D-3.2: Recommendations for technology-specific R&D activities in Smart Energy Systems

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Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Renewable Energy Investment Strategies –
A two-dimensional interconnectivity approach

Deliverable D-3.2

D-3.2 2021: Recommendations for technology-specific R&D activities in Smart Energy Systems

Work Package	WP3 – Investment strategies for Danish Smart Energy Systems in a volatile European context
Deliverable title	D-3.2 2021: Recommendations for technology-specific R&D activities in Smart Energy Systems
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Reviewer	Gorm Bruun Andresen, Poul Alberg Østergaard, Brian Vad Mathiesen
Delivery Date:	January 2022
Publisher	Aalborg University and Aarhus University

This project is funded by Innovation Fund Denmark. File No 6154-00022B

Innovation Fund Denmark

Contents

Main findings

The decarbonization of the European energy system towards 2050 requires a large, long and sustained transformation away from traditional fossil fuel-based technologies and towards a system based on renewable energy sources complemented by both new and well-known energy conversion, storage and transmission technologies. The goal of this deliverable is to identify the necessary and potential technologies for a transition towards renewable decarbonized energy systems. The necessary technologies are identified based on the studies presented in deliverable 3.1.

Based on the studies, the technologies can be grouped in to the following three readiness categories:

1) Known technology, which are key in both the short and long term
2) Partially known, partially new technologies that need to be developed both for short- and long-term effects.
3) New technologies that need to be developed now as we need them in the long term.

In Category 1, the following technologies and measures are identified:

- Energy savings in buildings.
- Implementation and expansion of district heating and cooling.
- Utilization of excess heat from industry and low-grade heat sources.
- Elimination of oil and natural gas boilers throughout Europe. Replace with district heating or individual heat pumps.
- Onshore and offshore wind turbines.
- Solar PV.
- Biogas production, and utilisation of biogas where suitable.
- Implementation of renewable heat sources like solar thermal and geothermal energy.
- Electrification of transport through electric vehicles, including cars, rail transport busses and light duty vehicles all able to operate on batteries.

In Category 2, the following technologies and measures are identified:

- Large district heating heat pumps, utilising various external heat sources like air, water, excess heat, waste water etc.
- Thermal seasonal storage implemented in district heating.
- Conversion to low-temperature fourth generation district heating.
- Utilisation of excess heat from data centres and electrolysis.
- Increase energy efficiency in industry.
- Eliminate coal and oil in industry. Focus on electrification and implementation of green fuels.
- Implementation of electrolysis in combination with hydrogen storage. Needs to be flexible to be able to integrate renewable energy.
- Development and implementation of e-fuel production, utilising hydrogen, carbon capture and utilisation and biomass conversion. Production of DME, methanol and ammonia.
- Smart charging of electric vehicles.

In Category 3, the following technologies and measures are identified:

- E-roads to enable electrification of long-haul trucks.
- Development of efficient electrolysis like SOEC.
- Further development of large-scale electrolysis integrated with e-fuel production and CCUS and chemical synthesis.
- Large-scale thermal gasification, pyrolysis and HTL, and other technologies that can convert biomass to gas and/or liquid fuels.
- Large upscaling of production of e-fuels for aviation and shipping.

1 Introduction

The objective of this deliverable is to highlight technology development either already established or required in the future to go towards 100% renewable energy systems. The deliverable builds on Deliverable 3.1, and the highlighted scenarios:

1) "A clean planet for all" developed by the European Commission and replicated in EnergyPLAN as part of the RE-INVEST project.
2) Smart Energy Europe, an alternative to the European Commission's scenarios developed in EnergyPLAN.
3) The "Early decarbonisation of the European energy system pays off" study published in Nature Communications, detailing an early and steady pathway versus a late and rapid pathway for the decarbonisation of Europe.
4) IDA Climate Plan, representing Danish scenarios.

From these scenarios, a number of key technologies can be identified. Figure 1.1 shows the technologies needed in the "A clean planet for all" 1.5 Tech scenario, both for heating supply, electricity production, hydrogen and fuel production.

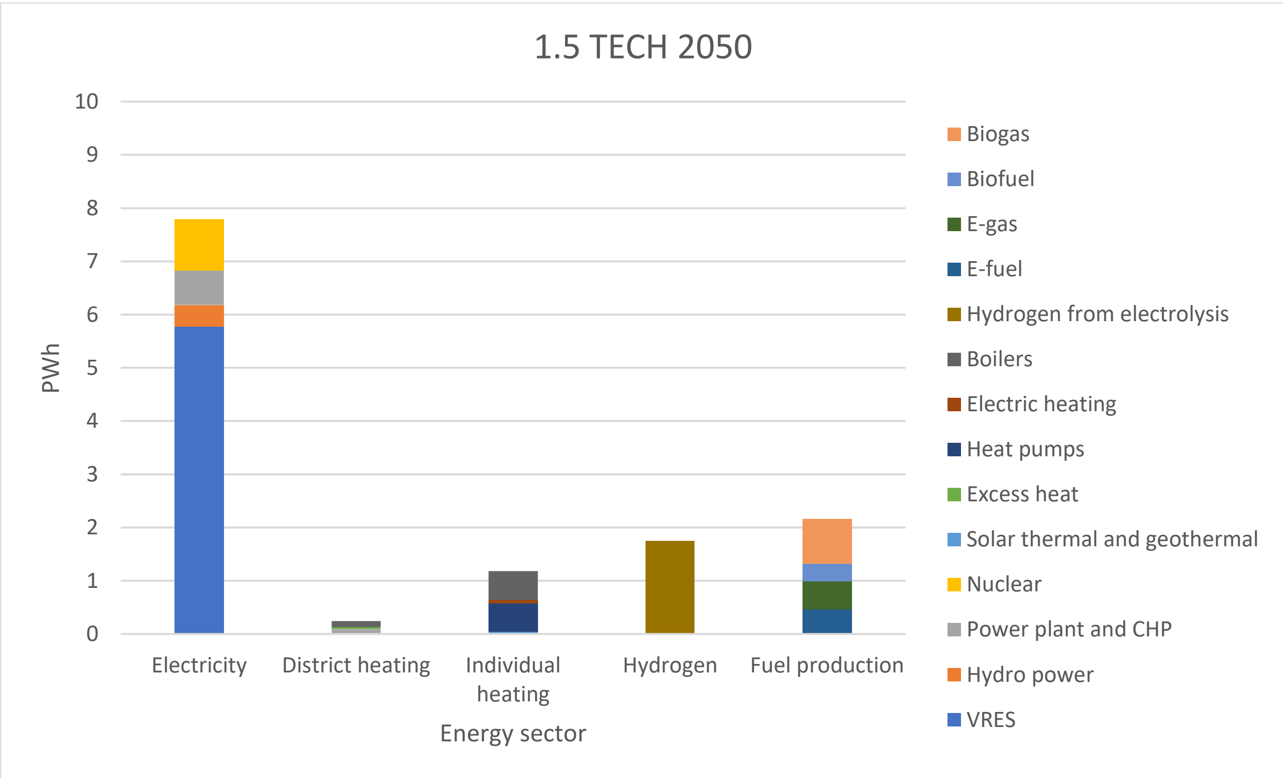

Figure 1.1. Energy production from different technologies in the 1.5 TECH 2050 scenario

Figure 1.2 illustrates the same for the Smart Energy Europe scenario, showing the production of energy based on different sectors.

