ETIP SNET

EUROPEAN TECHNOLOGY AND INNOVATION PLATFORM
SMART NETWORKS FOR ENERGY TRANSITION

FLEXIBLE POWER GENERATION IN A DECARBONISED EUROPE

ETIP-SNET WG3 “Flexible Generation”
White paper

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1. EXECUTIVE SUMMARY

A cost-effective and secure transition to a lower carbon society will require a fundamental transformation of the power system. EU Member States, by means of the Commission's Energy Union strategy and the National Energy and Climate Plans [1], have recently accepted more ambitious targets for the energy transition in EU by 2030 [2]. The updated legislative framework sets out quantified objectives in order to provide a stable, predictable environment for planning and investment, laying the foundations for work towards a modern and prosperous climate-neutral economy by 2050 [3]. Specifically, new targets are set for 2030 (Fig. 1), namely: "*to reduce greenhouse gas emissions domestically by at least 40% compared to 1990 levels; to reach a share of at least 32% in renewable energy, and to increase energy efficiency by at least 32.5%. The electricity interconnections target was set to improve security of supply by stepping up to 15% in each Member State by 2030"* [2].

	GREENHOUSE GAS EMISSIONS	RENEWABLE ENERGY	ENERGY EFFICIENCY	INTER-CONNECTION	CLIMATE IN EU-FUNDED PROGRAMMES	CO2 FROM:
2020	-20%	20%	20%	10%	2014-2020 20%	
2030	≤ -40%	≥ 32%	≥ 32.5%	15%	2021-2027 25%	CARS -37.5% Vans -31% Lorries -30%

Upwards revision clause by 2023

Figure 1 EU energy transition 2020 and 2030 targets, relative to 1990 levels [2]<<<

The ETIP SNET Vision for 2050 is a low-carbon, secure, reliable, resilient, accessible, cost-efficient, and market-based pan-European integrated energy system supplying the whole economy and paving the way for a fully CO_2-neutral and circular economy by the year 2050, while maintaining and extending global industrial leadership in energy systems during the energy transition [4]. To achieve this target, disruptive developments and changes are needed in all sectors. Industry, mobility, heat and power generation need to change the way energy is handled today.

The mission of WG 3 "Flexible Generation" is to *"address the business and technology trends considering the contribution of generation flexibility from conventional thermal power plants (bulk and distributed)".* It is a common understanding of ETIP SNET that RES should significantly contribute to a stable energy system operation in the future, allowing a growing percentage of renewable sources to substitute traditional dispatchable generation. It is our purpose to describe the different technologies and solutions of the flexible generation (including conventional power plants, embedded storage and fuel cells) and variable RES optimisation from a technological, environmental, economic, regulatory and acceptance points of view[1].

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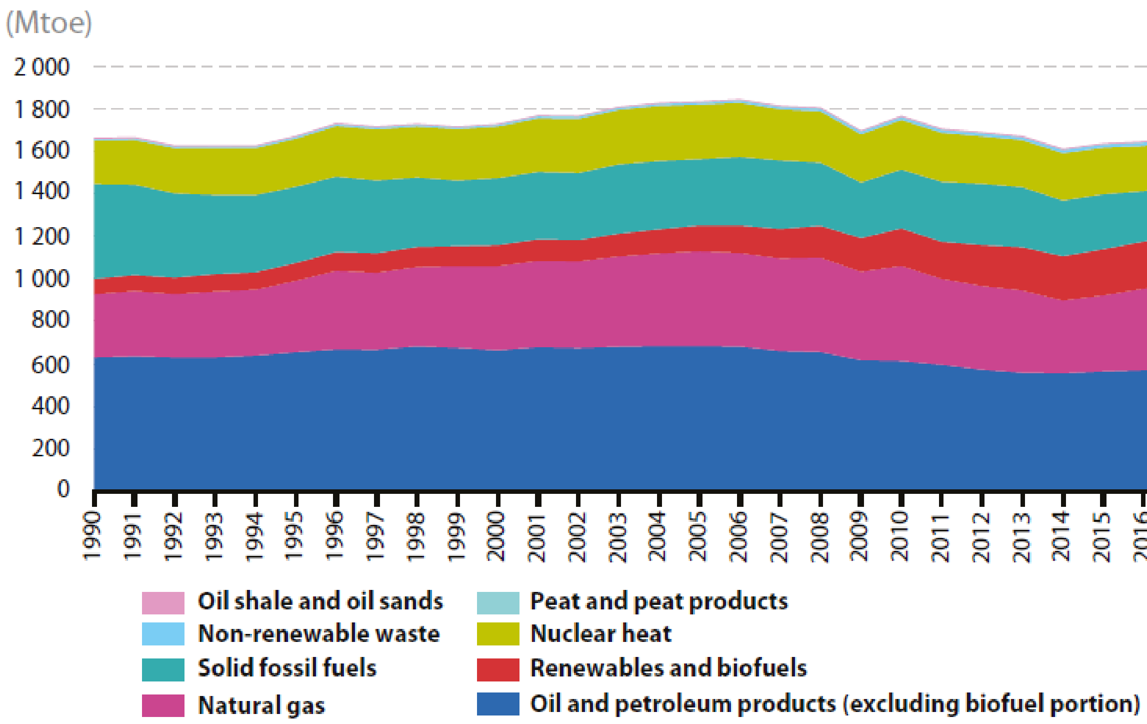
[1] WG3 Flexible Generation - Terms of Reference, https://www.etip-snet.eu/wp-content/uploads/2017/03/WG3.pdf

This White Paper describes the pathway forward in flexible power generation, starting with the state-of-the-art of flexible generation covering all means of energy sources, and describes the necessary steps to achieve the targets of ETIP SNET Vision 2050. Energy storage has to be extended and integrated in generation on a large scale. For short and mid-term storage, batteries and pumped storage are state-of-the-art. For seasonal storage, the generation of decarbonised hydrogen (PtX) using excess of renewable power and additional dedicated capacity is considered to play an important role in the future in many countries where hydrogen strategies have been already set up. This will be the basis for production of green fuels for all sectors. Besides further development of existing technologies and combining them, and the role of novel approaches in the future energy system, this document also highlights the needs for a regulatory framework to create incentives for the implementation of the technologies towards a low-carbon society as targeted by the EU. The messages of this White Paper are fully compliant with the overall mission of ETIP SNET to reach the state of full CO_2 neutrality for 2050. They reflect the current state-of-the-art of power generation in general and their potential role in a carbon-neutral EU 2050.

2. INTRODUCTION: THE STARTING POINT

Current energy systems do differ significantly in different countries and have historically grown into their actual configurations due to regional/national, specific geographic conditions (e.g. availability of different types of primary energy, different developments in various industrial sectors, choice of national policies/strategies, etc.). Nevertheless, some general patterns of national energy systems have been evolving in the past, particularly concerning electricity generation and distribution, which exhibit features that will no longer be compatible with future energy scenarios mainly based on (variable) RES. With current systems, mainly based on power generation technologies, which can be switched on/off and controlled in power output according to the demand profiles (mainly of the industrial and residential sector), the requirements and capabilities with respect to flexible operation of the systems can be matched pretty well. In the future, the operation and the respective flexibility and resilience requirements of the energy systems will need to adapt to the capabilities of vRES in a cost-effective manner. This will be the case for both power transmission and distribution systems since the largest share of (variable) Renewable Energy sources is currently connected to the distribution level. Need for flexibility will (strongly) increase and capabilities for flexible (on demand) generation will decrease, as power generation assets will switch from conventional fossil fuel powered systems to new renewable energy systems (mainly wind and solar).

For the given energy system in the EU, the gross inland energy consumption was 1675 Mtoe in 2017 (Fig. 2). This value has been relatively stable since 1990 and is correlated with economic trends (see decrease in 2009 due to financial crisis). During this period (1990-2017) there was a rise of over 200% in RES and 34% in natural gas, mainly to the detriment of coal (-50%). In 2017, the share of fossil fuels was 72.2% of gross inland energy consumption (34.8% oil and petroleum, 23.8% natural gas, and 13.6% solid fuels). The share of nuclear and renewable accounted for 12.6 % and 13.9 % respectively.



Source: Eurostat (online data code: nrg_bal_c)

Figure 2 EU Gross inland energy consumption by fuel, EU-28, 1990-2017 [5]

One of the EU's main targets is to reduce both primary and final energy consumptions[2]. In Fig. 3 the evolution and the objectives for 2020 and 2030 are shown, compared to 2005, which are -13.8% (1483 Mtoe) and -26.0% (1273 Mtoe) for primary, -9.0% (1086 Mtoe) and -19.9% (956 Mtoe) for final energy consumptions, respectively. The difference between primary and final energy consumptions is due to energy sector, which includes energy carrier conversion (electricity generation, heat production and petroleum refining). In the period 2000-2017, the share of the energy sector in primary energy consumption was 28.1%, and the 2030 target is 24.9% which supposes a decrease of 39.9% compared to 2005 values (from 527 to 317 Mtoe). The main drivers to achieve this objective are a higher rise of renewable energy sources (for electricity and heat), up to 32% of final energy consumption in 2030, and the increase of energy efficiency in industry, buildings, tertiary and transport.

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[2] "primary energy consumption" means the gross inland consumption excluding all non-energy use of energy carriers (e.g. natural gas used not for combustion but for producing chemicals).
"final energy consumption" measures the energy end-use excluding all non-energy use of energy carriers ; only covers the energy consumed by end users, such as industry, transport, households, services and agriculture; it excludes energy consumption of the energy sector itself and losses occurring during transformation and distribution of energy.

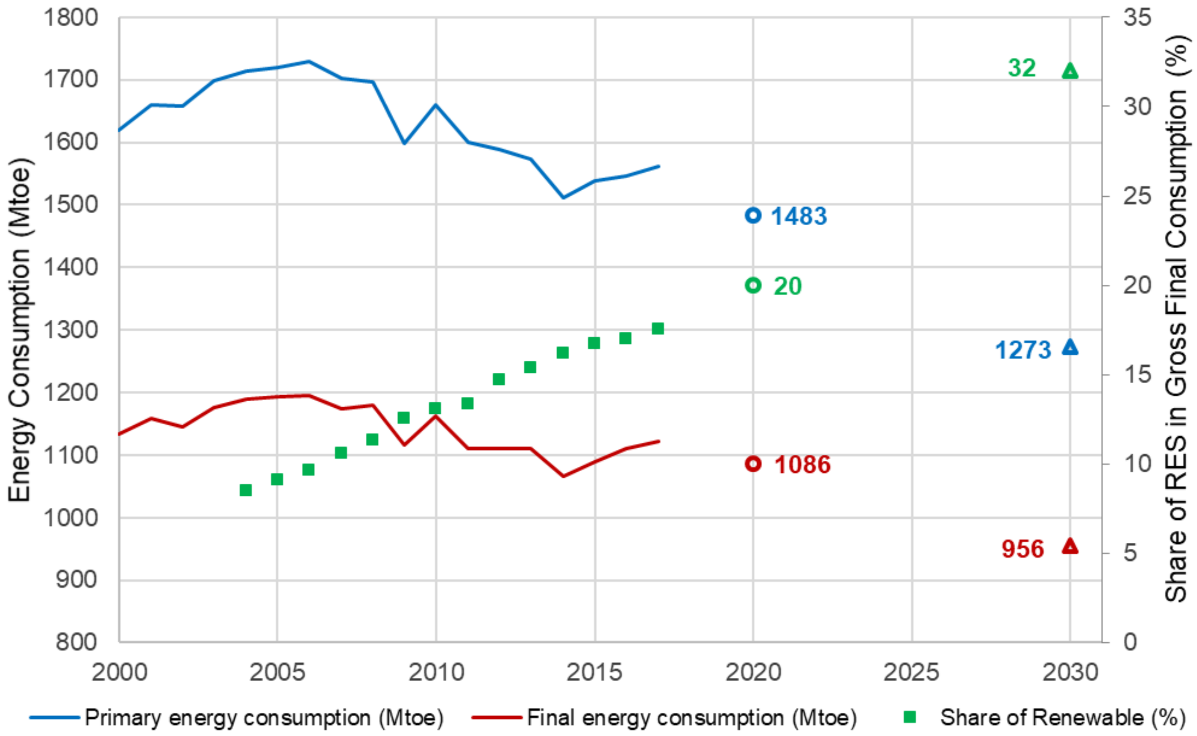

Figure 3 EU-28 Primary and Final Energy Consumptions and Share of RES and targets for 2020 and 2030.

