National Scale Assesments For Austria And Denmark

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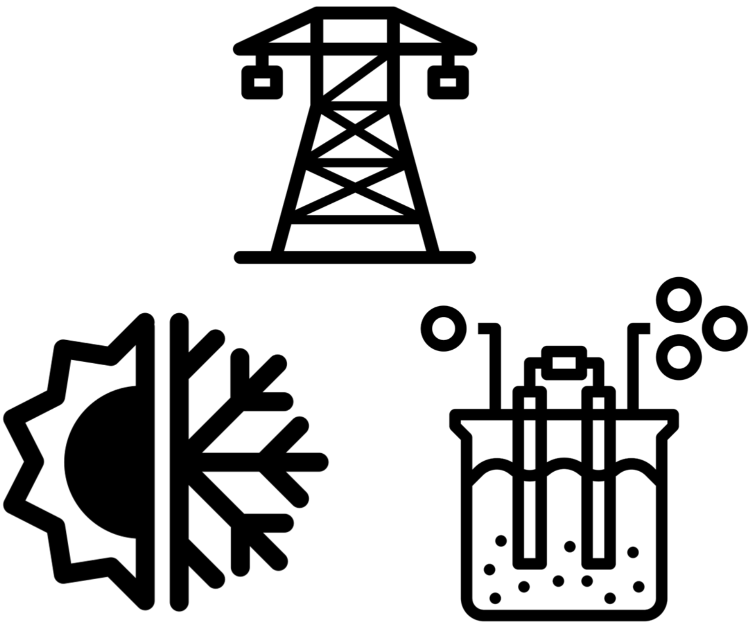

GUIDEBOOK

IEA DHC ANNEX TS3: HYBRID ENERGY NETWORKS

DISTRICT HEATING AND COOLING NETWORKS IN AN INTEGRATED ENERGY SYSTEM CONTEXT

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District Heating and Cooling Networks in an Integrated Energy System Context Guidebook

Final Report of the IEA DHC Annex TS3

Hybrid Energy Networks

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EXECUTIVE SUMMARY

Coupling different energy sectors, in particular electricity and gas with heating and cooling, is considered one of the key measures to decarbonise the energy system. District heating and cooling (DHC) networks have traditionally linked the heating and cooling sector to the electricity sector and often also to the gas sector through gas-fired combined heat and power (CHP) plants. However, with the phasing out of natural gas and the increasing share of renewable electricity generation, the role of CHP plants is likely to change significantly in the future. Thus, the use of other heating (and cooling) sources will have to be intensified to meet the demands in DHC networks, and other interconnection points will have to be integrated to provide flexibility between the different sectors. In addition, hydrogen (H2) is playing an increasingly important role in the energy system and the resulting synergies need to be considered.

The IEA DHC Annex TS3 is an international collaboration platform under the supervision of the IEA DHC - the International Energy Agency's technology cooperation programme for district heating and cooling. The aim of the IEA DHC Annex TS3 is to identify key opportunities and make recommendations to address challenges for DHC networks in an integrated energy system context. It ran from autumn 2017 to early 2023 and included several workshops, webinars, and special sessions at various conferences, as well as working meetings and bilateral discussions. A collaboration with the IEA International Smart Grid Action Network (ISGAN) was established to facilitate a better understanding of the integrated energy system.

This guidebook is the main outcome of the IEA DHC Annex TS3, the findings can be summarised as follows:

Concepts and Technologies

Within the IEA DHC Annex TS3 the following definition has been established: *"A Hybrid Energy Network is an approach, in which electricity, thermal, and/or gas networks are combined and coordinated to utilize synergies between them, to achieve an optimal solution for the overall energy system".* To connect the different networks, Hybrid Energy Networks can use a wide range of technologies:

As mentioned above, gas-fired CHPs have traditionally linked the electricity, gas, and heat networks. However, when operated with renewable fuels such as biogas/biomethane, electrofuels or biomass, they can provide flexibility for the future decarbonised energy system. In addition, heat pumps (HPs) are a dominant technology for coupling the electricity and heat sectors. They have a high conversion efficiency of the used electrical energy into useful heat (considering the external heat source) and can provide high resilience to increasing electricity prices. Another power-to-heat technology is electric boilers (EBs). They allow the production of heat at high temperatures and very fast heating gradients at relatively low investment costs. These aspects make them typically useful for peak load applications or in short-term electricity balancing markets. An increasingly important technology for linking the electricity and gas sectors is power-to-gas (PtG), which produces high-value fuels for hard-to-abate sectors, for long-term (seasonal) storage of excess renewable energy, and for security of supply in back-up or peak-load scenarios. However, PtG processes themselves generate large amounts of waste heat that can be used in district heating networks. Further on, there are some important enabling technologies:

Storage allows a time shift from seconds (short term) to seasons (long term). Short-term electricity storage can be realised by a wide range of technologies and is important not only for shifting energy production or demand, but also for providing a range of ancillary services. Short-term thermal storage is widely used, dominated by hot water tanks due to their relatively low cost, simplicity, and versatility. For long-term electricity storage, dammed hydropower and compressed air energy storage are used. In the heating sector, several seasonal storage technologies are available, allowing a seasonal shift of surplus heat from summer (waste heat, geothermal, HP, CHP...) to winter, as well as providing short-term flexibility. In the gas sector, underground caverns are widely used.

Networks are not unified entities, allowing different Hybrid Energy Network connections: Gas networks can be operated with biomethane or synthetic methane; and separate H2 networks are being discussed. For DHC networks, four different technology generations have been identified with increasing efficiency and flexibility. Alternative DHC configurations are also possible, e.g. "cold heating networks" using decentralised heat pumps, allowing bidirectional heat and cold supply and the integration of several prosumers; or the double-loop network concept, allowing the supply of cooling to end users and a higher degree of flexibility.

System Perspective

From the point of view of the European Transmission System Operators (TSOs) for electricity and gas, district heating offers good potential for heat recovery from a wide range of processes, either directly or as a heat source for high efficiency heat pumps. With the expected development of electrolysis, heat pumps can help reduce the energy losses of the conversion process by recovering the associated excess heat. It is therefore important that energy modelling considers the energy efficiency and flexibility that could be offered by district heating systems. In the Ten-Year Network Development Plan (TYNDP) for 2022 developed by the European TSOs for electricity and gas, scenarios with specific load profiles for heat pumps operating in the district heating network have already been used. It is expected that district heating modelling will be further integrated soon.

The role of CHP and HP from a European perspective is discussed based on three studies carried out for the European Commission. One of the main conclusions is that in decarbonisation scenarios the share of CHP (based only on renewable fuels) in district heating production will be rather low (3-7%), while the share of HP will be between 40% and 75% (with some additional renewable fuels for peak load). However, H2 and electrofuels imports could change the picture if import prices are significantly lower than generation costs in Europe and if substantial quantities can be imported. In this context, new geopolitical dependencies should be discussed very carefully. For biomethane, the literature does not indicate very high potentials. To ensure stable decarbonised electricity generation, CHP will be needed to a much lesser extent than in the past, provided that electricity grids, storage and demand response are sufficiently developed. Uncertainties regarding the relevance of large-scale HPs lie in the costs of other renewable heat sources, the availability of biomass and large-scale heat storage, the potential for reducing system temperatures in DH and the stringency of implementing climate targets.

Some of the most prominent energy conversion technologies are analysed in more detail at national level for Austria and Denmark. The results show that electric boilers allow a potentially larger installation of variable RES without increasing the amount of unused electricity production. However, this solution is more expensive and significantly less energy efficient than the use of HPs, and HPs have a higher potential to reduce biomass consumption and should therefore be prioritised for the electrification of DH. Due to the relatively high investment costs of HPs, their optimal installed capacity depends on the full load hours they can operate, which in turn depends on the available thermal storage. When using combustible gaseous fuels, high-efficiency combined cycle gas turbines offer the lowest costs, lowest primary energy consumption and lowest biomass consumption. Biomass-fired CHP plants have the highest energy system costs. However, while the role of CHP plants may change to serve mainly as a back-up for intermittent renewables in the electricity system, there are still important energy system benefits from using the excess heat from these plants. Finally, the analyses showed that the use of excess heat from the production of electrofuels (including hydrogen) offers lower costs, lower primary energy consumption, lower biomass consumption and reduces the need for variable renewables in the energy system.