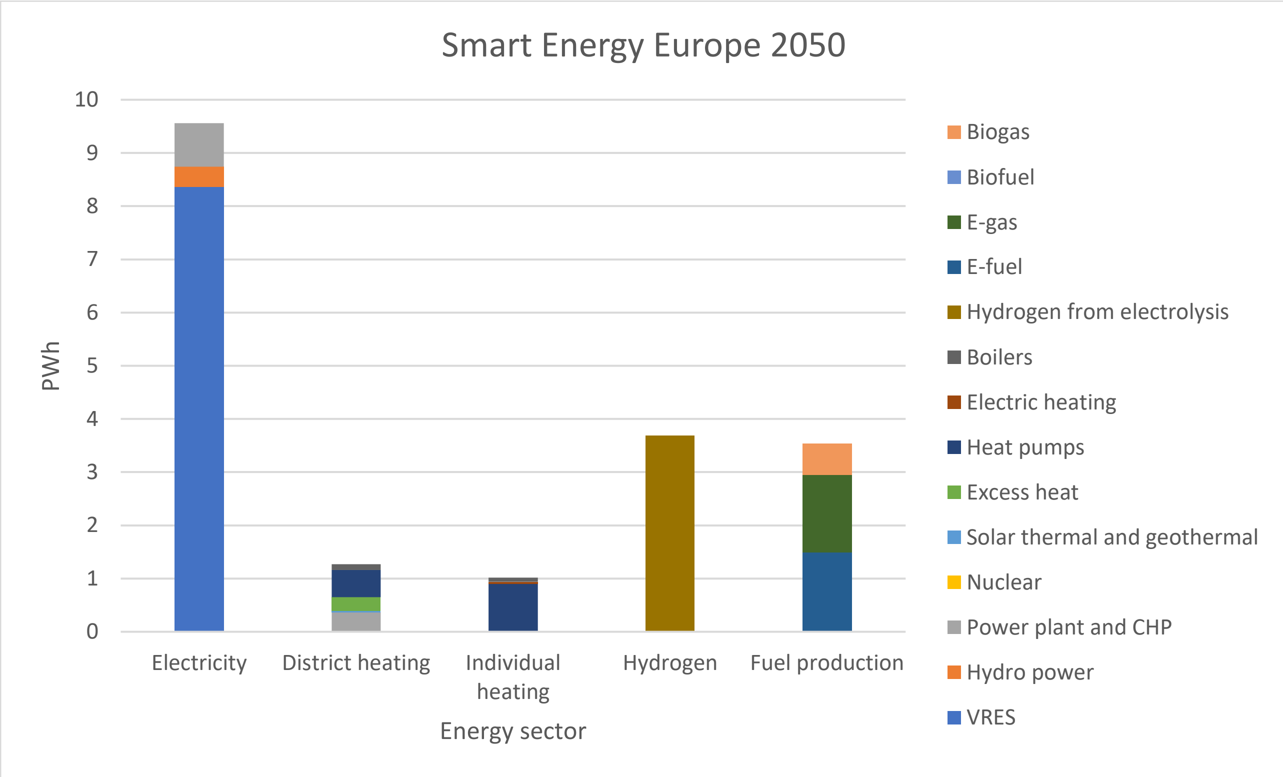

Figure 1.2. Energy production from different technologies in the Smart Energy Europe 2050 scenario

When comparing Figure 1.1 and Figure 1.2, it is important to mention that the Smart Energy Europe has an energy sector completely free of fossil fuels, whereas the 1.5 TECH, additionally to productions shown in Figure 1.1, also still uses oil and natural gas in transport, industry and heating. In total there is still a fossil fuel demand in the 1.5 TECH scenario of 0.89 PWh.

Figure 1.3 show the deployment over time of power capacity in Europe, based on the Early Steady vs Late Rapid scenarios. It shows the high demand for renewable energy, and also that this is already at a development stage where it can be deployed in large scale. From the same study, heat pumps are also being installed rather early in the energy transition in a large scale, showing the already existing potential of electrification of the heating sector.

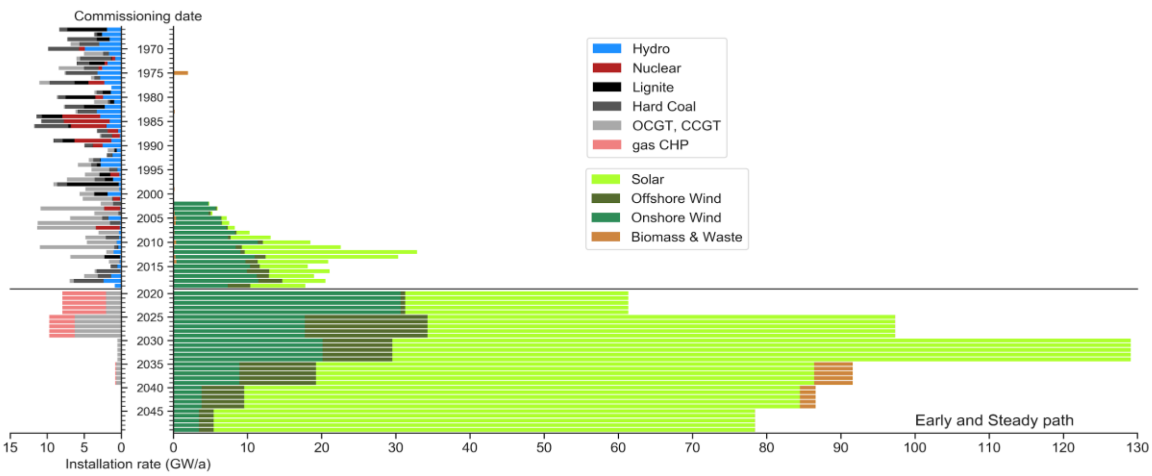

Figure 1.3. Deployment of power capacity over time in Europe [1].

When looking at Figures 1.1 – 1.3, certain technologies are similar across the scenarios, but there are some differences due to the exact composition of scenarios, uncertainties in technology development or differences in modelling.

The common development sees a large increase in technologies exploiting variable renewable energy sources, the implementation of energy efficiency through energy savings and/or district heating, a desire to limit the use of biomass, a need for flexibility through the use of hydrogen electrolysis, power to heat and e-fuel production.