Approximately, 23% of final energy consumed in the EU is based on electricity, and this sector is the backbone of the energy system. During 2017, 44 % of the electricity consumed in the EU was generated in power stations burning fossil fuels. The rest was produced in nuclear power plants (25%) or from RES (31%). The shares of main RES were wind (11%), hydropower (10%), biofuels (6%) and solar (4%). It is very important to mention the heterogeneity on the different national electrical markets (Fig. 4). For example, 71% of electricity in France comes from nuclear, meanwhile other countries (such as Italy) do not have any nuclear power plants at all. The share of fossil fuels spreads from 91% in Cyprus to 3% in Sweden. Regarding renewables, around 60% of electricity produced in Austria comes from hydropower plants and 48% in Denmark from wind.

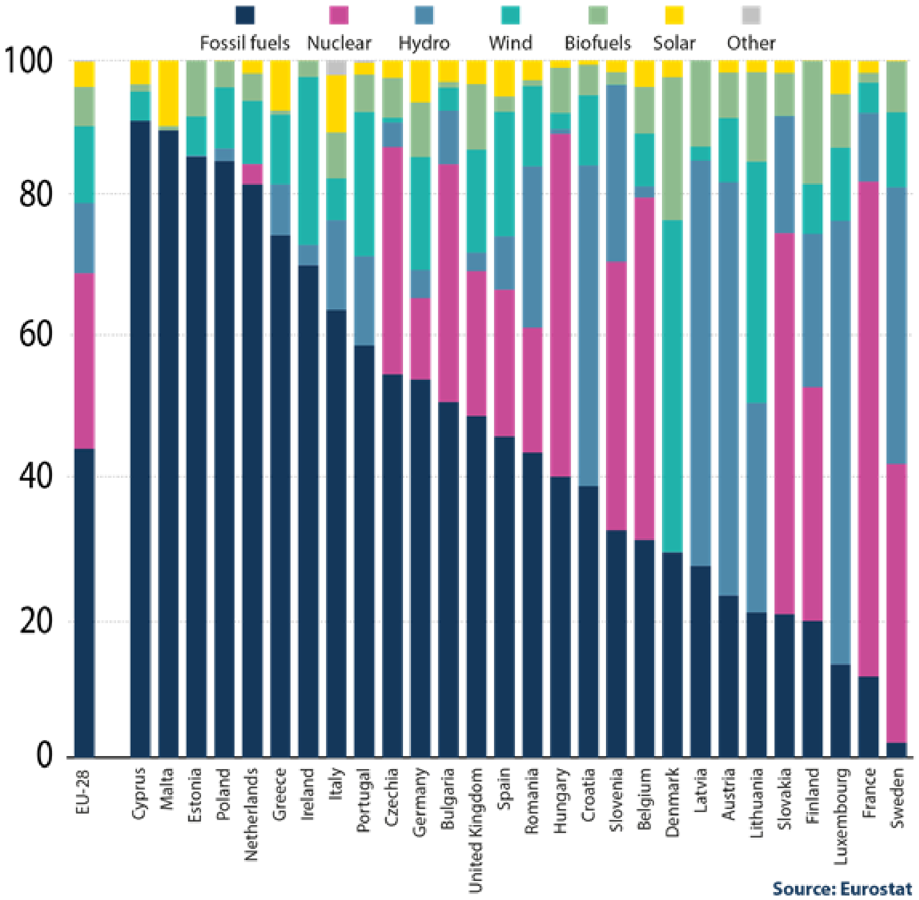

Figure 4 EU-28 Production of electricity by source, 2017 (%) [6]

Renewable energy sources must become the basic primary energy source in the EU. Only in a few EU countries is nuclear energy an option for the future, and thermal use of non-recyclable waste will also be further limited, due to improved recycling technologies and the need to move toward a circular economy, Fig. 5. Combustion of C-based by-products from industries like blast furnace gas and refinery gas will have to be reduced or eliminated as much as possible. Currently, these C-based by-product gases represent some must-run capacity of base load power production (driven by chemical processes or steel mill operation) which reduces the flexibility potential in today’s electricity markets. This “must-run” capacity can sometimes be that large that it forces the curtailing of RES plants (which must be avoided in the future). Finally, only wind energy, PV, geothermal and solar thermal energy, hydropower and (local) biomass would be available to serve all primary energy needs and sectors.

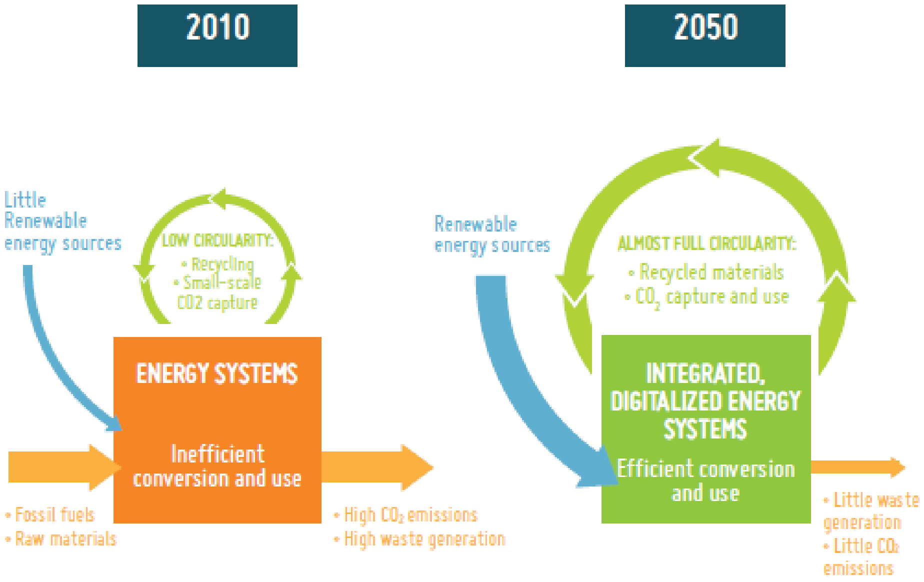

Figure 5 From the past quasi-linear to the circular economy in 2050 (ETIP-SNET's Vision 2050, [4])

The energy transition is ongoing at different rates in the various EU countries. In most European countries, the timetables for the coal phase-out are set between 2025 and 2038. Even natural gas appears only as a transitional fuel. The pioneers for strict carbon reduction via hydrogen are the North Sea countries like Great Britain, the Netherlands and Norway, where a (substantial) switch to CO_2-free energy systems is expected by 2030 with “blue” hydrogen[3], wind energy for “green” hydrogen[4] as well as with more biomass combustion in existing coal-fired power plants [7], [8]. There is a vast effort to study how hydrogen, for the whole EU and globally, will play an important role in the decarbonisation [9], [10], [11]. The vast majority of existing and new thermal power plants are necessary in the transitional period. In the future, thermal power plants running on low carbon fuels will be needed in order to ensure the necessary flexibility and security of supply of power and heat.

In this scenario with a high penetration of renewables, flexibility of the power systems will become the cornerstone of electricity security, with an essential paradigm shift in power plants, grid and storage, and unlock demand-side response [12]. The rise of solar PV and wind power gives unprecedented importance to the flexible operation of power systems in order to have a stable and resilient energy system. Nowadays, conventional power plants and interconnections are the backbone of this flexibility. However, due to the evolving nature of electricity demand and supply, the role of energy storage and demand control will be crucial to further integrate variable renewables into the energy system.

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[3] „blue“ hydrogen: fossil fuel based hydrogen with Carbon capture
[4] „green“ hydrogen: renewable based hydrogen

3. CONSEQUENCES AND REQUIREMENTS FOR THE ENERGY SECTOR

Renewable energy has made a significant contribution to power generation over the past decade. Global investments in wind energy and PV in particular, have led to a drastic decrease in the generation costs of renewable energy sources (RES). In many cases and for several technologies, "grid parity" is already in place today, i.e. renewable electricity can be fed into grids in principle without subsidies. However, there are also setbacks.

1. Due to the rapid expansion of vRES (variable RES) electricity production, more frequently a temporary surplus of generating capacity occurs, while at other times backup power (via electricity storage and dispatchable thermal capacity) is needed to cover the residual load. This is true particularly for seasonal “dark doldrums”.
2. The high penetration of high vRES in the power system results in important challenges for the grid in terms of balance, flow, stability and quality [13]
3. In addition, sectors such as industry, mobility, residential and agriculture have made slow progress towards lower CO_2 emissions due to the lack of incentives, long investment cycles and technical alternatives. On the other hand, the rising share of renewable power has made power prices much more volatile (e.g. in Germany, where negative prices have become a non-negligible phenomenon)

On a daily basis, energy can be stored by MW scale batteries, pumped hydropower and hydro dams as well as other mechanical energy storage technologies (e.g. compressed air energy storage = CAES, liquid air energy storage = LAES) and thermal storage (as molten salts installed in RES CSP power plants). Each type of energy storage can be further exploited but each has its own limitations e.g. by cost, topography, permitting procedures and public acceptance. Up to now, only **hydro dams** in alpine areas and the Nordics are functional for limited seasonal storage of larger amounts of energy, but new project development is difficult due to environmental concerns and public perception.

Generally, the storage of electricity for longer than a few hours or days via new battery or other direct electricity storage technologies cannot be expected. Chemical energy carriers - like hydrogen and methane – produced via PtX processes -- have the potential for large scale, long term (seasonal) energy storage capacity [14].

The extension of the electricity grid and installation of High-Voltage direct current (HVDC) lines enables the transportation of Giga watts (GW) over thousands of kilometres and helps balance local demand and vRES production. Even if battery-powered electric vehicles may replace all cars moved by combustion engines today, there remain challenges for aviation, shipping and heavy-duty vehicles which need storable, high energy density fuels.

The connectivity of all sectors into the decarbonisation process is documented in a recently published ETIP SNET White Paper on Sector Coupling [15]. The contents of this present White Paper is compliant with the statements in [15]. Where reference is made in this paper to the different sectors, they are considered from the point of view of flexible generation, and messages are complementary to other ETIP SNET publications.

It can be concluded that:

1. RES production must be increased a lot to fulfil the future demands of all sectors, and
2. far-reaching efficiency-optimised sector coupling has to be implemented to use renewable electricity for seasonal storage and for the use across all sectors, Figure 6.

