid of Texas to collapse entirely, the grid managers had to deliberately disconnect whole regions from the power supply. Power providers in Texas are not bound to provide emergency capacities. In Texas the electricity grid is almost entirely isolated from the rest of the US power grid due to mutual political decisions. The weather conditions in the coming years will be more unpredictable than in the past and consequently, historical records are not usable for predictions of future extreme weather events.[37]



Source: U.S. Energy Information Administration, *Hourly Electric Grid Monitor* (ERCOT net generation by energy source)

Figure 6: Hourly net power generation in Texas, USA by energy source [GW] from Sunday, 7th of February until Wednesday 17th of February 2021. Harsh winter conditions started on 7th of February and caused non-frost-proof wind rotors to freeze up. Natural gas and coal power plants had to step up their production n to compensate for the failure of wind and solar. From 14th of February on even gas, nuclear and coal power plants dropped in energy production due to failures caused by severe cold climate.[38]

Future robust and resilient energy systems must be able to cope with ever more severe and unpredictable weather events. An interconnected system of small- or medium seized decentralised plants is always more stable than large single plants with equal capacity. The innovative interconnection of production and consumption sites as well as the transportation/transmission of input materials, electricity and finished products is a key element of such a system. A possible scheme is shown in Figure 7 and explained in the following.

Electricity base load settings are characterised by a reliable, predictable and controllable power supply and should cover base load demands. The produced power is directly fed into the power grid for immediate consumption. Currently power plants run from biomass-, deep geothermal heat, hydropower dams and solar parabolic trough setups do meet these requirements. Vast and untapped renewable electricity production possibilities from deep geothermal heat and buffered by hydropower dams are e.g. available in Iceland. A deep sea cable between Iceland and Scotland was repeatedly discussed in the past years, but it was never build because of cheap electricity supply from fossil sources.[39]

Solar and wind power plants have unpredictable and thus unreliable production properties. Therefore, such power should be fed into the electricity grid with first priority in higher than base load situations. The then still available surplus power should be used with the following priority: (1) physical storage in pumped hydropower dams, (2) alternative fuel production, and (3) district-heating systems.

The minimum power supply needed for the operation of chemical storage production plants should be generated by renewable power plants exclusively built for this purpose. Otherwise, the minimum of 4 000 FLH (Full Load Hours) for cost effective production cannot be guaranteed. The variable surplus power from "grid supplying" renewable power plants could be used in addition. Both power supplies combined increase the degree of capacity utilisation of the alternative fuel plants.

It must be stated again, that the direct usage of electricity for appliances, motors or heating is economically and environmentally much more sensible than any kind of alternative fuel production and subsequent on-demand re-conversion into electricity in power plants. Direct electric power usages should therefore be prioritised. Large scale electricity production from renewable sources in close proximity to the customer is in most cases not feasible because wind, solar and geothermal plants are typically located in remote areas. Therefore national, continental and intercontinental electricity grids are needed to make full use of regional variations in renewable power production. High Voltage Direct Current technology can fulfil this task and new transmission line projects like NordLink will be started in the future.[40] However, covering the entire future power demands with renewable electricity alone seems currently not possible. Alternative fuels will still be needed for terrestrial and air mobility and naval transportation. Whether the electric power is transported to alternative fuel production plants or the alternative fuel plants are located in close proximity to renewable power production sites, has to be decided on a case by case basis.