In general, the two latter scenarios find that district heating combined with power to heat provides the most efficient transition of the heating sector, and the implementation of heat savings should be discussed in this context. This is compared to a solution suggested in 1.5 TECH that utilizes boilers and hydrogen to a larger extent, which is more cost intensive.

In the study, "Early decarbonisation of the European energy system pays off", we investigated different transition paths. We considered a budget of 33 $GtCO_2$ for the cumulative carbon dioxide emissions from the European electricity, heating, and transport sectors between 2020 and 2050, which represents Europe's contribution to the Paris Agreement. We have found that following an early and steady path in which emissions are strongly reduced in the first decade is more cost-effective than following a late and rapid path in which low initial reduction targets quickly deplete the carbon budget and require a sharp reduction later.

Thus, large expansions of variable renewable energy are already viable, implementing this alongside a steady improvement of energy efficiency in buildings and industry, and a transition of the heating and cooling systems are no regret options. Furthermore, the development of power to X technologies, flexible storage technologies, further electrification of transport, and carbon capture utilization and storage technologies also need to happen as they will play important roles in the energy transition. Investments in these technologies should happen sooner rather than later to ensure the necessary technology developments.

In the next chapters, the individual technologies, resources and infrastructures are described further, to document and detail current and future development stages. This includes an expected development both in Europe and Denmark.

2 Energy efficiency

2.1 Energy savings

For the three scenarios mentioned in the introduction, energy savings and the "energy efficiency first" principle are key. This means that demands should be lowered in the categories classical electricity demands, heating, cooling, industry and transport. Energy efficiency improvements in buildings are key components in achieving the energy transition. In the Early and Steady transition pathway, heating demands in Europe are suggested to be decreased with 40% compared to today. In Heat Roadmap Europe, one of the foundations for the Smart Energy Europe scenario, the space heating demands are lowered by around 30% compared to 2015. For both these cases, this is achieved with existing technologies by renovating and refurbishing buildings. The 1.5 TECH Scenario from the European Commission includes 48% reduction in the heat demand compared to 2015.

What is shown in all these analyses is that energy and heat savings are important measures and also cost efficient, however this is primarily if the implementation rate of energy savings is early and steady, and that savings are achieved in accordance with the general refurbishment of households. From a cost perspective, it matters a lot that the investments can be paid over long time periods, and that the costs are only marginal compared to the general investment to be made in the households. This is illustrated in Lund et al. [2], illustrating that in a Danish context high level of energy savings are economically feasible if only the marginal extra costs of achieving the desired energy saving is allocated to the energy saving, compared to the whole energy savings activity. This is also pointed out in Aggerholm[3], where most of the energy benefits of renovations are attributed to bringing buildings to the current standard "for free". Thus, to achieve these benefits, energy savings needs to be implemented already now, and have to be implemented steadily over the next 30 years, achieving the right standards in buildings, as it will be more expensive, if renovation only happen for the sake of energy efficiency.

2.2 Electrification of industry and transport

With the three scenarios mentioned in the introduction, sector integration is a key parameter, however the Smart Energy Europe scenario and the "Early decarbonisation of the European energy system pays off" study utilises not only sector integration through electrification, but also the widespread integration of thermal grids (district heating) and gas grids. Potentially this allows for utilising waste heat from industry and electrolysis, thus linking the gas and heating sector too.

However, a main component is electrification and to increase the energy efficiency of scenarios, especially electrification of fuel-intensive sectors like industry and transport is important. In a Danish context, the recent IDA's Climate Response 2045 report [4], points to 1.3 million EVs in 2030 and 3.3 million EVs in 2045 in Denmark, and having 75% of busses and 100% of light duty vehicles running on battery electric drive trains in 2045. Furthermore, heavy duty vehicle should be electrified as much as possible through batteries, plug in hybrids and potentially e-roads. Currently electric vehicles for personal transport is growing, and the technology is ready to be commercialised, while there is still an expected technology development required in electrifying the heavy transport sector. Rail is already electrified in most places in Europe, but the remaining rail networks still running on fuels should be directly electrified rapidly. Here Denmark stands out as one of the places with a relatively high reliance on diesel-based trains. By direct electrification of transport, the system is more energy efficient than when relying on an extensive use of hydrogen and power to X, as these are less energy efficient due to conversion losses. Thus, power to X should only be used in sectors where direct electrification is not possible in practice. The Smart Energy Europe scenario and the 1.5 TECH scenario also have large implementation of electric vehicles, where the 1.5 TECH scenario assumes electric vehicles to cover 80% of the transport demand for cars, vans, busses and coaches in 2050.

Regarding industry, direct electrification of the processes will also increase the energy efficiency of the system. The 1.5 TECH scenario assumes an increase in electricity demand for industry from 895 TWh in 2015 to 1232 TWh in 2050 for all of the EU [5]. Furthermore, direct fossil fuel demands are lowered. In the Smart Energy Europe, a similar electrification of industry is expected, and in the IDA Climate Response Danish industry has an increase of 4.5 TWh electricity while lowering fuel demands [4]. In the Danish context, fuel demands are lowered also through connections to district heating and the implementation of heat pumps to make space heating more efficient. Again, electrification here allows for more fuel efficiency, as in a 100% renewable system, less conversion losses are achieved, compared to the utilisation of e-gas and/or hydrogen directly. Here, there will be system losses due to hydrogen conversion, carbon capture, biomass gasification, and then going back from fuel to process heat demand. However, all the studies still expect a fuel demand in industry as a complete elimination right now does not seem feasible.

3 Energy resources

3.1 Variable renewable energy sources for power generation

Fluctuating renewables are expected to play a major role in the future energy supply of Europe according to the scenarios described in Section 1 as well as other studies analysing the European energy transition [1] [2]. The share of electricity as a final energy carrier is expected to increase [3], correspondingly leading to a higher share of the electricity demand being covered by renewable sources. A common result among scenarios examining the future European energy system is that solar photovoltaics (PV) and wind power will be the dominant renewable energy sources.

In the case of solar PV, earlier developments have addressed technology scale-up and manufacturing, and cost reductions. However, in recent years, research and development have shifted focus towards increasing the efficiency of PV solutions and thus their overall system value [5]. Similarly, the perspective of wind turbine research and development steer towards reducing costs, increasing reliability and improving wind forecasting methods, as well as looking into public acceptance issues [5].

Within the context of a Smart Energy Europe, the current best available PV and wind turbine technologies are expected to already provide an adequate and cost-effective energy supply. Further technology development would thus provide even better system value, resulting from the potential increased efficiency, reliability, and lower costs. Moreover, under the prospect of more efficient solutions the technologies could not only likely lower their overall installed capacities but also their spatial footprint, in turn potentially mitigating implementation and public acceptance issues.