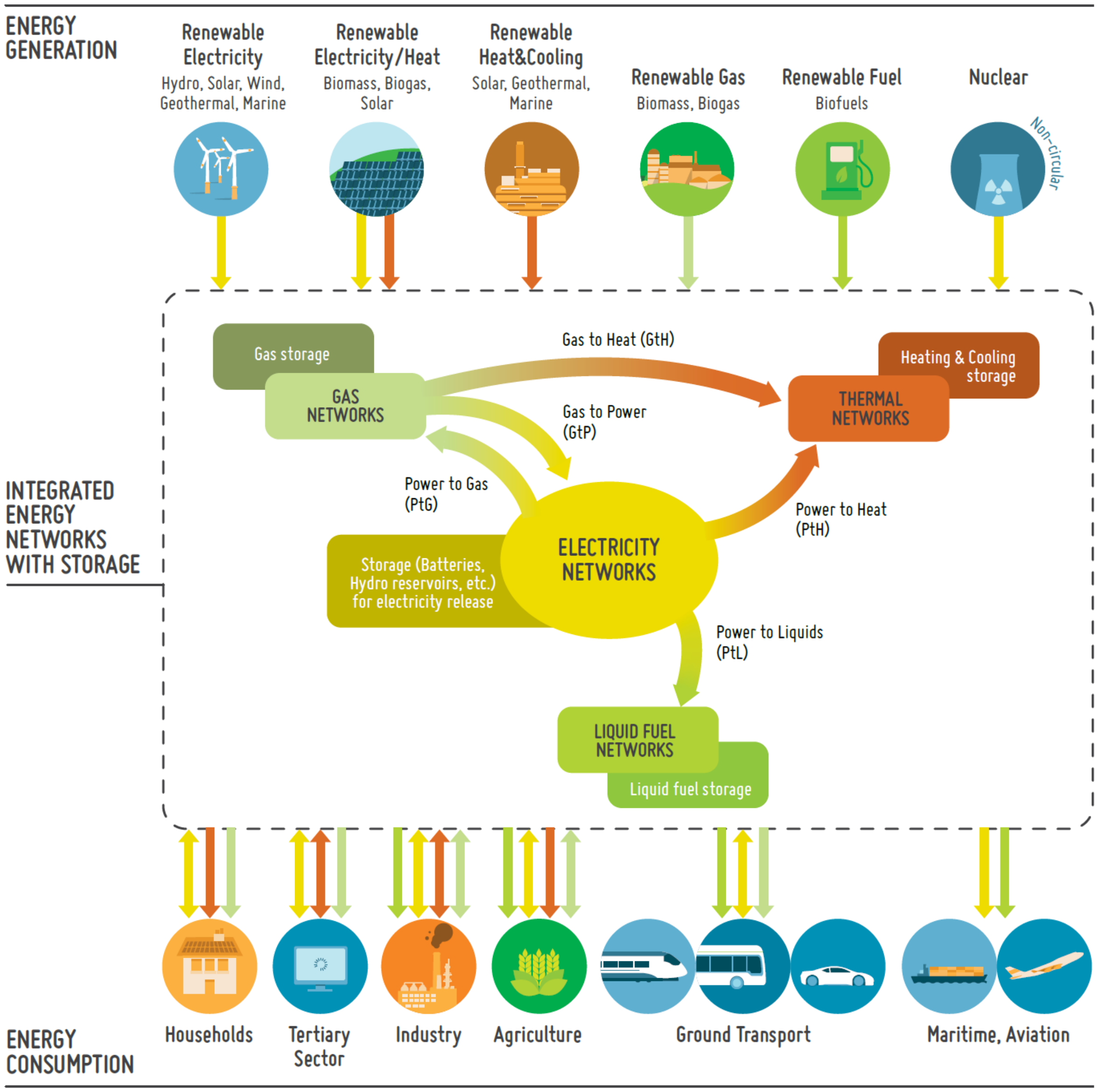


Figure 6 Integrated energy networks with storage interacts with all sectors [4]

Electrification of the heat sector is ongoing via small heat pumps, and electric heaters are more frequently used for grid services and supplying heat to heating grids. It can be expected that more and more large MW scale heat pumps will be integrated in heating grids, including low temperature (water) heat storage.

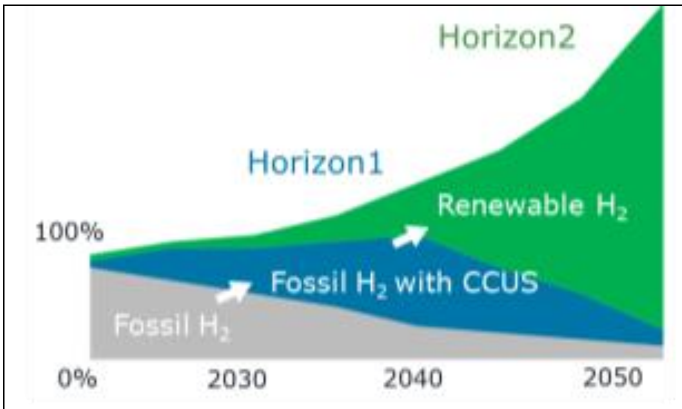
The supply of fuels to the transport sector as well as to industry remains more difficult, especially to those that need high temperature energy. The basic molecule for all chemical energy storage media is hydrogen produced via water electrolysis or gasification/steam reforming of hydrocarbon fuels. If only biomass and RES electricity is involved in the production process, this is called “green hydrogen” (Renewable hydrogen, see Fig. 7).

Thermal power generation can efficiently use the hydrogen directly to secure dispatchable heat and power from gas turbines, reciprocating engines, fuel cells or boiler plants. Compressed hydrogen can be used in fuel cell vehicles or in trucks and busses using either fuel cells or internal combustion engines. Aviation and marine applications require high energy density fuels which can be derived from hydrogen by chemical synthesis processes together with captured (recycled) CO_2 (carbon capture and utilisation=CCU). Examples for such “e-fuels” are **synthetic natural gas** (SNG), methanol and its derivatives such as gasoline, diesel or kerosene.

The infrastructure for hydrogen refuelling stations (HRS) is under consideration / under construction in many EU countries, and the e-fuels will be handled by adapting today’s infrastructure (gas pipelines and LNG infrastructure and liquid fuel transport via pipelines, ships and trains).

Hydrogen for large scale application does not have the suitable infrastructure yet, except for big chemical clusters where fossil fuels based “grey” hydrogen is already distributed in GW scale to refineries, fertiliser plants and other users in pipeline systems (e.g. in the chemical industries in the western part of Germany and in the Rotterdam area in the Netherlands). Consequently, this infrastructure is considered as the entrance point for large electrolysers up to 10-100 MW. These electrolysers should also serve grid balancing and avoid curtailment of vRES. However, such huge amounts of RES cannot be expected in the next two decades to produce the significant amounts of hydrogen that could serve all needs. Therefore, a coordinated planning of hydrogen demand, vRES deployment and conversion plants (all of them both as amount and as location) is needed to optimise the decarbonisation process at minimum overall cost.

Taking into account a 2050 target round-trip Power-to-Gas-to-Power efficiency of about 45% [16] on average, a huge increase of RES capacity would be required to provide enough “green hydrogen” to overcome dark doldrums in winter seasons during which solar/wind generation is very low. This is where the use of fossil resources must be reconsidered in the transitional phase. “Blue”, carbon free hydrogen can be produced by today’s state-of-the-art technology of steam methane reforming (SMR) if combined with cost-effective carbon capture and storage (CCS) or carbon capture and utilisation (CCU), which viability is not yet demonstrated. Indeed, cost-effective CCS/CCU can be applied also in fossil generation plants in the transition period, so the decarbonisation mix becomes more complex. This technology would be an important contribution to decarbonise energy-intensive industry sectors (e.g. steel, chemical and cement industries) [17], which today cover about 20% of green-house gas emissions [18]. If the economics support it, it could be initiated quickly today, starting to store existing CO_2 emissions from today’s existing SMR hydrogen production (instead of releasing it to the air) but also adding new SMRs and new users after that. The idea of making grey hydrogen “blue” by CCS first, adding more blue hydrogen after that and finally adding more and more green hydrogen according to the increase of RES electricity is shown in Figure 7.



Horizon 1: Medium term
Fossil H_2 with CCUS to be the initiator and accelerator of the hydrogen society (“blue” hydrogen)

Horizon 2: Long term
Renewable H_2 to become dominant through successive /disruptive innovation & significant cost reduction (“green” hydrogen)

Figure 7 Hydrogen Generation Roadmap [19]

One project development in this direction is the Northern Light project in which CO_2 is going to be stored in the North Sea area, collected from different sources in the North Sea regions, particularly the Leeds region in the UK and the Dutch North Sea cost. In the Netherlands, the biggest project to use blue hydrogen is the Magnum Power Plant in Eemshaven where in 2025 the first 440MWel CCPP is expected to start operation running on pure hydrogen [20], [21]. Recently, the German government established a regulatory-sandbox funding system (“living labs”) and prioritised projects related to green hydrogen production as important cornerstone to set up a hydrogen economy [22].

The pipeline system and CO_2 transport via barges will allow balancing hydrogen production and demand as well as CO_2 storage. The existing infrastructure can be extended to large GW scale and can be interconnected between the chemical clusters, industries and thermal generation units with a re-use / retrofit of natural gas infrastructure. Following this way, necessary infrastructure investments are minimised and shared by all sectors. Power to hydrogen production facilities should be added to the system in parallel to the RES capacity increase. As industry and power generation are usually connected to large capacity gas and electricity grids, they are the most suitable places for such new installations.

On a global scale, different countries and industry consortia also investigate the possibility of large-scale liquid hydrogen and/or ammonia as a hydrogen carrier for the import of hydrogen from remote locations where RES electricity can be produced cheaper than in the EU. Especially for long distance ship transport, ammonia has the advantage of being transported easily in liquid form as LNG while hydrogen would have to be cooled down to -253°C for liquefaction which bears some challenges. Other technologies for hydrogen storage and transport are under development, e.g. liquid organic hydrogen carries (LOHCs) which can be loaded with hydrogen and release hydrogen gas later for use.

One must not forget the carbon demand of the chemical industry. Any hydrogen with a low carbon footprint being available in the future, combined with carbon from non-avoidable CO_2 emissions (via CO_2 capture), non-recyclable waste or biomass/biogas (via pyrolysis, gasification or reforming) or finally air captured CO_2 can serve this need via synthetic fuels [23].

4. CHALLENGES: REPLACING CARBON FUELS BY LOW/NO CARBON FUELS

More than 20 years ago, the northern European countries started to convert coal-fired power plants to biomass or to design new power plants directly for biomass. The sector has seen retrofits / fuel switches of about 2.5 GWel power plant capacity just over the last 15 years [21].
This very large-scale central biomass utilisation (200-600 MWel) on a scale of over a million tons per year is not transferable to all existing power plants in countries with a large industrial sector such as Germany. There, during the energy transition, first natural gas will be the bridge and intermediate solution for carbon emission reduction. Hydrogen can be used later in the same (modified) assets or in new, efficient power technologies that replace older plants.

Challenges in conversion or re-design of thermal power technologies, namely gas turbines, internal combustion engines, fuel cells, steam cycles from natural gas as today's design base to hydrogen are addressed as follows:

4.1 STEAM POWER PLANTS AND GAS TURBINES

Due to their operational flexibility (part load behavior, load-follow operation, short and reliable start-ups, etc.), gas turbine plants are already among the best available technology engines as back-up for the renewables [24],[25]. Due to their highest plant efficiency for combined cycle (gas turbine) power plants - CCPP (currently up to nearly 65%) and fuel utilisation rate in combined heat power plants – CHP (currently ~ 85%), they comply with the strongest EU emission requirements which are under discussion (e.g. 550 g/kWh CO_2) or which have been set as industry standards (e.g. 25 ppm NO_x). Different measures have been developed to reduce the CO_2 emissions significantly. This can be achieved by further optimisation of the thermodynamic cycle parameters (leading to a higher turbine efficiency), by admixture of hydrogen to the fuel or by utilisation of CCS/CCU technologies (particularly in industry sectors).

In addition to their operational flexibility, new combustor technologies of modern gas turbines also offer extended fuel flexibility. Therefore, they have become capable of dealing with different fuels at varied qualities (Wobbe indices[5]). Natural gas/H_2 mixtures (up to 100% hydrogen) at all power ranges fully compliant with emission laws with after treatment or diluent injection can be burnt. Natural gas/biomass derived syngas mixtures, H_2-rich fuel gases (e.g. syngas, by-product refinery gas or coke oven gas), LNG/LPG, unconventional

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[5] The Wobbe index is the ratio of the specific energy of a gas (heat value of the fuel) to its relative density (specific gravity), providing an indication of the volumetric flow rate as shown by its constituent components.required to deliver a certain thermal input to the engine. It is one of the main indicators of fuel gasses interchangeability in the application of gas turbines.

natural gas, syngas based liquid fuels and even non-carbon fuel (e.g. ammonia) can also be burnt efficiently.