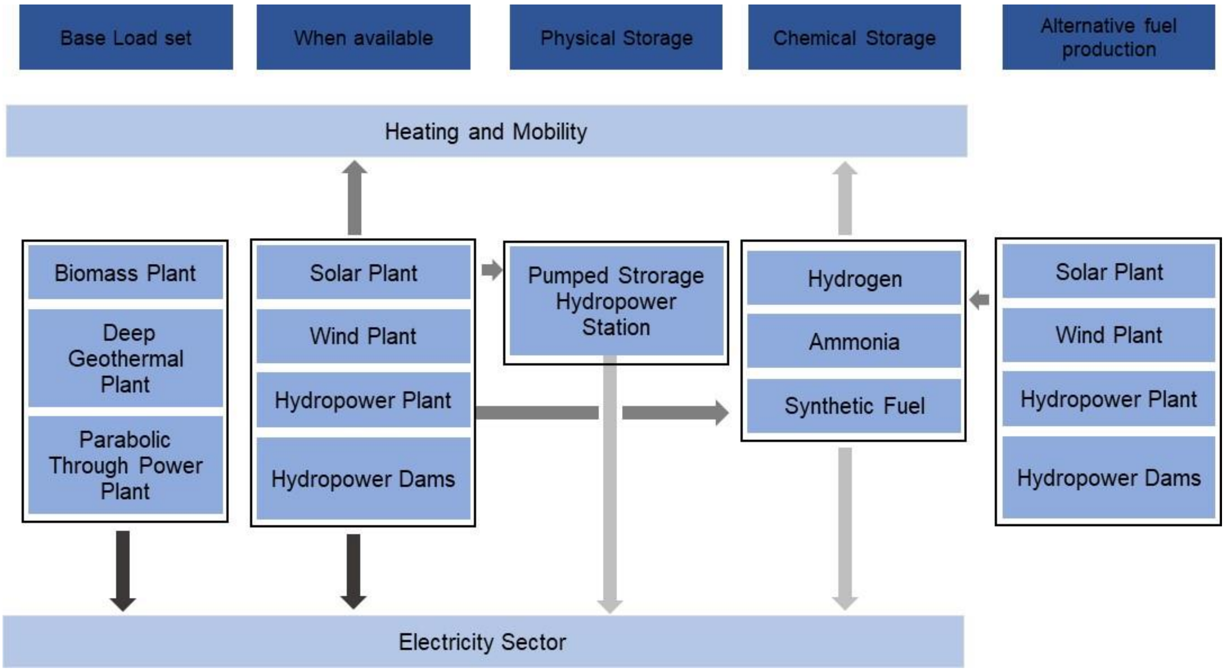


Figure 7: A robust and resilient sector integrated electricity system may consist of: (a) "Base load sets" which are able to run without interruptions to meet the demands of the base load. (b) "When available" plants with unpredictable production. (c) "Physical" storage and (d) "Chemical storage" (e) "When available" plants with unpredictable production like (b) which were built solely to supply alternative fuel production plants. Dark grey arrows: Direct use of electricity. Grey arrows: Excess electricity from unpredictable sources feed into physical or chemical storages. Light grey arrows: Electricity or fuels fed into the energy system.

The most cost effective alternative fuel is H_2 from direct electrolysis of water. It can be produced in close proximity of renewable electricity plants. The electrolyser technology is well established, needs not much space and is constantly refined.[41] However, the purified water demand for electrolyses is considerable. As many projected solar and wind farms are planned to be built in arid and semiarid regions, a shortage of water or even competition for water resources between people and power plants might become a serious issue.[42] In these cases, electrolysers could be installed in water rich regions with long distance power transmission lines from renewable power plants.

Ammonia production requires H_2 and Haber-Bosch-process plants. The limitations for H_2 generation from electrolysis apply as described above. Enlarging existing NH_3 production capacities seem easily possible. However, H_2-pipeline connections may have to be built if H_2 is produced off-site. Currently, H_2 is produced by steam gas reformation which uses natural gas i.e. a fossil carbon source. Retrofitting of these pipelines is possible. The German plant manufacturer Thyssen Krupp already offers a small-scale hydrogen plant powered by solar electricity which produces H_2 generated from electrolysis.[43]

The production of mainly liquid synfuels is the most innovative and less mature process of all alternative fuels. It requires several technologies and production steps: (1) Electrolysers for H_2 production, (2) CO_2 capture technology from CO_2 rich waste gases or from DAC, (3) Reverse water gas shift reaction for CO production from CO_2 and H_2 (which is not yet in a mature stage of development) and (4) Fischer-Tropsch or methanolisation reactors. Such complex plants require a huge amount of investments and well trained operators.

The generation of climate neutral carbon (by not using fossil fuels such as in steam gas reforming processes) as base material for synfuels only seems sensible as direct CO_2 capture from DAC or capture from industrial plants where carbon emissions cannot be avoided (e.g. during cement production). CO_2 capture from fossil fuel burning processes does not seem sensible, because the big scale emitters will phase out in the coming decades and small-scale emitters are too expensive to be retrofitted for carbon capture. Carbon dioxide emitted from large industrial sites could be best captured at the source, while the CO_2 emitted from small sources (e.g. domestic heating, agriculture and small industrial plants) has to be captured via DAC. It should be kept in mind that DAC facilities require huge amounts of space, water and energy, and therefore have to be built in rural areas with a sustainable water supply. Using sea water is also possible, but it has to be desalinated first.

Conclusions

At the moment the design and development of robust and resilient renewable energy systems is in its infancy. An important obstacle is the fact that the technological and market preferences for alternative fuels are not yet clear. Various possibilities are currently discussed or exist as pilot projects or are in a small scale development phase. Which technological options for power and fuel generation will dominate the energy system in the future is currently not predictable. With several alternative fuels available, the resilience of energy systems to disruptions is certainly increased. However, the benefit of enhanced robustness and resilience comes with an increased price tag on energy costs, as economies of scales are missing or starting with a time lag, especially in the early stages of the energy sector's transition from fossil to renewable energy.

In terms of energy security the following priorities for a robust and resilient renewable sector integrated energy system are suggested:

1. Enhancing electricity production from base load facilities such as deep geothermal plants to meet the base load demand.
2. Increase physical storage possibilities for peak demand like pumped hydropower dams.
3. Increase electricity grid connectivity for geographically levelling out peak supply and demand.
4. Feed surplus power into alternative fuel production facilities, i.e. DAC and Fischer-Tropsch plants.
5. Supply alternative fuel production facilities with sufficient power from renewable plants to ensure a minimum of 4 000 Full Load hours per year.
6. Build or re-purpose power generation plants for alternative fuels use for covering peak demand, i.e. convert gas power station for natural gas to synthetic methane.
7. Re-purpose coal power generation plants for alternative fuels for covering base load demand.

These measures will take decades and require huge financial investments to implement. However, the environmental costs of climate change with all its negative consequences on infrastructure and societies are expected to be much higher than that. Implemented wisely, renewable sector integrated energy systems may contribute to a more equal distribution of wealth and, therefore, have a stabilising effect on societies globally.

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