Other variable renewable energy sources will likely play a role in the future decarbonization of the European energy system, to varying extents. One such example is wave energy solutions [6], which have promising perspectives but currently are only in development stages [5]. The potential expansion of this renewable solution must therefore be accompanied by further technological development. Mature technologies like hydropower will also be expected to contribute to the future energy mix; however, their potential for expansion is limited as most of the adequate locations in Europe are already used.. Nonetheless, in the case of hydropower, the existing storage capacities can provide a valuable solution for balancing fluctuating renewable sources and improving system flexibility [7].

[1] M. Victoria, K. Zhu, T. Brown, G. B. Andresen, M. Greiner, Early decarbonisation of the European energy system pays off, Nature communications 11, 6223 (2020) https://www.nature.com/articles/s41467-020-20015-4

[2] D. Connolly, H. Lund, B.V. Mathiesen, Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union, Renewable and Sustainable Energy Reviews 60, 1634-1653 (2016)

[3] In-Depth Analysis in Support of the Commission Communication (2018) 773: A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, EC-European Commission and others, 2018.

[4] Denmark's Integrated National Energy and Climate Plan, 2019, https://ec.europa.eu/energy/sites/default/files/documents/dk_final_necp_main_en.pdf

[5] Danish Energy Agency, Technology Data Generation of Electricity and District Heating - https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf

[6] Lund, H., Mathiesen, B. V., Thellufsen, J. Z., Sorknæs, P., Chang, M., Kany, M. S., & Skov, I. R. (2021). IDAs Klimasvar 2045 – Sådan bliver viklimaneutrale. Ingeniørforeningen IDA.

https://vbn.aau.dk/ws/portalfiles/portal/413672453/IDAs_klimasvar_2045_ver_02062021.pdf

[7] Lund, P.D. ,Lindgren J., Mikkola J., Salpakari J., (2015) Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable and Sustainable Energy Reviews 45, 785-807.

https://doi.org/10.1016/j.rser.2015.01.057

3.2 Biomass

Biomass resources represent in many cases a direct substitute to fossil fuels, this being in power generation, heating, industry or transport. In the race towards total decarbonisation, all energy sectors compete for the same valuable resource, and even with the maximum levels of sustainable bioenergy the competition remains high. This is the reason why biomass resources must be prioritized towards those parts of the energy system that need it the most, such as heavy-duty long-distance road transport, maritime transport, aviation and not the least, towards the part of the industrial demands that cannot be electrified.

While it is clear that bioenergy in general is not sufficient for decarbonising all energy demands, it should not be overlooked in the transition to renewable or decarbonised energy systems. In fact, Korberg et al. [6] has demonstrated that energy systems that use bioenergy are more efficient and more affordable than energy systems that do not make use of it. Therefore, biomass should always be used as long as it is sustainable, e.g., does not have net positive emissions. Fuel pathways that can use feedstocks such as waste biomass, that would otherwise not be utilized, can bring new possibilities in the energy system, in particular hydrothermal liquefaction.

Biomass utilization must also be understood from the perspective of carbon sequestration, where the biochar from gasification or pyrolysis may be in closer reach for achieving negative emissions than other, more expensive CCS equipment in combination with power plants and industry.

Consequently, it is of utmost importance that biomass resources are used and converted in the most beneficial way for society. There are several different biomass conversion technologies relevant to be considered for this purpose, all described in more detail in Section 4.2. In addition, some PtX pathways with

CCU are needed to relieve the biomass demand. Many of these technologies are not commercially ready at relevant scales, but are necessary when discussing decarbonization strategies and 100% renewable energy systems. These are also discussed in the next chapter on Energy conversion.

4 Energy conversion

The majority of the primary energy consumption in highly renewable energy systems will likely come from variable renewable energy sources and biomass. A large part of the wind and solar energy can and should be used directly through electrification strategies in all energy sectors, but some of the electricity and some of the biomass must be converted to chemical or thermal energy for the parts of the energy system that cannot be electrified, but which also benefit of renewables. Such energy conversion technologies are Power-to-X (PtX), biomass conversion and Power-to-Heat (PtH).

4.1 Power-to-X including electrolysis and carbon capture

Power-to-X (PtX) represents one of the technological solutions that can aid the complete defossilisation of future energy systems. PtX will play an increasingly important role within future energy systems, which is why this technology needs to find its place among the other components of the energy system where it can replace fossil fuels in the sectors most difficult to decarbonise.

The work in RE-INVEST has identified that the primary beneficiary of PtX should be the transport sector, specifically those parts of it that cannot be electrified, such as heavy-duty long-distance road transport, deep-sea shipping and medium- and long-haul aviation. In addition, hydrogen may also be used in industry, either directly or as feedstock for the production of electromethane.

Electrolysis is the key part of the P2X deployment in any of the carbon-neutral or 100% renewable energy systems. The results show that the total hydrogen demand in the Smart Energy Europe scenario reaches 3,000 TWh, which means between 500-800 GW of electrolysis dedicated only to producing hydrogen for the above-mentioned sectors. This is a very large increase from the several tens of MW today, so significant upscaling will be needed. All electrolysis technologies will need to contribute to reach this figure, so from an R&D perspective, focus should be on the industrialisation of the manufacturing concomitantly with establishing a hydrogen market, i.e. a supply and a demand for hydrogen. This must come in place with a dedicated infrastructure in clusters to handle the local demands or the inter-connections with other grids. In general, electrolysis must focus on improving efficiency, lifetime and performance especially in connection with flexible operation. In this regard, efforts will have to be put on ensuring pressurised operation, diversifying production materials (specifically for PEM) and improving the lifetime of the stacks.

Carbon capture utilisation and storage (CCUS) is the next important component for PtX and negative emission strategies. More than 500 Mt CO_2/year will be necessary in the Smart Energy Europe model to produce PtX fuels, even with high levels of electrification in industry and transport. This also means that carbon will be a resource in high demand, so future CCUS should emphasize on the “U” part (utilisation), leaving the “S” (storage) as a last resort to deal with the remaining emissions or to achieve negative emissions.

CCU will therefore need upscaling, and efforts should be put into identifying the most sustainable emission sources. First, efforts should be put on capturing CO_2 from point sources, particularly those emissions from bioenergy conversion, such as biogas purification, gasification upgrade, pyrolysis or hydrothermal liquefaction. Power plants or combined heat and power plants operating on biomass or some type of renewable gas can also be suitable for capture, however, one must be aware that such plants will likely operate fewer and more intermittent hours in future energy systems, due to the integration of variable renewable energy sources. Secondly, emissions can also be recycled from other non-biogenic sources, such as the unavoidable emissions from cement production, often in abundant quantities and with continuous production, which is an important aspect when discussing TWh-scale electrofuel production. In general, industrial carbon emitters are good candidates due to the specific long operational hours. The investment cost for carbon capture technology and its energy consumption are main factors to improve in the future, as well as a more flexible operation, which in combination with flexible electrolysis and fuel syntheses can reduce the need for hydrogen storage.