Hydrogen has been already used successfully in various fields of power engineering for over a century. In the beginning, coke oven gas from the steel industry containing more than 50% hydrogen was used in city gas networks, and today essentially as boiler fuel in steam power and gas turbine plants. The industry has long experience with burners for firing of more than 60 vol.-% in conventional power plants and gas turbine combustors, and almost 100% in duct burners. These installations can be found in industries that use by-products, e.g. in steel industry, refineries and the chlor-alkali industry.

Due to the high adiabatic flame temperature and flame speed of hydrogen, existing burner systems for hydrogen-enriched fuels need to be further developed in order to comply with the lowest emissions limit values and to enable safe operation (avoidance of high flame temperatures and flame flash back). If necessary, for a fuel switch, flue gas cleaning systems must be retrofitted during plant conversions. The safety-related systems, material selection and seals must be adapted towards the changed conditions.

Besides the combustion of hydrogen and other low carbon fuels, development is ongoing, advanced high-efficiency cycles using e.g. sCO_2 as working fluid are under development. “Triple Cycle” technology using fuel cells as main producer and burning the remaining combustibles afterwards in a CCPP installation are considered for future power plants but may need another decade to be demonstrated at a large scale (incl. geothermal, solar thermal, steam boiler, nuclear reactor) and economically.

The manufacturers of power plants have also extensive knowledge from past fuel switches / power plant conversions and developments and can thus offer all the necessary technologies for furnaces and gas turbines on demand [21, 26].

4.2 FUEL CELLS

In decentralised applications, hydrogen can increasingly be used as clean fuel in fuel cells (FC) for electricity and heat production. There are fuel cell systems in the stage of commercialisation with single stack power output of 1 MWel [27]. The main advantages of FC technology are the high electrical efficiency and low pollutant and noise emissions. Solid oxide fuel cells (SOFC) also have a high fuel flexibility (natural gas through biogas to hydrogen) by the integrated reforming step.

The recognition of decarbonized hydrogen as an attractive and important energy storage platform by energy utilities, the interest of major global telecommunications in fuel cell backup power, and the commercialisation of fuel cell electric vehicles by the world’s major carmakers are the proof that the existing technology is promising and worthy to be improved and expanded. In the case where decarbonized hydrogen is the main fuel, there are no polluting emissions at all, while in the case of other fuels, such as natural gas and biogas, the quantity of the polluting emissions can be approximately two orders of magnitude lower than that in the case of the conventional **electro-productive** systems (with the exception of nuclear produced electricity).

It can be expected that with increasing demand (also in the mobility sector), the production rates for fuel cells will increase and costs will drop. This means that in the MW range fuel cells also will become an alternative to internal combustion engines for stationary CHP applications.

4.3 INTERNAL COMBUSTION ENGINES

Renewables- dominated energy system of the future will require flexible decentralised thermal co-generation plants to provide residual load within a short-term. Plants driven by small and mid-sized gas engines can meet this demand, particularly in industry sector. The variability of renewable energy sources wind and solar demands for systems capable to respond to changes of different time scales. In general, short-term flexibility means lead-times ranging from few seconds to minutes, medium-term means half an hour or a few hours and long-term flexibility means days, weeks and months as e.g. seasonal changes. Modern energy systems must be able to bridge all ranges of flexibility needed for different aspects to guarantee supply [28]. Gas engines are capable to start from standstill to full output within a few minutes - the fastest gas engine can start within less than 1 minute. Over the last decades, gas engines have been installed in thousands for natural gas CHP applications achieving 90% fuel utilisation and more, many of them are running on raw biogas.

Gas engines have experienced a booming market for co-generation over the recent years. The commercialisation of the latest engine generation in the 10 MWel class typically means installations as multiple unit concepts for power plants with a total output of up to around 200 MWel. Gas engines are ideally combining flexible operation and high efficiency. One of the gas engine lighthouse projects is the Küstenkraftwerk Kiel (Germany) with 20 units of 9.5 MWel engines achieving a total output of 190 MW and 91% fuel utilisation.

There is also a significant experience with non-natural gas such as process gases with high hydrogen content and admixing of hydrogen up to 70 % (vol). Gas engines in the MW scale capable to run on 100 % hydrogen are under development and should be available within a few years [29]. Very successful prototypes in the range of 200 kWel class engines (truck application) have been already installed to run on 100 % hydrogen. Efficiencies of over 40% [30] can be reached with such small engines, enabling competitiveness against FC systems and offering solutions for other applications.

Gas engine technology running on hydrogen fuel can be the basis for future medium-sized decentralised CHP applications. It is a proven and reliable technology with low capital and low operating cost. Gas engines are also an ideal solution for other renewable fuels such as biomethane, carbon-neutral produced methanol or even carbon-free ammonia.

4.4 AMMONIA AND SYNTHETIC, CARBON-BASED FUELS

The combustion of ammonia would produce even a larger amount of NO_x compared to combustion of hydrogen (depending on the combustion conditions). However, it is favoured as an energy carrier. Ammonia can be used in combustion equipment by catalytically splitting ammonia into nitrogen and hydrogen before combustion. Combined with the necessary investment in infrastructure, ammonia is likely to be suitable initially for large, centralised consumers who have port access and can build large-scale ammonia cracking facilities. Combustion (unlike the use in fuel cell vehicles) does not require absolute purification of the fuel. Nitrogen as ballast in the combustion gas rather simplifies the combustor design. All the necessary technologies for the ammonia value chain are also known, and ammonia is already the largest chemical commodity traded internationally.

Likewise, synthetic fuels such as methane, and methanol, dimethyl ether (DME) or other follow-up products derived from methane or methanol could be used without significantly changing the existing infrastructure for heat and power applications. Based on methanol also drop in-fuels for existing reciprocating engines can be produced by commercially available processes like the MTG (methanol-to-gasoline process). These synthetic drop-in fuels can be optimised towards minimised emissions like soot and higher efficiencies of the engines.

4.5 TECHNOLOGY REQUIREMENTS: NEW TECHNOLOGIES AND FLEXIBILITY

Flexibility is one of the core features of power generation in the future to enable balancing variable RES. This flexibility has different components depending on the specific technology and application.

Operational flexibility has significantly improved over the last decade for all thermal power plant technologies and also for hydro turbines. Operational flexibility covers reduced minimum loads of the generators/turbines, a quick start possibility and fast ramp rates as well as black-start capabilities in case of hydropower. Challenges in this area are especially material stress and wear of the equipment due to cycling. Improvements by material selection and re-engineering are ongoing. Also, the efficiency for part loads has to be further increased by innovation when plants operate in flexible mode [24],[25].

Fuel flexibility is a core technology where development is ongoing. The challenge is on one hand, the handling of aforementioned different combustion properties for hydrogen, but also the real consideration of having unlimited fuel flexible designs where different fuels can be mixed at arbitrary shares depending on availability without hardware changes. R&D and engineering is ongoing for this purpose, both for new power equipment, but also for retrofits/conversions of existing power generation as in some EU regions mixing of hydrogen in natural gas pipelines is considered.

Emission reduction technologies must be adopted for the cycling operation, fuel flexibility and minimum loads. While flexible operations usually increase emissions in combustion systems, lower emission limit values by regulation require further system optimisation and new approaches on the other hand.

Product flexibility is important, with regards to sector integration, to allow delivering on demand heat, electricity but also synthetic fuels in integrated plants. Product flexibility between fuels and electricity as an output is a core technology to make power output more flexible, while heat storage in CHP and district heating grids (hot water storage) is already state of the art for de-coupling of electricity and heat markets. New CHP plants are also often equipped with electric heaters or in future with heat pumps to effectively utilise excess capacities of RES electricity (e.g. [31]).

Power generation with integrated energy storage is a supportive technology to balance vRES in the future and avoid constraints in the electric grid infrastructure. Such storage can be simple hot water heat storage in co-generation thermal plants, but also high temperature heat storage based on molten salt, thermal oil or solid materials for energy storage on a daily basis. Molten salts technology is currently commercially available in CSP power plants and extended as thermal storage device in conventional fossil plants [32]. RES generation can be aggregated and coupled with batteries or hydrogen production, storage and re-conversion as this is already considered for thermal plants [33]. Implementation of hydrogen production and infrastructure (pipelines/cavern storage) can overcome the future challenge of seasonal energy storage, too. Hydro dams and reservoirs can be increased when technically and environmentally feasible and/or combined with batteries for short-time storage and flexibility increase.

The flexible operation affects all types of power generation equipment, and **improved materials** must be developed. Furthermore, new designs must be derived in the next years.
With decreasing inertia from large rotating masses (generator/turbines of central power plants) in the electric grid, **synthetic inertia technologies** (e.g. inverters) or mechanical inertia technologies (e.g. flywheels) must be implemented.

New technologies must be significantly scaled-up not only in size but also in production capacity. Examples are fuel cells and electrolysers. Alkaline electrolysers are mature for decades while PEM electrolysers are a still young technology. Nevertheless, for both technologies, the manufacturing capacity is not big enough in the world to satisfy the increasing demand.

Alternative storage technologies like redox flow batteries, (adiabatic) LAES and CAES (liquid air energy storage, compressed air energy storage) are ready for demonstration but still have a high potential left for technology improvement.

Waste gasification and chemical use of gaseous by-products must be further developed as the low hanging fruits of circular economy implementation. The chemical use of these by-products of industry and civil society bear a high potential not only for the energy sector but also for the reduction of fossil energy use for raw materials.

Ocean energy represents technologies that use tidal currents or the power of waves to generate electricity from seawater. These include hydrokinetic (river, ocean and wave), tidal barrage and tidal stream. These technologies can often overlap. For example, storage projects can often involve an element of pumping to supplement the water that flows into the reservoir naturally and run-of-river projects may provide some storage capability. For all technologies new environmental impacts occur which are under investigation in parallel to technology development and testing.

5. TRANSITION SCENARIO: FUEL SWITCHES, FLEXIBILITY

The energy transition of all European countries is currently developing rapidly and generally based on a – as fast as possible - deployment of vRES. Due to national policies (and economic capabilities) the transition is not executed uniformly. On one side, the need for CO_2 reduction according to the objectives of the Paris Agreement is agreed and common within all countries. Most EU Member States have recognised the need to abandon coal combustion and set national roadmaps for the coal phase-out. However, the handling of alternative technologies such as nuclear energy and biomass is very different, which has an impact on the speed of increase of RES capacity as well.

5.1 SHORT-TERM DEVELOPMENT: FUEL SWITCH TO BIOMASS AND NATURAL GAS

Biomass: Increased biomass use began over 20 years ago, particularly in the northern EU countries via retrofit of coal plants to biomass and newly built units. Several GWel power plants' capacity for the use of wood pellets or wood waste chips have so far been commissioned or retrofitted globally (with a focus in Europe). Assuming the rollout of new technologies for the use of waste biomass via hydrothermal treatment or gasification, a high potential of further biomass resources could be utilised. Biomass retrofits and new builds are mid-term solutions, as new value-chains (from forestry to pellet factories up to logistics and trading) need large investments and time.

Natural gas: Centralised biomass use on a scale of several million tons per year is, however, not transferable to countries with a large industrial sector such as Germany. There, natural gas is needed as a bridging solution during energy transition. The retrofit of existing power plants to gas (co-) firing as well as development of new build projects is ongoing. All-natural gas technologies are represented in ongoing fuel switch projects that are driven by the refurbishment demand of aging assets all around Europe.