Flexibility, efficiency and low costs should be defining aspects in future PtX strategies, reasons why stress should be put on the fuel production pathways that score well on all three aspects. In the case of transport fuels, this should be methanol production, since this synthesis can achieve high hydrogen and carbon conversion efficiencies, can operate flexibly (thus reducing the necessity hydrogen storage) and produce a fuel that is easy to store and transport. Methanol can also be used as feedstock for the production of other fuels, as DME, gasoline or jet fuel. But methanol is not the only potential transport fuel, as ammonia can be another solution that can score well on the same parameters, making it a potentially suitable solution for shipping. These pathways should therefore be prioritized for R&D and upscaling to build up a competitive e-fuel market.

4.2 Biomass conversion

Although PtX with CCU will likely have key roles in replacing a large amounts of fossil fuels, investments should not overlook the potential of biomass conversion technologies. As mentioned previously, carbon capture should first take place from the biomass conversion technologies, while the same technologies are capable of producing fuels of their own, with or without hydrogen addition.

The production of these fuels implies the need for transforming diverse biomass resources into liquid or gaseous products, which poses challenges in process development to improve conversion efficiency and overall sustainability while decreasing the production costs. For these reasons, multiple technology solutions should be promoted with a focus on synergies between them, in which one technology can replace another, in case of some technologies may not be commercially ready at a proper scale in time. Therefore, in order best to make use of the sustainable biomass resources, a combination of the following conversion technologies should receive more attention in the R&D efforts: biogas plants, thermal gasifiers, hydrothermal liquefaction plants and pyrolysis plants.

Biogas plants are a mature technology in many countries across Europe [7], with Denmark at the forefront, where already about 20% of the gas in the national "natural gas" grid is purified biomethane , with plans to further increase this share in the coming years [8]. The Smart Energy Europe scenario also includes biogas in the modelling, accounting for almost 600 TWh/year. All biogas is purified to methane quality and sent to the grid, where it is then used for balancing purposes in power plants.

The assumption is that the majority of biogas is originating from the digestion of manure and other organic and industrial wastes, but in the future, straw may be a valuable input that can increase the methane output in the biogas by approximately 30%, which may be a good addition to a gas grid where significant demands will remain for power generation and industry [9]. But straw may also be needed for thermal gasification, where together with woody biomass (both dry biomass inputs) can aid in the production of syngas, an intermediary for methane or methanol production and jet fuels. The same dry biomass can also be used for producing pyrolysis-based bio-oils and negative emissions via the biochar generated in the pyrolysis process, making the prioritization of such resources even more difficult.

Not all biomass conversion technologies are equally ready for large-scale deployment, with pyrolysis and gasification still lacking sufficient maturity for upscaling. Moreover, the choice of biomass conversion technology should also consider the potential and system effects of combining with hydrogen from electrolysis in the production of the so-called bio-electrofuels. While the increase in the yields through hydrogenation is possible for all conversion technologies (since all include CO_2 as a by-product), not all can have an equally beneficial role in the energy system. For example, methanation from biogas is not found particularly necessary in the energy system, but that the use of biogas and biomethane for power production and industry is more energy and cost-efficient [8] which is also the assumption in Smart Energy Europe scenario. Pyrolysis uses large amounts of biomass due to the low efficiency, and since the feedstock is the same as for gasification, a potentially more efficient biomass conversion technology, it is difficult to identify a role for it, even when including the hydrogenation potential [10]. Moreover, pyrolysis can only produce liquid fuels, which is a limitation compared to the other pathways using the same feedstocks. For these reasons, gasification is given a significant role, and at least if disregarding the technology readiness level, it is the most suited solution for the efficient conversion of dry biomass. It implies large gasification capacities starting at 20,000 MW, only considering liquid fuel production. These capacities must be six times higher if thermal gasification must also fulfil the remaining gas demands for the power sector, assuming it is only technology that converts dry biomass resources. And this is an important finding, i.e. gas demands will remain high in the power production sector, so the technological solutions that can ensure the supply of low cost, carbon-neutral gas are key for reaching 100% renewable energy systems [9].

On the other hand, HTL can use a variety of biomass and waste products, which can give it an edge compared to the other technologies that require more specific inputs at certain moisture levels. Although HTL can only produce a liquid fuel, just as pyrolysis, the quality of the bio-oil appears better suited for refining compared to bio-oil from pyrolysis [11]. The key advantage of HTL bio-oils will therefore be the potential to reduce the biomass consumption if more waste is used for this purpose, which is the reason why the R&D on HTL should be accelerated, so the first commercial plants come in operation.

4.3 Power-to-Heat

Individual heating is anticipated to be less CO_2 intensive due to the expectation that oil and gas boilers will be substituted by heat pumps and district heating. As of today, approximately 20% of the homes in Denmark are heated individually[1] of which approximately 80,000 are provided by oil and 380,000 by natural gas boilers[2]. With the Danish oil and natural-gas boiler scrapping scheme, initiated for oil in 2018 and later for natural gas in 2020, households with such boilers located outside the district heating network are qualified for a heat pump subscription which prevents a high initial investment cost that some householders might not be able to finance. Heat pumps are already utilized and continuously deployed in individual heating. In 2020, 65,000 heat pumps were installed in Denmark. However, approximately 80 % of them were air-to-air and would, thus, require supplementing heat generation from other sources, e.g., gas or oil, where ground source heat pumps are better for winter conditions. By 2030, the Danish energy agency expects that approximately

[1] Energistyrelsen, "Heat", https://ens.dk/en/our-responsibilities/heat
[2] Energistyrlesen, "How to be climate-friendly", https://ens.dk/sites/ens.dk/files/Varme/04_ens_faktaark.pdf

250,000 households will still have gas and, to some extent, oil boilers as their primary heating[3], but most likely a complete phase out of oil and gas for individual heating should be expected.

On a European level, district heating is not as entrenched in the heating sector as in Denmark. Only 10 % of the heat demand in EU is covered by district heating[4]; thus, the majority is individual heating solutions, mostly based on fossil fuel. A switch towards renewable energy sources for the heating supply is, however, expected to happen. E.g. solar and geothermal can potentially supply 133 Mtoe in 2050, contributing to an energy saving of 217 Mtoe[5]. For the utilisation of geothermal and ambient energy, heat pumps with a high coefficient of performance are the key and can be used as individual units or in the district heating. Furthermore, an increased focus is laid on energy efficiency of the buildings, and emerging innovative insulation solutions which perform better than the existing is anticipated to be adopted by the future market[6]. The challenge that remains in this context is the renovation needed in buildings due to barriers such as split incentives between landlord and tenant, complexity in the insulation process, high costs, etc.[7]

5 Energy infrastructure and storage

5.1 District heating and cooling

On both a European and Danish scale, heating demands are quite substantial, and need to have a clear transition path towards decarbonisation. In Europe, in 2010, the annual heating demand was approximately 12 EJ [12] and in Denmark, the heating demand was 181 PJ in 2018[4]. One of the key, and most efficient supply technologies to cover heating demand is district heating. District heating is already a well-established technology in many countries, whereas other European countries still rely primarily on individual heating (and cooling) solutions. Thus, there are two main considerations to be considered in the transition path towards decarbonisation.

In countries with well-established district heating, two main developments need to happen. An upgrade of the existing grid, to allow for lower supply and return temperatures. This is also known as fourth generation district heating (See Figure 4.1), where the supply temperature is lowered to around 55-65 °C [13]. By upgrading the grid, it is possible to utilise lower-grade excess heat sources, more renewable energy and increase the efficiency of heat producing units like heat pumps.

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[3] Energistyrelsen, "Klimatestatus og fremskrivning", 2021, https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pdf

[4] In-Depth Analysis in Support of the Commission Communication (2018) 773: A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, EC-European Commission and others, 2018, https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[5] In-Depth Analysis in Support of the Commission Communication (2018) 773: A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, EC-European Commission and others, 2018, https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[6] In-Depth Analysis in Support of the Commission Communication (2018) 773: A Clean Planet for all A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, EC-European Commission and others, 2018, https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

[7] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

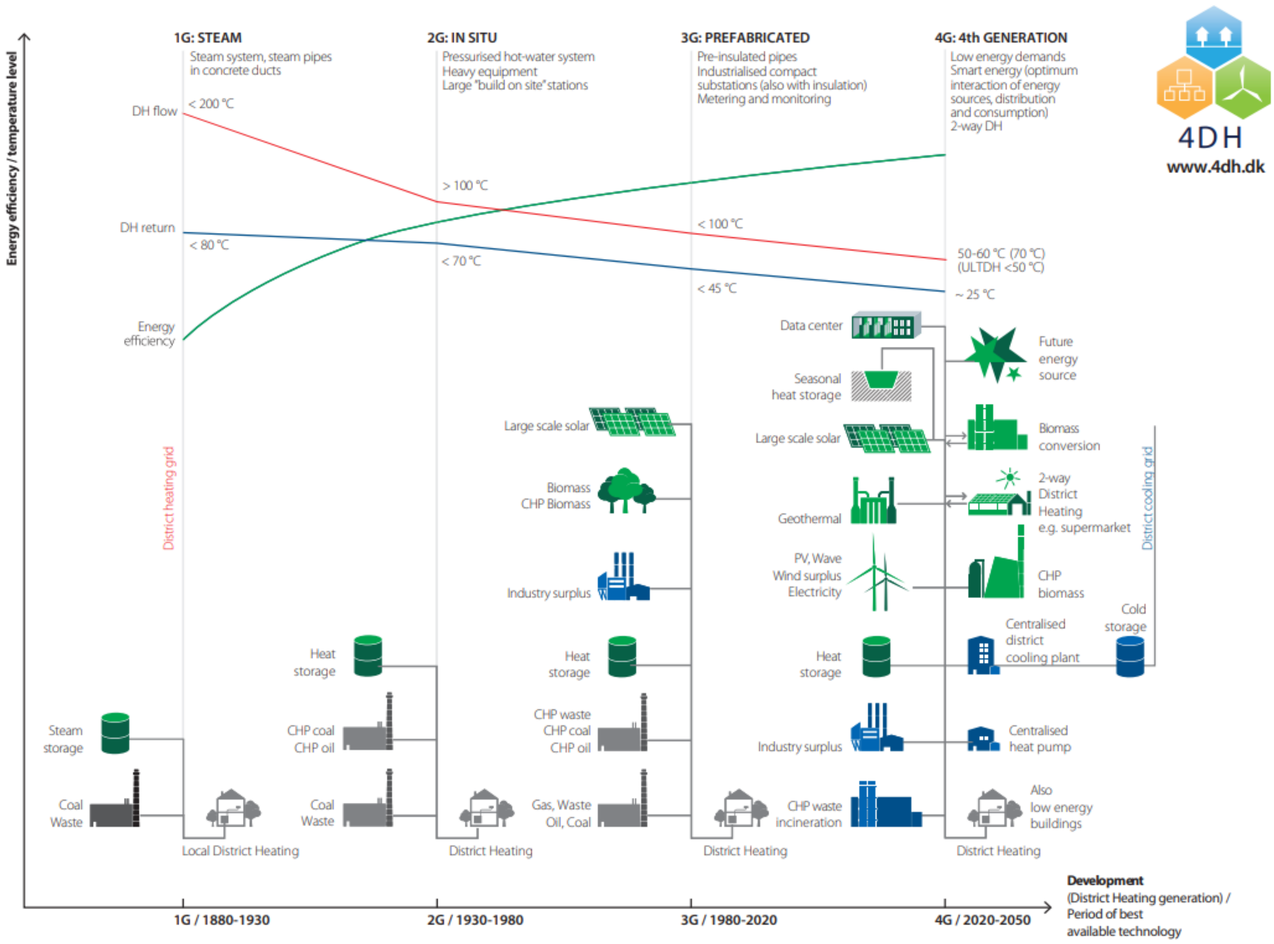

Figure 4.1. Illustration of the development from 1st generation district heating to 4th generation district heating. [14]

Furthermore, possible expansions of the district heating grid should also be investigated. For instance, in Denmark, currently around 50-55% of the heat demand is covered by district heating, and potentially this can be increased to 63%. This is achieved both by converting households now being supplied by individual boilers into district heating, and increasing the heat supply efficiency by implementing fourth generation district heating.

However, in Europe, many countries still rely primarily on individual heating solutions such as gas boilers and electric boilers. The current district heating level in Europe is 13 percent of heating demand of 3.3 PWh. When looking at many European plans there is not necessarily a plan to develop the level of district heating, but the Heat Roadmap Europe projects (1-4) have assessed the potential for increasing the level of district heating, and also looked concretely at specific countries in Heat Roadmap Europe 3 and 4. [15–17] Overall, the district heating level is increased to 32 to 68% in the 14 countries investigated in Heat Roadmap Europe 4, with an average of 45% of heat demand covered by district heating. [16]. Already now the technology is at a readiness level to be implemented, even in countries without district heating. The main difficulty in implementing district heating is creating the right political framework and establishing an investment scenario that makes it profitable to invest long term without the risks. These factors may hinder the level of investment, but technologically 3rd generation district heating (see Figure 4.1) is already a ready product with years of experience, and fourth generation district heating is ready to be invested in both in new projects and in development of already existing district heating infrastructure.