- New constructions of smaller combined heat and power units and retrofits of coal boilers with simultaneous installation of topping cycle gas turbines for municipal heat supply
- Compact combined gas turbine or gas engine power plants in small and medium-sized cities
- Steam generators for primarily heat-dependent industry
- Highly efficient gas-fired combined cycle power plants in the electricity market in competition with subsidised reserve power plants (open circuit gas turbines)

In eastern Europe, the transition from coal to gas is being prepared by building up new gas pipelines and LNG terminals. The necessary structural change from coal mining and coal-based power generation to other industries begun there quite later than in the rest of Europe.

5.2 FUEL FLEXIBILITY, LOAD FLEXIBILITY AND ENERGY STORAGE

In particular, systems for electricity and heat supply are becoming more complex. To operate independently in the electricity and heating market, new district heating power plants are almost exclusively equipped with **water heat storage.** Thus, heat storage in GWh scale is technically feasible just as at the power plant Avedoere in Denmark or in the Küstenkraftwerk Kiel in Germany. **Topping cycle gas turbines** attached of steam power plants (Avedoere II) or the possibility to **operate the heat recovery steam generator of CCPPs in air mode** (no GT operation, only steam production) allow to respond quickly to positive or negative load demand. Fuel flexibility can also be implemented as in the power plant Avedoere, which in the boiler can be fired with mixtures of coal, biomass and natural gas over a wide range, allowing maximum fuel flexibility and security of supply.

5.3 HYDROGEN AS A NEW ENERGY CARRIER, SECTOR COUPLING, PTX

Regarding **mixed firing of biomass and hydrogen** in the future, the first preliminary studies have been carried out. Here, too, the integration of topping (hydrogen) gas turbines in existing steam cycles is being investigated.

In Germany, the Netherlands and the United Kingdom, the first investigations are also being carried out on demonstration plants that will integrate electrolysers, hydrogen storage and HRS supplemented by small gas turbines for peak power supply (integrated storage plus external hydrogen commercialisation). By combining various technologies (Figure 8) and end-products, economic operation should already be possible in the coming years.

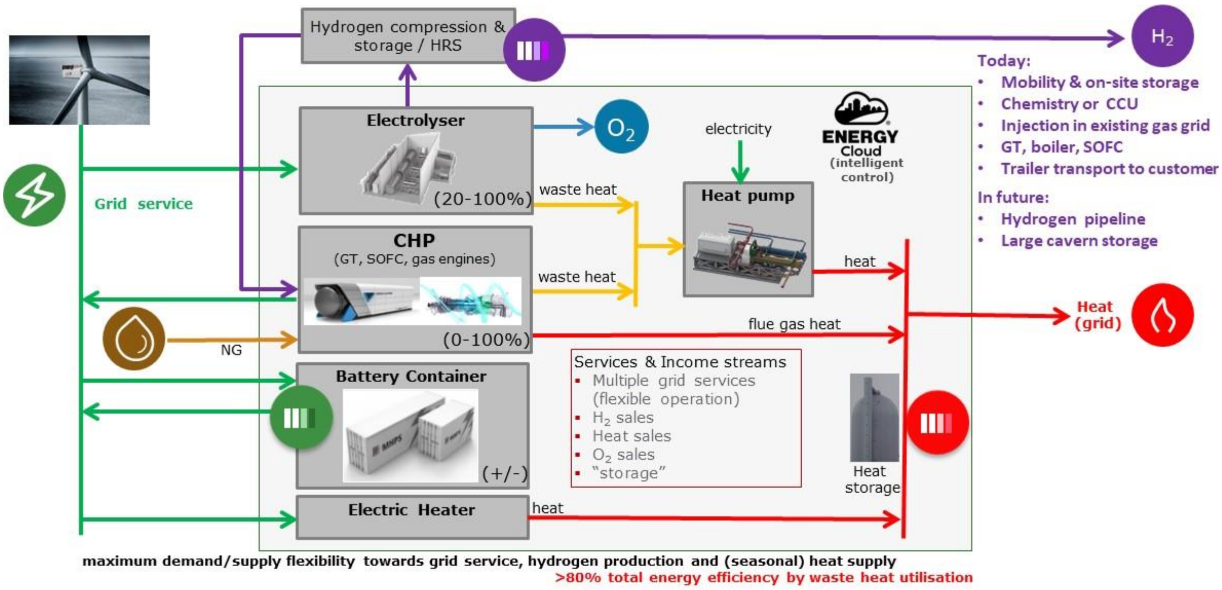

Figure 8 Technology blocks under consideration for power generation flexibility and sector integration, energy storage [21]

Moreover, CHP plants used for district heat production have already partially integrated electrical steam/hot water generators. Initial planning is also under way for large heat pumps, which can completely take over the supply in summer operation using environmental heat (rivers) or wastewater heat. In addition, compressed air energy storage combined with hydrogen is under consideration in some locations.

"Hydrogen readiness" of new equipment is now on the agenda for new investments like CCPP and CHP plants, as gas grid operators are going to plan injection of decarbonised "green" hydrogen into their pipelines in near future [34, 35]. A clear policy for the decarbonisation strategy of the EU natural gas grids and the role of hydrogen would also support decision making of industry for the urgently needed replacements of aging assets and to avoid investments in stranded assets or a shift to "capacity markets" only.

6. CONCLUSIONS

Beyond extending variable renewable energy technologies towards large scale usage there are additional challenges to be addressed to achieve energy flexibility required by future energy systems. Hand in hand with the efforts of various EU-countries to set up hydrogen-based energy strategies, flexible thermal power generation technologies operating on low carbon fuels will contribute to a secure and sustainable energy supply in the future. Corresponding Research and Development needs are shortly outlined in this White paper.

Besides renewable energy generation, the role of thermal power systems will remain crucial for the mid-term transition period; but also beyond, in order to achieve a low-carbon, secure, reliable, resilient, accessible, cost-efficient, and market-based, pan-European, integrated energy system. The shift towards decarbonised "green" fuels, whose production is connected with significant losses, demands for highest efficiencies and fuel conversion rates of plant components. Stability and resilience of the power systems depend on the flexibility of existing and novel processes in order to offer the highest possible level of dispatchability in combination with a high share of vRES power generation.

The flexibility of the power generation is coupled with other issues covered by the different ETIP-SNET WGs on smart grids, integration of vRES in the grids, storage, and digitalisation. For a successful pathway forward, public awareness has to be raised to create a basis for investments in the transition towards a decarbonised power generation in Europe such as a regulatory framework to create incentives and public acceptance. This is not only true for power generation itself but for all topics across all ETP SNET working groups. Finally, the role of the EU emission trading system (ETS) for CO_2 is very important (a detailed analysis is beyond the scope of this white paper), not only for the electricity sector, but for the overall energy system. Some general thoughts and recommendations for creating clarity for developers and investors shall conclude this White Paper.

6.1 POLICY MUST CREATE INCENTIVES

New technologies for making the electricity supply and energy use more sustainable in all sectors are already available and some of them need to be upgraded to large scale application. First of its kind installations and technology demonstration are suffering from unclear political regulation, missing incentives for low carbon solutions and regulatory burdens. Unless CO_2 emissions do have a certain cost impact in all sectors, it is difficult to develop business models for carbon reduction. This way, a balanced approach of financial support for the deployment of such technologies is needed as well as the removal of regulatory hurdles for cross-sector applications. Barriers like high levies or taxes on electricity used in storage or cross-sector applications must be removed on a national level, and a common European approach is needed to avoid market distortion.

In addition, new standards are needed to have a fast implementation of synthetic fuels and fuel blends that have different characteristics compared with today's standard fuels. This is especially true for energy infrastructures like hydrogen pipelines or emissions of legacy equipment currently connected to the gas grid. Similarly, low carbon fuels, as gasoline blends with higher (low-carbon) alcohol contents in favor of higher efficiency of reciprocating engines, are not defined in the fuel sector and, thus, a roll out of fueling infrastructure or cars is restricted to fleet tests. Low carbon fuels derived from renewables for transport purposes are intended in the Renewable Energy Directive II. However, certification, recognition and application are detained by missing commission's delegated acts with regard to the life cycle analysis and other issues.

Environmental impact assessments and permitting **procedures** hinder or delay not only the necessary extension of electric grids, but also act a hurdle for other energy infrastructure installations. Hydroelectric structures affect a river's ecology mainly by changing its hydrologic characteristics and by disrupting the ecological continuity of sediment transport and fish migration through physical barriers, such as dams, dikes and weirs. As for the social impact, hydropower might require the relocation of local population, but it is usually a driver of socioeconomic development. The main environmental and social issues related to hydropower projects, as well as the extent of their positive and negative effects, are typically site-dependent, as each hydropower plant is uniquely designed to fit the site-specific characteristics of a given geographical site and the surrounding society and environment. Run-of-river HPPs do not alter a river's flow regime, while, on the other hand, the creation of a reservoir for pumped hydropower storage entails a major environmental change. In general, hydropower leaves a significant environmental footprint at local and regional levels but offers advantages at a macro-ecological level.

In summary, most large power generation, storage and transport infrastructure suffer from complex and long permitting procedures, which discourage investors. Further streamlining of the procedures and political support – especially in favor of more complex cross border projects – is needed. Since previous policy initiatives, especially outside the power sector, have not provided a broad impact, the discussion about a general pricing of CO_2 emissions is at the forefront of political debate. It is obvious that further regulation (either through further support of low-emission technologies or CO_2 taxation) is needed to enable investments in low-carbon solutions.

6.2 RECOMMENDATIONS

When the industrial and the transport sectors are included in the considerations, there is a convergent picture: on the basis of hydrogen renewable energy can be provided to all sectors and seasonally stored via using existing and extended infrastructure. The cost burden is carried by all sectors, which also have the benefits of low-carbon energy. This reduces the overall economic cost impact, and a more-or-less smooth transition is possible through the connection of hydrogen clusters and decentralised applications. The available RES capacity as well as the acceptance and diffusion of hydrogen technologies are a limiting factor in the speed of transition. Here, the expansion of the coastal hydrogen infrastructure in the Netherlands and Germany, which today already includes hydrogen pipelines, plays an important role. There it will also be possible to commercialise blue hydrogen early with CCS, starting via CO_2 collected and transported with barges as e.g. intended by Equinor. Although the spread of infrastructure to areas further away from the coast will be somehow slower; nationwide or across the EU coverage will take about one to two decades, partly because additional RES installations will cost a lot of time and money. Nevertheless, compared to the introduction of electricity and natural gas networks, this would be faster.

At the same time, further low-carbon technologies will be needed to meet the emission reduction targets in all sectors, as shown in Figure 9. However, the achievement of decarbonisation targets will depend on the willingness of policy makers and the public to bear the necessary costs and to accept building new energy infrastructures (hydrogen pipelines, reserve power plants, enhancement and build-out of the electricity transmission sector, etc). At least in the initial phase, significantly higher costs for new infrastructures and increasing RES shares in the energy mix are to be expected. Therefore, the realisation of the presented, future energy world can only succeed, if CO_2 emissions in all sectors receive a higher price in the near future, if demonstration plants are promoted, and at the same time if a technology-based consensus is reached between politics, population and economy about the right pathway and the speed of implementation.

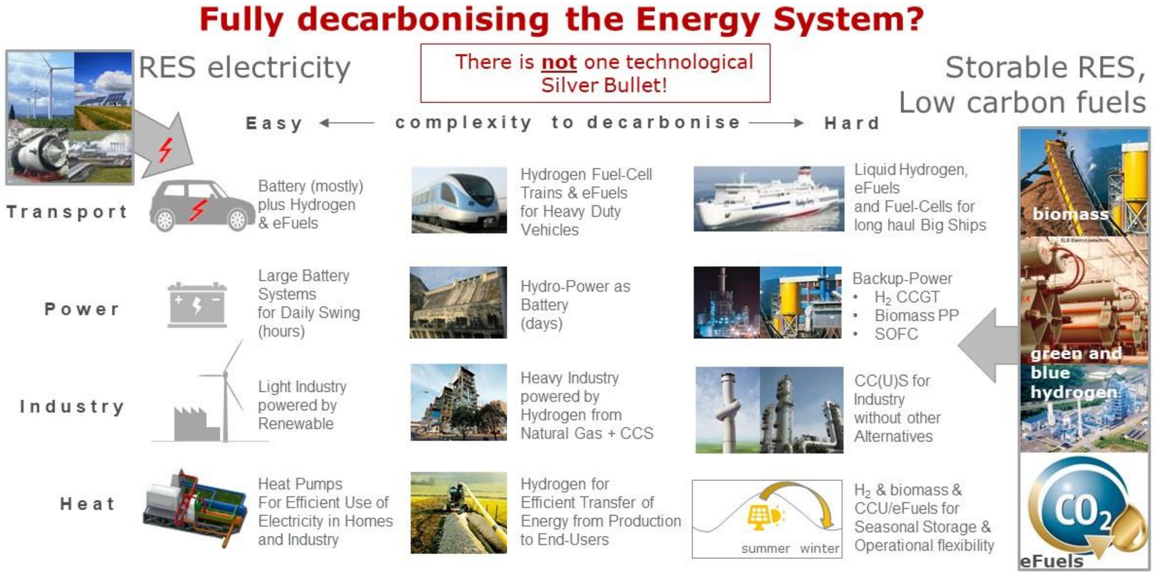

Figure 9 Low-carbon energy technologies enabling the phase out of fossil fuels [21]

7. GLOSSARY

AC/DC	Alternate/direct current
AQCS	Air quality control system
BWR	Boiling water reactor
CAES	Compressed air energy storage
CCPP	Combined cycle power plant
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CHP	Combined heat power
CSP	Concentrated solar plant
DME	Dimethyl ether
EOR	Enhanced oil recovery
ETS	Emission trading system
FC	Fuel cell
GT	Gas turbine
HPP	Hydro power plant
HRS	Hydrogen refueling station
HVDC	High-Voltage direct current
IGCC	Integrated gasification combined cycle
LAES	Liquid air energy storage
LNG	Liquified natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquified petroleum gas
MOX	Mixed oxide fuel
MTG	Methanol-to-gasoline
ORC	Organic Rankine cycle
PEM	Polymer electrolyte membrane
PtX	Power-to-X
PV	Photovoltaic
PWR/PHWR	Pressurised (heavy) water reactor
RES	Renewable energy sources
vRES	variable RES
SCPP	Simple cycle power plant
sCO2	Supercritical CO2-cycle
SOFC	Solid oxid fuel cell
SMR	Steam methane reforming
SNG	Synthetic natural gas
ST	Steam turbine

8. APPENDIX: POWER CONVERSION TECHNOLOGIES: STATE-OF-THE-ART AT A GLANCE

8.1 WIND TURBINE BASED POWER GENERATION

Wind energy conversion is a mature and competitive technology, being a key part of Europe’s industrial base, with 260.000 quality high skilled jobs. The European wind industry has a 40% share of all the turbines sold globally, exporting technology and services.

According to expectations from IEA, wind will become the primary source of power in Europe in 2030. In a central scenario from WindEurope (considering the previous 27% renewables energy target for 2030), 323 GW of cumulative wind energy capacity would be installed in EU by 2030 (253 GW onshore and 70 GW Offshore), producing 30% of EU´s power demand.

Wind energy is the kinetic energy of the wind that is converted into electrical energy through a wind turbine generator. Wind is generated when solar energy heats the Earth’s surface, which in turn heats the surrounding air, increasing its volume and causing differences in the atmospheric pressure. When the wind flows around wind turbine blades it causes the generator to rotate, and kinetic energy is converted into mechanical energy in the rotor. This mechanical energy is then converted into electrical energy through a generator.

However, due to wind speed reduction when passing through the blades, theoretically only 59% of the kinematic energy can be converted into mechanical energy in the rotor, called Coefficient of Power (Cp) by Albert Betz. This factor (Cp) should be considered for the calculation of energy produced.

In practice, this theoretical limit is not reached as mechanical, aerodynamic and electrical losses must also be considered.

Most of the commercial wind turbines are lift type turbines. In the lift type, wind flows through both sides of the blade (with different profiles) creating a pressure difference between both. This pressure difference creates a lift force and then the rotation about the axis.

Wind turbines are normally classified depending on the rotation axis (Vertical or Horizontal), and number of blades (2-3). Most extended configuration is horizontal axis, 3 blades, as it is been considered as the optimal configuration.

Another important consideration is the huge EU offshore wind resource that is much greater and more stable than onshore, which is driving the growth of offshore wind installed capacity. Due to this higher resource, wind turbines are currently reaching nameplates of 8-9 MW with some designs reaching 12 MW and expectations to reach even bigger machines. Most importantly, offshore wind has the potential to deliver the bulk power needed to deliver the needed EU energy transition on time. For onshore wind, wind turbines are currently in the range up to 4-5 MW although there exist some designs in the range of 6-7 MW.

8.2 SOLAR-BASED POWER GENERATION

Solar photovoltaics (PV) is the direct conversion of solar radiation into electricity. Solar PV global power installed at the end of 2018 produced more than 500 GW (114.5 GW in EU) which corresponds to 4% of renewable energy sources. The installed capacity in the EU is dominated by Germany (45.2 GW), followed by Italy (20.1 GW), UK (13 GW), France (9.4 GW) and Spain (4.7 GW). Despite its low share on global markets (4% in EU), it is considered one of the most promising markets in renewable energy, mainly due to its fast growth. Only both in 2017 and 2018 the global PV market grew by 100 GW approximately (an average annual increase of 29%, mainly driven by China). The EU experienced an increase in new PV installations recently, with 5.7 GW in 2017 and 7.6 GW in 2018 being more stable in the EU with a maintained growth of 10%. A further exponential rise is expected in the next following 5 years, with the trend showing that worldwide installed capacity will exceed action of 1000 GW (with at least 300 GW distributed PV) [36].

The main advantages of solar PV are the high availability of a clean and free source (the sun), the low cost of operation and maintenance (due to the absence of moving parts), the noiseless operation, and the closeness between generation and consumption. The expansion of distributed generation is key in the growth of PV due to its generation in commercial, industrial and residential environments, additionally to the utility-scale projects. However, solar PV still suffers from important disadvantages related to its high start-up costs and investments, the low efficiency, the need of large land areas for installation, and the variable performance as function of location and meteorological conditions.

Typical solar PV installations are built of four elements: a PV module, a charge controller, an inverter, and a battery system (if necessary). The critical section is the photovoltaic module, where solar radiation is directly converted into DC electricity by means of PV cells. Charge controllers have the function to regulate power in order to meet the requirements of the system and to increase usage life of batteries (avoiding overcharges and full discharges). In the inverter, the electricity is converted to AC to the grid voltage and frequency. Finally, batteries are used to store the surplus of electricity in order to ensure the supply during night hours and overcast days.

Concentrating solar power (CSP), also referred to as concentrating solar thermal power, uses mirrors to concentrate solar radiation onto a receiver for various purposes such as heating, cooling, or electricity generation. CSP technology requires strong and direct sunlight for efficient operation. It hence requires clear skies, and, thus, promising locations for CSP technology within the EU are limited to its most southern parts. Since CSP technology is typically combined with thermal energy storage and/or back-up firing, it comes with high operational flexibility and guaranteed generation capacity and can also provide electricity in cloudy periods of the day, early in the morning or after sunset. In CSP plants, the heat is used to drive a steam cycle with a steam turbine. At the end of 2018, the total capacity of CSP plants in the EU was 2.3 GW, 99% of which in Spain, and just Italy, Germany and France having a few more installations. This accounts for more than 40% of the global installed power (5.6 GW). Even though the market in the EU has been dormant over the last 6 years, a number of CSP projects were reported to be under operation at the end of 2018, with a total power of 312 MW [37].

8.3 HYDRO-BASED POWER GENERATION

Hydropower is a versatile, flexible technology that at its smallest can power a single home, and at its largest, can supply industry and the public with renewable electricity at a national and even cross-border scale. In terms of generation capacity, hydro accounts for eight of the world’s ten biggest existing power stations.

There are four broad hydropower typologies:

- **Run-of-river hydropower:** a facility that channels flowing water from a river through a canal or penstock to spin a turbine. Typically, a run-of-river project will have little or no storage facility. Run-of-river provides a continuous supply of electricity (base load), with some flexibility of operation for daily fluctuations in demand through water flow that is regulated by the facility.
- **Storage hydropower:** typically, a large system that uses a dam to store water in a reservoir. Electricity is produced by releasing water from the reservoir through a turbine, which drives a generator. Storage hydropower provides base load as well as the ability to be shut down and started up at short notice according the demands of the system (peak load). It can offer enough storage capacity to operate independently of the hydrological inflow for many weeks or even months.
- **Pumped-storage hydropower:** provides peak-load supply, harnessing water that is cycled between a lower and upper reservoir by pumps which use surplus energy from the system at times of low demand. When electricity demand is high, water is released back to the lower reservoir through turbines to produce electricity. Pumped storage water can be activated for generation at peak times, provide grid stability, flexibility and other ancillary grid services. Pumped storage hydropower can also absorb renewable power generation during times of surplus, thus reducing potential curtailment.
- **Ocean energy:** a less established but growing group of technologies that use tidal range, tidal currents or the power of waves to generate electricity from seawater. These include hydrokinetic (river, ocean and wave), tidal range and tidal streams.

Energy storage is becoming an increasingly flexible and cost-effective tool for grid operators to help manage instability on their networks. This is especially so, given with the growing amount of variable renewable energy generation being deployed in major markets worldwide, such as that from solar PV and wind. According to the Global Energy Storage Database [DOE, 2017], the rated power of operational stationary energy storage reached a total of more than 170 GW, globally, by October 2016. More than 96% was provided by pumped hydro storage, followed by thermal storage (1.9%), electro-chemical batteries (1.0%) and electro-mechanical storage (0.9%). Three quarters of all energy storage was installed in the top 10 countries, led by China (18.8 %), Japan (16.7 %) and the United States (14.1 %).

8.4 GEOTHERMAL-BASED POWER GENERATION

Geothermal is currently engineered as an "always on" baseload supply. It becomes a fundamental pillar for the future of the electricity sector. It provides a stable, flexible and dispatchable renewable supply that allows moving toward a fully decarbonised electricity sector. Being able to provide grid services, geothermal electricity possesses a crucial significance that goes beyond the simple value of the kWh produced. Moreover, the development of geothermal electricity capacity makes geothermal heat available for businesses, communities or industries that are located nearby the power plants. Due to its flexibility, geothermal holds a unique position in the future energy landscape as it creates a bridge between the heating and cooling sector and the electricity market [38].

Geothermal is already a well-established market covering different technologies. Electricity production using geothermal resources started in Larderello in Tuscany, Italy in the first decade of the 20th century. Today, there are 102 geothermal power plants in Europe with a total installed capacity amounting to around 2.5 GWe, producing some 14.6 terawatt-hours (TWh) of electric power every year.

8.5 GAS TURBINE BASED GENERATION AND COMBINED PLANTS

Open circuit gas turbine cycle, consisting of a compressor, a combustor and a turbine, is that of a Simple Cycle Power Plant (SCPP) without a steam turbine. In combined cycle power plants (CCPP), the heat of the gas turbine exhaust gas is utilised to generate steam in a heat recovery steam generator (HRSG) which is then expanded in a steam turbine. The condenser of the bottoming cycle is usually cooled by an external heat sink such as river - or seawater, ambient air or a cooling tower. CCPP can be operated in single shaft (consisting of one gas turbine, one steam turbine, with the gas turbine and steam turbine coupled to the single generator in a tandem arrangement on a single shaft) or multi shaft configurations (more than one gas turbine-generator, each GT has its own HRSG that supplies steam through a common heater to a separate single steam turbine-generator). Any upgrade from SCPP to CCPP is possible, which increases the power output and electric efficiency and reduces such the specific emission rate by provision of additional green MW.