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5.2 Electricity transmission and energy storage

5.2.1 Transmission capacity

The European electricity transmission network is continuously being developed. Apart from maintenance activity obviously, a noteworthy development consists of capacity expansions but also the construction of completely new transmission lines. In line with further electrification and thereby increasing power demands together with increased infeed of fluctuating renewable generation, an increase in transmission capacity is inevitable. This includes both new network access, transmission and distribution grid extensions and cross-border transmission capacity extensions.

A major challenge for transmission line development is timely implementation of projects, with delays often caused by public acceptance issues. Resistance to overhead transmission line projects can stem from multiple factors including perceived negative impacts to local landscapes, diminishing property values, endangerment of local species, and health concerns [11]. Consequently, public acceptance issues can result in project implementation delays, leading to higher costs [12]. Underground cables would mitigate some these issues, but do not fully solve them. Moreover, the higher cost of undergrounding might lead to increases in energy prices to finance such projects, which can therefore decrease public support for said solution [13]. This, then, raises the questions of where and how much transmission capacity should be placed, how can these developments gain public support, whether other options are preferable, and how these affect electricity prices.

In turn, some additional considerations for further research are how to achieve lower costs of transmission as the electricity demand is expected to rise and financing transmission line projects. This is both an issue on national and international scale as different interest groups want to influence the decision processes. In the case of Denmark, a recent shift in policy is manifesting. Since the 1990s it has been customary for the local transmission operator to pay for the network access of new renewable capacity. The latest climate deal changes this. Going forward, part of the bill for network access and transmission extensions due to added renewable installations will go to the renewable energy developers instead. That developers not only need to pay for network access lines but also participate in a general transmission grid expansion could mean that some projects become economically infeasible. On the other hand, it incentivises the installation of renewable capacity close to the load centres or places with sufficient transmission capacity, hence reducing the cost for the end customer.

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5.2.2 Energy storage

With a higher share of the generation from fluctuating renewable energy sources, storage is becoming critical. Several storage technologies are already used to provide flexibility and to balance supply and demand. Pumped hydro storage has been in operation for more than a century. Large grid-scale stationary batteries have developed rapidly in recent years. Seasonal storage technologies like power-to-gas have reached enough maturity to the extent that they are considered a technology that will take care of the seasonal fluctuations in future electricity production. Several other alternative storage technologies exist at different maturity levels. Technologies like flywheels, supercapacitors, lead-acid batteries, Sodium-Sulphur, Vanadium redox-flow batteries provide options to store electricity for short-term efficiency. These technologies are not suitable for long-term storage because of the high storage losses and a large CAPEX [1].

The biggest batteries existing today have a range of no more than 100 MW/MWh. Although GWh capacity battery storage is already in consideration, [2] batteries are unlikely to provide bulk storage similar to that of the pumped hydro. Pumped hydro storage, on the other hand can better provide bulk electricity storage (good efficiency, reliability, and proven) with a discharge duration of a few hours to days. It fits in well with short-term storage technologies and seasonal storage technologies. The biggest drawback of pumped hydro is that the technology's potential for expansion in the industrial world is low as most convenient locations are already exploited [4].

While these mostly focus on electricity storage, other forms of storage can be used in a sector-coupled Smart Energy System. The downside of focusing on storages for the electricity sector only is that electricity storage can be around 100 times more expensive than thermal storage, and significantly more expensive than fuel storages, as seen in Figure 5.1. Therefore, cheaper, and more efficient solutions can be found utilising thermal, gas, and liquid storage technologies to integrate more variable renewable energy sources, like wind or solar power, in a system with well-integrated energy sectors and cross-sector energy conversion technologies [0].

In a sector-coupled system, thermal energy storages can be connected to the electricity sector by means of heat pumps, which could supply heat to district heating systems in densely populated areas or to individual buildings in rural areas. To this end, hot water storage tanks are often used for short term storage, being a simple and a very mature solution. However, other forms of thermal energy storage might be case-dependent and warrant further research when considering long-term seasonal applications like, for example, using pit or borehole storages to store the heat supplied by solar thermal plants, or using aquifers or ice storages for district cooling applications [8].

Likewise, power-to-gas and power-to-liquid technologies (including hydrogen, ammonia, and electrofuel production), can enable the use of fuel storages which do not have significant storage losses if appropriately stored in large containers [3][0] and can be used for both medium and long-term bulk seasonal storage, as well as stored in vehicles when integrating, for instance, the use of electrofuels in the transport sector. These also provide a comparatively low-cost to electricity storages, albeit further development to improve the efficiency and costs of Power-to-X conversion technologies is needed. However, the use of electric battery storage can take place when integrating the electricity and transport sectors, and the ensuing demands from electric vehicles.

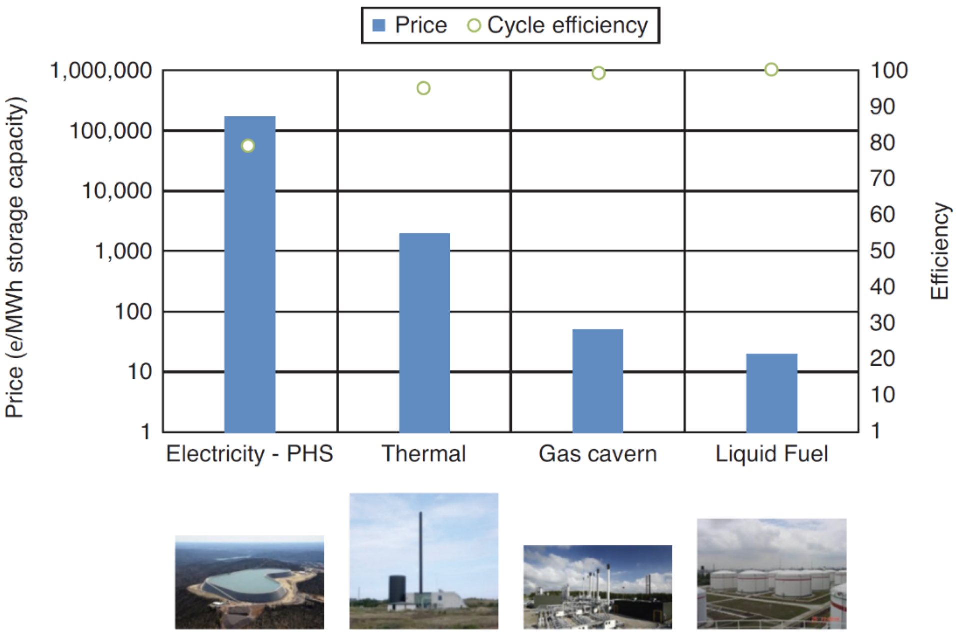

Figure 5.1. Comparison of investment costs and efficiency for different types of energy storages [0] .