Dependent on the customer use case, CCPP can be operated to provide electricity only or as combined heat and power generation unit (with heat extraction for addressing the heating sector). Smaller gas turbine plants are mainly driven by heat demand produced in a heat or steam generator. They are mainly operated as combined heat power plants (CHP) at municipal utilities for local heating and electricity supply, or for steam, heat, cold, and electricity production for industrial use (as e.g. chemical or food processing plants). SCPP will typically be used as peaker plants to provide short term ancillary services, therefore they are not subject of capacity mechanism.

A special application of gas turbines for syngas is the integrated (coal) gasification combined cycle (IGCC), a power plant using synthesis gas (syngas). IGCC is a technology that uses a high-pressure gasifier to turn coal, biomass or other carbon-based fuels into pressurised synthesis gas (syngas). Benefits are the reduction of pollutants, such as sulfur, lower emissions of sulfur dioxide, particulates, mercury, and in some cases carbon dioxide.

8.6 INTERNAL COMBUSTION AND DECENTRALISED POWER GENERATION

Engines are classified, based on two main different internal combustion processes. Engines of the Otto-process are operated with external ignition using a spark plug, and the Diesel-process with self-ignition. Turbochargers are common for power augmentation and to achieve higher electrical efficiencies up to ~50% for large units (>10MW). In Europe, most of the engine installations are gas engines and most of them run as CHP applications. For CHP applications, a fuel utilisation rate of 90% and more can be achieved. Gas engines are characterised by excellent part load behaviour and can be operated down to less than 50% load without considerable loss in performance. Many gas engine power plants are installed as multiple unit concepts. That allows shutting down engines if not needed and running the remaining units at base load and optimal efficiency.

Gas engines are very often provided as standard containerised / modular thermal power stations for fast and low-cost distributed power plants with units ranging from less than 100 kW to >10 MW in size. In 2014, about 5.3 GW was covered by all installed decentralised power and heating blocks with less than 10 MW output. This means a 16% share of all installed combined heat power plants in Germany at that time. In the power range up to 10 MW gas engines are most commonly used because of their higher electrical efficiencies, better part load performances, fast start-up and lower investment costs. Further, specific operating and maintenance costs and low level of noise emissions are in favour of gas engines in plants when operated close to densely populated areas. The most common fuels for gas engines are natural gas, biogas, sewage gas, landfill gas, but also process gases and highly hydrogen- enriched gases are widely used. Gas engines running on pure hydrogen are under development.

For decentralised power generation, integrating micro gas turbines (range 1kW-400kW) along with wind turbines, photovoltaics system, biomass plants, fuel cells and energy storage, would provide a secure, stable and efficient energy production-system, connected close to the consumers load and providing the end consumer with the heat and electricity needed. An important advantage of micro gas turbines for decentralised application is their capability to operate with a variety of renewable fuels (e.g. hydrogen, bio-methane, syngas) with lower emissions, noise levels and maintenance costs compared to other technologies in the same range.

8.7 MEDIUM AND LOW TEMPERATURE BASED ENERGY CONVERSION

The majority of the thermal power plants operate as Rankine cycles with water/steam as fluid (or other working fluids). The steam generators can be fuelled with different types of renewable or fossil fuels, municipal or industrial waste (solid, liquid or gaseous) or heated by nuclear energy, solar heat, geothermal heat or also waste heat from industrial processes.
In the steam turbine-based process feed water is heated, evaporated and superheated in the boiler by heat transferred from the hot combustion flue gas (or the respective other energy source).

- The steam is expanded in the turbine while its energy is converted to mechanical power.
- In so called "condensing turbine" plants all steam is expanded through different turbine stages with condensation occurring in the last turbine stages.
- The remaining steam is condensed afterwards.
- The condensate is fed back to the boiler.

In condensing mode, the maximum efficiency can be reached as all steam energy is driving the turbine and thus the generator. It is important to note that large units can reach highest electric efficiencies as more technical optimisation on the steam cycle (heat integration) and turbomachinery (fluid dynamic design) can be done. Such measures are steam reheating after expansion in the first (high pressure) turbine stage, feedwater preheating with bleed steam, temperature and pressure increase of the live steam as well as temperature reduction in the condenser by better cooling systems.

Small units have electric efficiencies of 20-25%. For decentralised combined heat and power plants this is not a general disadvantage, since those plants are optimised to provide steam and heat to industries and public heating grids. Therefore, large amounts of steam or all steam is extracted before the low pressure turbine ("extraction turbine" or "backpressure turbine" in 2nd case) allowing to use 80-85% of the fuel heat (=fuel efficiency) on the one hand to produce electricity and secondly for heat production. The main loss in this case is the remaining heat of the flue gas. To further increase the efficiency, some power plants have so called flue gas condensers as the last step of the air quality control system (AQCS, cleaning emissions down to emission limits), further cooling the flue gas and providing additional low grade heat for building heating purpose. Medium size plants with extraction or backpressure turbines are also common for industrial steam supply e.g. in chemical industry, refineries and pulp and paper industry.

In all cases, the boiler size is not only related to the total heat and power production but also to other local boundary conditions like fuel availability (e.g. local biomass resource, need for waste or by-products to be burnt) as well as technical restrictions of the combustion system suitable for a certain fuel. Simple grate firing technically is restricted to a range up to 150 MWth, fluidised bed combustion usually is used in the range of 5 MWel up to 600 MWel (800 MWel been available) and pulverised fuel power plants have been built in EU from 20MWel up to 1100 MWel.

For decentralised applications, small grate firing with biomass (e.g. wood chips) is commonly used. In the range < 15 MWel ORC (Organic Rankine Cycle) with other working fluids instead of water/steam have proven commercial advantage. Such ORC processes are also advantageous for low temperature geothermal application and waste heat recovery from exhaust gases (as well as liquid streams) for electricity production as e.g. in steel or cement industry, behind gas engines or small/medium gas turbine plants. For the application of geothermal high temperature resources and solar thermal power plants, steam cycles are commonly used, and ORC results competitive in case of small sizes.

8.8 FUEL CELLS

Fuel cells are devices capable of producing electricity, exploiting chemical reactions between a fuel and an oxidant. The specific application limits the performance and availability of materials; nonetheless, actual technology is mature enough to promptly design novel devices according to the urgent requirements of carbon footprint reduction, sustainable energy production and mitigation of large-scale energy demand.

Fuel cells differ according to their operating temperature, efficiency, applications and costs. The major advantage of fuel cells is their high thermodynamic efficiency, which can take realistic values in the range of 40-60%. The performance, reliability and durability under different operating conditions constitute some of the main technical barriers to overcome.

Solid Oxide Fuel Cells (SOFC), mainly based on perovskite oxides, can reach up to 70% efficiency with fuel regeneration; one major issue is due to the high operating temperature (~900 °C) to achieve high ionic conductivity (~0.1 S/cm). Several pre-commercial SOFC demonstrators are operational in Japan (250kWel and 1MWel) and more than 20 000 h of operation experience is collected there.

8.9 CO_2 REDUCTION TECHNOLOGIES USING CCS/CCU

While fossil power is still one of the main sources for electrical energy generation for the coming decades, the establishment of economically feasible carbon capture technologies is one viable option to reduce carbon emissions and hence, mitigate climate change. Besides carbon capture and storage (CCS), carbon capture and utilisation (CCU) have come into focus to co-generate CO_2 for usage e.g. in enhanced oil recovery (EOR) or PtX concepts.

Several technologies for CO_2 emission reduction / CO_2-capture have been developed: pre-combustion (separation of CO_2 from a gas stream before combustion), oxyfuel (combustion with pure oxygen results in a rather pure CO_2/water exhaust) and post-combustion (separation of CO_2 after combustion) technologies, Figure 10.

Although amine-based CO_2 scrubbing is a mature technology that has been applied in chemical industry since decades, CO_2 capture faces several challenges which must be met when establishing this technology on a grand scale in power generation or industry:

- Size of the equipment: The size of a full-scale carbon capture plant poses special challenges to e.g. constructability, operability and maintenance and thus requires a subtle completion concept.

- Capex: Significant capital investments must be done when applying carbon capture to power plants. These investments need to be decreased in order to achieve lower CO_2 separation cost and to downsize “emotional” hurdles for erecting a capture plant. A clear regulatory environment needs to be created by politics in order to provide security for such an investment.
- Energy demand: Typical energy requirement for post combustion carbon capture lies in the range of 2.5-4 GJ/t CO_2 (or at least 1 ton of steam per ton of CO_2). Energy demand is needed to be minimised in many cases in order to achieve reasonable capture cost in the range of the achievable CO_2 price for e.g. EOR or CCU and to create a positive business case.
- Emissions: During process operation, capture solvents may form degradation products by thermal stress or reactions with SO_x, NO_x and oxygen contained in the flue gas. These degradation products as well as the capture solvent itself must be prevented from being dispersed into the atmosphere. Industry has proven that most strict emission limit values are kept during operation of large-scale plants.
- Operability: Transition in the energy market causes a trend to operate power plants more flexibly. Capture plants suitable for power generation must follow these dynamic operation regimes and must have in turn lowest impact on the operation of the power plant. Post-combustion carbon capture is most suitable to comply with that.

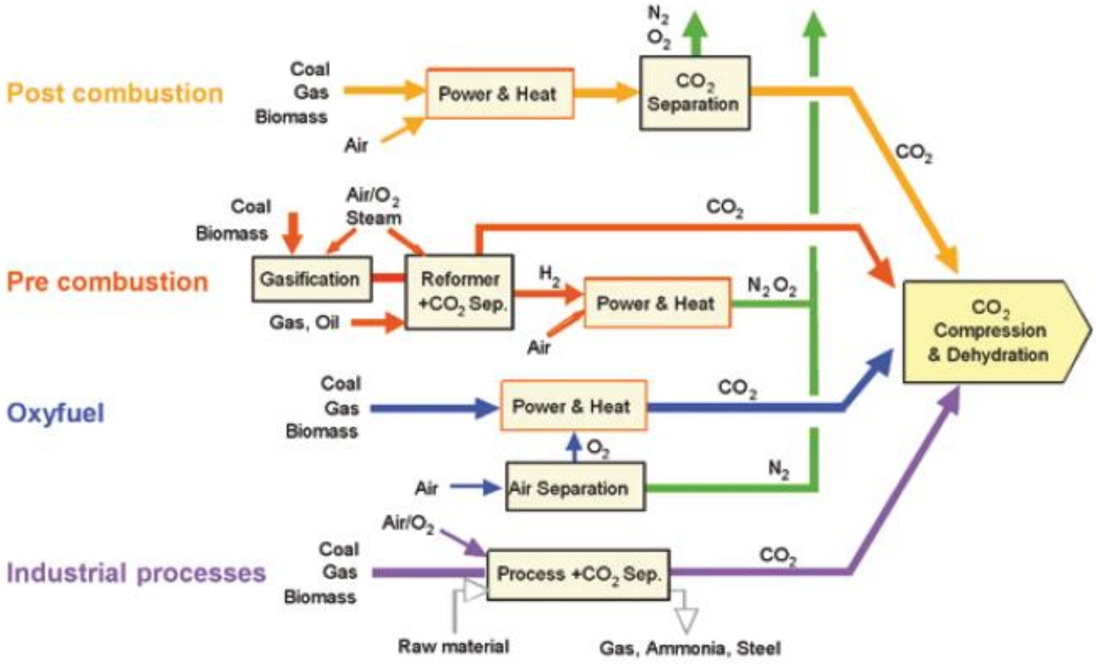

Figure 10 Schematic flow chart of CO2 Capture Systems [38]

The largest post combustion capture plant in the world is the Petra Nova Plant in Texas, USA where more than 4500 t CO_2/day (equivalent to 250 MWel coal power generation) are captured and used for EOR.

Alternatively, to amine-based scrubbing technologies, there are organic solvent technologies commercially available (e.g. Rectisol or Selexol processes).

Other promising technologies to CO_2 capture are related with the use of solid sorbents, at low temperatures (based in adsorption processes and using zeolites or carbon/metal-organic materials) and at high temperatures (mainly based in Calcium Looping technologies). Finally, other technologies are at different development status such as Chemical Looping Combustion, Ionic Liquids, and membrane-based CCS. An assessment of the available technologies with respect to the TRL is shown in Fig. 11.

Two crucial aspects must be noted regarding CCS/CCU technologies. On one hand, the retrofitting potential of current power plants must be considered in order to integrate the CCS/CCU as a core section in the flexibility of the plant. On other hand, the integration of these technologies in energy intensive industries supposes a fundamental opportunity to boost the circularity of the carbon as an energy carrier and a feedstock, linking the carbon capture with the carbon use in industries.

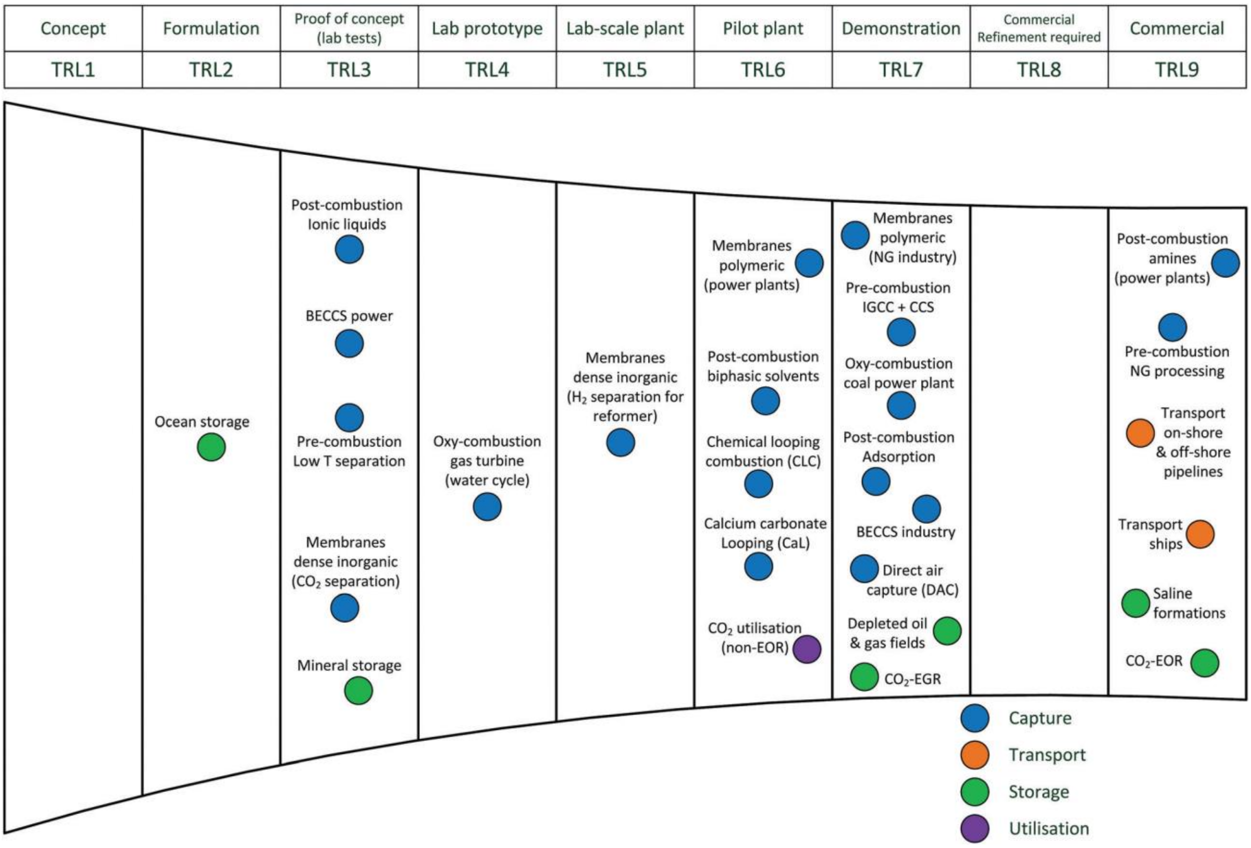

Figure 11 Current development progress of carbon capture, storage and utilisation technologies in terms of technology readiness level (TRL) [39]

8.10 NUCLEAR FISSION

Nuclear Power Plants were, for decades, the basis for reliable, emission-free and economical power generation. The first commercial nuclear power plant started its operation 1956 in Calder Hall (UK). End of 2017, 448 nuclear reactors with 393 GWe in 31 countries were in operation, 59 units were in construction (Source: IEA).

With unit sizes up to 1.6 GWe (e.g. European Pressurised Water Reactor EPR), they built the backbone of energy networks all over the world. Nuclear power plants provide best results at continuous full-load operation (capacity market), due to their design characteristics they provide limited capability for peaking applications, fast load follow operation and extended part-load operation.

Beside the risk of nuclear accidents (release of fission products to the environment in case of core melt), the question about dealing with the spent fuel is not finally solved. Fuel reprocessing plants for MOX fuel elements can significantly reduce the amount of spent fuel elements. In Finland, the first final storage facility for nuclear waste is under construction.

Most nuclear power generation is based on three reactor types: pressurised water reactors PWR (63.2%), boiling water reactors BWR (18,3%) and pressurised heavy water reactors PHWR (6.5%) – totally representing 88% of the nuclear fleet [40].

PWR and BWR use uranium oxide or MOX fuel elements (enriched with plutonium oxide) and are cooled by light water. PHWR use natural uranium or low enriched uranium oxide and are cooled by heavy water.

The latest accidents in Chernobyl and Fukushima changed the mindset of the community, especially in Europe. More and more countries decide to step away from the nuclear power generation or to reduce the nuclear portion in their energy mix, replaced mainly by renewables and decentralised hybrid generation.

In Germany, nuclear power plants generated 75.9 TWh electricity, this is equivalent to 11,6% of the market share 2017 (gross electricity generation). This is a significant decrease compared to 2000, with a 29.5% market share.

8.11 NANOGENERATORS

The burgeoning field of nanoenergy has in the front energy devices that can harvest energy passively from the environment, recovering power that is usually wasted as heat and materials wear in everyday life (human motion, walking, mechanical triggering, vibration, wind, water flows, tide and so forth). Though not yet explorable at a larger scale this technology shall not be omitted as it offers an interesting alternative to known technics.

Wearable/coating power generating electronics are based on devices that typically take the form of flexible fibres with diameters ranging from tens to hundreds of micrometres, accommodating complex deformations, such as twisting and stretching on irregular substrates. Such fibre-based devices are the basis of the fabrication of energy harvesting and storage breathable textiles. Since the appearance of 1D energy harvesting devices in 2002, technological efforts have been invested into the field of power self-producing materials, leading to the design of nano-supercapacitors, photoactive materials coatings, piezo- and triboelectric nanogenerators.

Nanogenerators (NGs) own the ability to convert simple mechanical solicitations (rubbing, elastic deformations) into usable energy current. Attempts to produce electricity from friction between moving parts proceeds from Van de Graaf generator for high voltage applications and leads to actual nanotribogenerators as an alternative source of distributed power suppliers. Many variants of application schemes have been successfully demonstrated; nevertheless, power optimisation schemes are still at their early stage.

With the actual technology, the area and volume of power density of a single nanogenerator device reaches 500 W/m^2 and 15 MW/m^2, respectively, with an instantaneous conversion efficiency of about 70%. The output of NGs allow their application either in common electronic devices and large-scale energy harvesting plants from wind and ocean waves. Another outstanding feature is their simple and diverse structural properties, which make them suitable for flexible and stretchable electronics, required in application areas such as wearable electronics, bendable displays and bioinspired artificial skins.

The macroscopic mechanism (i.e. friction and deformation) at the basis of electric current generation in nanogenerators occurs in so many diverse human activities and environmental conditions (either natural, either artificially induced) that very different families of materials can be exploited to create novel and more efficient nanogenerators. For example, carbon nanotubes as nanoelectric generators were already studied in 2001 through theoretical calculations and experiments realised in 2003. An output voltage of 2.67 mV was produced in water at a flowing velocity of 1.8 mm/s, reaching 8 mV in single-walled carbon nanotubes. Piezoelectric properties of nanogenerators have been exploited for sensors transducers, energy conversion and electronics, reporting excellent power conversion up to 30%. However, difficulties arise when manipulating atom-thin layers hinder high performance applications in nanoelectromechanical systems. Two-dimensional layered materials, such as hexagonal boron nitride and transition metal dichalcogenides have recently gained attentions for their application as energy converter from body movement, muscle stretching and blood vessel contraction

8.12 THE ROLE OF THE POWER GENERATION TECHNOLOGY PROVISION OF BACK-UP POWER

Not all the technologies mentioned are able to release dispatchable power on demand. Based on their physical principles, a rough evaluation is added in the following table:

	Physical principal	Existing unit size	Existing plant size	generation products	fuel flexibillty	load flexibility characteristics		Pro's	Contras
Fuel cells	electro-chemical	< 1MW (in 2019)	<10 MW	electricity; heat; (transportation)	PEMFC/PAFC (w/o reforming): limited to H2 SOFC: gaseous (incl. H2), liquid, high-and low calorific fuels,	(PEM/SOFC) dispatchability fast load change frequency support	 ++/- ++/- ++/-	No carbon emission (with H2 as fuel)	limited unit size
Gas turbine based (GT/CCPP)	combustion (continuous)	up to 500 MW (GT only)	up to 800 MW (CC)	electricity, high T heat; propulsion; mechanical power	**Yes:** gaseous (incl. H2), liquid, high-and low calorific fuels	dispatchability fast load change frequency support	++ + ++	Flexible in fuel and operation, low emissions with green gases (H2)	emissions of NOx, CO, CO2
Hydro turbines	Hydrodynamic forces	50 ~ 2000 MW	up to 6 GW	electricity	**No** (Water only)	dispatchability fast load change frequency support	+ + ++	Fully renewable, no emissions	adverse impact on nature and environment
Solar photovoltaic	Photovoltaic effects	< 1kW	up to 1500 MW	electricity, low T heat	**No** (Sun)	dispatchability fast load change frequency support	-- O --	Fully renewable, no emissions	volatile
Reciprocating	combustion (intermittent)	< 10 MW	up to 200 MW	electricity, medium T heat, (transportation)	**Yes:** gaseous (incl. H2), liquid, high-and low calorific fuels	dispatchability fast load change frequency support	++ ++ +	Flexible in operation and fuel, low emission with green gases (H2)	emissions; noise/vibrations
Thermal Plants	(External) heat source	1 to 1500 MW	up to 3 GW	electricity, heat	**Yes:** gaseous, liquid, solid, nuclear, waste, geothermal, concentrated solar	dispatchability fast load change frequency support	O -- ++	Fully flexible in fuel, working fluid decoupled from external combustion with carbon neutral fluids	limited operational flexibility
Wind energy based	Aerodynamic forces	3.5 - 5 MW for onshore, 8-12 MW offshore	up to 100 MW (onshore) up to 1000 MW (offshore)	electricity, (transport sector)	No (Air)	dispatchability load change frequency support	-- -- O	Fully renewable, no emissions	volatile
Nanogeneration	electro-mechanical, electro-thermal	up to kW range	not applicable	electricity	N/A	dispatchability fast load change frequency support	+ O --	use of otherwise wasted energy	limited operational flexibility

Table 1 Evaluation of Energy Sources

Fuel cells - list of abbreviations:
PEM FC: Proton-exchange membrane fuel cell, also known as polymer electrolyte membrane
SOFC: Solid oxide fuel cell
PAFC: Phosphoric Acid Fuel Cell

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