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5.2.3 Molten salt storage

Molten salt is the most widespread storage medium in Concentrated Solar Power (CSP) applications. More than 95% of global thermal energy storage in operation on CSP plants is based on molten salt technology. It is estimated to have a total storage capacity of 21 GWh at the end of 2019[5]**.** Molten salt storage is a mature technology marketed by several multinational companies, including MOSAS from MAN, eTES from Flagsol, Pintailpower, Yara international, Aalborg CSP, Alpha Laval, as a storage technology for CSP power plants.

Molten salts have unique thermo-physical properties that make them an ideal storage medium. They have a high boiling point, low vapor pressure, low viscosity, and high specific heat capacity. A low melting point is desired to increase the temperature range (difference between the boiling point and the melting point) between which the storage can operate. A high melting point of molten salt is also disadvantageous because it requires a freeze protection system.

By changing the chemical composition of salts, the thermophysical properties of the storage medium can be adjusted. Commercially available "HITEC" salt used in solar plants consists of potassium nitrate (53% by weight), sodium nitrite (40% by weight), and sodium nitrate (7% by weight) with a liquid temperature range of 149 - 538°C. Salts like Sodium hydroxide have a boiling point of 800°C and a liquid temperature range of 480°C, but it is highly corrosive. Molten salt can easily be used as a standalone storage technology without CSP.

The following challenges should be overcome before being considered viable storage technology for power-to-power energy storage:

- Molten salt is an electrolyte, which at high temperature is corrosive. Large-scale storage depends on using low-cost construction materials. Finding appropriate low-cost storage tank material is a challenge.
- The high melting point of the salt mixture means additional energy is needed to avoid the solidification of salts. Salt mixtures with lower melting points and higher boiling points would broaden the application.

5.2.4 Rock storage

Siemens Gamesa started model development of electric thermal energy storage with rocks in 2002. In 2004 the first such test site with 5 MWh capacity was built. Under the support of the Federal German Ministry of Economic Affairs and Energy, a demonstration plant was commissioned in 2019. The pilot plant located in

Hamburg, Germany, uses over 1,000 tons of rock and has a thermal storage capacity of 130 MWh. Based on these demonstration and research projects, Siemens Gamesa has commercialized the technology as scalable and modular units at different capacities.
In Denmark, EUDP funded the HT-TES (High-Temperature Thermal Energy Storage) demonstration project (2016-2019), which analysed the potential of using various rocks under cyclic thermal loading. The project found that the rock storage is technically sound and has socio-economical feasibility in the long term. However, the project also concluded that the current tariff structure might not support the corporate feasibility of rock storage.

In 20021, Stiesdal Technology and the fiberfibre-optic group Andel signed an agreement to build a prototype of a full-scale new rock storage system based on the innovation of Stiesdal technology for long-term energy storage. This project, partly supported by the Danish EUDP programme, plans to commercialize the technology as soon as possible. Rocks are thermally and chemically stable in a wide temperature range. They are non-toxic and non-flammable, and they have good thermal properties; high specific heat, good thermal conductivity, low thermal expansion coefficient, and high mechanical resistance to thermal cycling. Some types of rocks can efficiently be heated up to 1000 °C and transfer heat effectively with air. These properties make solid rocks an excellent storage medium for high-temperature energy storage. During charging, electric power is converted into heat either using electrical heaters or a heat pump. Discharging can be done by producing steam as a Rankine cycle or with hot air in Brayton Cycle.
Following are the main technological challenges that remain to be solved:

- Rocks slide towards each other and generate dust. The dust wears the turbomachinery. Dust management should be investigated further.
- When the rocks are heated and cooled, they expand and contract. The thermal expansion of steel is twice the thermal expansion of rocks. It is still a challenge to solve expansion stress in the steel tanks cost effectively.

Following are the technological challenges that are applicable for all sensible heat storage technologies:

- Charging and discharging setup is optimized for other applications, for example, CSP, oil, and coal-fired power plants. More knowledge is required to optimize synergy with high-temperature storage.
- A larger storage tank (diameter) is always more efficient than a smaller storage tank. But logistics sets an upper limit to how large the storage tanks can be. Getting the right balance to minimize storage losses and cost is a major challenge.

5.3 Hydrogen, gas grids and liquid fuel

Chemical energy, in the form of liquid and gaseous fuels will remain a key energy vector in future energy systems as a complement to electrical and thermal energy. Like the other energy carriers, gaseous and liquid fuels require transport and storage but it is often that this type of energy is the most easy and cheap to handle at a large scale (at least compared to thermal and electrical energy) [18]. Moreover, the transport and storage of chemical energy uses the most extensive and well-spread infrastructures, in particular due to the historical reliance on fossil fuels.

The new fuels proposed in the energy conversion chapter have many of the properties of the existing fossil fuels, in which case much of the existing infrastructure can be repurposed. For example, methanol can reuse oil/petrol/diesel storage and transport infrastructure with low conversion costs [19,20], since both are liquid and non-pressurised. Electro jetfuels are also compatible with existing infrastructures, as the final jet fuel has the same composition as the fossil equivalent. Electromethane can also use the existing gas infrastructure with minimal modifications, since it is in essence the same chemical as natural gas. But transporting other fuels than the ones mentioned above may pose additional challenges due to their different properties. Hydrogen is one of these fuels, which requires significant infrastructure modifications and dedicated new infrastructure for a potential TWh scale adoption.

Independent on how hydrogen will be used, either as feedstock for electrofuels or as end-fuel, it will require significant infrastructure investments. Some type of hydrogen storage appears necessary for integrating the large amounts of renewable electricity and to deliver the necessary flexibility to the energy system. The most recommended types of storage systems would be steel tanks, since these can deal better with hourly intermittencies and the varying demands for hydrogen than underground cavern storage would do. But steel tanks remain an expensive solution, so R&D should go towards new technologies that can reduce their high cost. Underground hydrogen storage may be a solution, but highly dependent on the location, quantity and final use of the hydrogen gas. Caverns are large storages that may pose difficulties with handling the gas in system designs with distributed hydrogen generation, and would be directly linked to the development of new transport and distribution infrastructure, which may not be a desirable solution for all cases.

In a different setup, hydrogen would be transported in large pipelines that can also act as a storage medium called linepack. The results in RE-INVEST have shown that supplying hydrogen in pipelines to power plants or for industrial purposes can be beneficial to the energy system as method for reducing the reliance on biomass but only in limited quantities. Hydrogen cannot be a singular fuel for this purpose, and should be combined (understood both as a blend or as a share of the total gas demand) with methane from biomass gasification, biogas purification or electromethane. The cost of the hydrogen transmission lines is not a major cost in the overall system picture, but any additional green hydrogen production that replaces other more efficient solutions and fuels (as electrification or biomass), will increase the overall primary energy supply and inevitably the system costs. Therefore, careful consideration must be put when proposing new hydrogen transmission infrastructure as the reliance on this fuel in energy sectors that do not need hydrogen may create system imbalances and uneven use of resources.

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