As hydrogen and DH are seen as two essential pillars of a sustainable and fully renewable future energy system, the synergy potentials are discussed in more detail: On the one hand, a transition to pure hydrogen or hydrogen dominated gas networks will require a modification of existing CHPs. Fuel cells could replace today's CHPs with higher combined efficiencies. However, as the operating hours of CHP plants may decrease in the future, the cost-benefit ratio of new investment in CHP infrastructure needs to be carefully assessed. On the other hand, the waste heat potential of the two main relevant electrolyser technologies (alkaline and PEM electrolysis) is assessed based on scenarios for their expected capacities and a comparison is made with the projected heat demand in DH. As a result, the theoretical waste heat potential could cover up to 64% of the European DH demand in 2040.

Implementation

Based on various research and demonstration projects of the IEA DHC Annex TS3 participants, regulations and new roles and actors in energy trading as well as business models involving consumers were discussed in the context of Hybrid Energy Networks. The general trend is towards integrated energy markets. The traditional division between electricity consumers on the one hand and large production plants on the other is changing: decentralised PV plants and flexibility provision via heat pumps are playing an active role and are likely to be more closely integrated into energy trading. This trend has been going on for several years, as the idea of energy cooperatives has become very popular in some European countries. Another finding is that climate change itself is the main driver for the installation of new zero-emission equipment and thus the basis for new business opportunities.

A wide range of Hybrid Energy Network case studies have also been collected and grouped into the following categories:

- Various projects showcase the integration of technologies to enhance energy efficiency. For instance, Livø Island in Denmark incorporates electric boilers, heat storage, and HPs. Similarly, several projects in Vienna explore the integration of HPs in different contexts.

- Different projects employ advanced operation and portfolio management strategies to achieve self-sufficiency, flexibility, and economic performance. Examples include the use of smart monitoring equipment in the 2050 Homes project, the development of digital twins in the Ferney Voltaire project, and the implementation of model predictive controls in the smart district of Innsbruck. Other approaches include the virtual heating plant concept in the Gleisdorf wastewater treatment plant project and advanced analytics and optimization algorithms in the East Milan DH System. Business value for stakeholders is also emphasized, such as the implementation of a local energy market in the FED project and the utilization of a direct power line from a wind farm to a HP in the Hybrid DH Demo Neusiedl project.

- Examples for projects focus on leveraging flexibility and demand management include the Maria Laach project, which adjusts substation controllers to exploit the thermal inertia of buildings remotely. The Eskilstuna DHC system explores the thermal inertia of apartment buildings and the combination of individual HPs and DH. The Parc Bit tri-generation and DHC network in Palma de Mallorca investigate flexibility through storage, network, and individual customer flexibility utilizing the thermal inertia of a heated swimming pool.

- Cold district heating networks prioritize energy-efficient supply of low-temperature heat via decentralized HPs, including the Bamberg cold DHC system, which utilizes low-temperature heat from geothermal collectors, and the Ospitaletto cold DH system in Brescia, which utilizes waste heat and aquifer wells.

- Several projects focus on repurposing waste heat from electrolysers generated during hydrogen production processes for production processes, laundry, and DH. Examples include the MPREIS supermarket chain in Austria, the PtG pilot project in Ibbenbüren, the WindGas Falkenhagen project, the Green Hydrogen Esslingen project, and the H-Flex project in Nieuwegein.

These examples highlight various initiatives and innovations aimed at improving energy efficiency, renewable energy integration, and the utilization of waste heat in different sectors.

Evaluation

Traditional domain-specific approaches struggle to cover all above mentioned aspects of Hybrid Energy Networks. Therefore, different innovative tools for modelling, simulating, and optimizing Hybrid Energy Networks are discussed. These tools focus not only on the integration of coupling points, but also on the effects of coupling energy networks at the system level. Care has been taken to select only tools that are publicly available and whose use for the assessment of Hybrid Energy Networks is documented. Four application areas were defined, and an expert review was carried out. The results can be summarised by classifying the tools into the following application categories: a) Technical assessments: Pandaplan, Modelica, Co-Simulation, COMANDO, SAInt; b) Operational Optimisation (technical & economic): energyPRO; c) Planning at the scale of cities/regions: EHDO, EnergyPLAN, ESSIM, Integrate, rivus; d) planning at the scale of nations / continents: GasPowerModels.jl, PLEXOS, PyPSA-Eur-Sec.

A resource exergy analysis (REA) of Hybrid Energy Networks has been carried out as a proven type of exergy analysis that can replace primary energy analysis with a more comprehensive and consistent methodology. It compares six energy systems covering the heat demand (space heating and domestic hot water) of a residential area. In summary, the REA shows that Hybrid Energy Networks and low-temperature district heating can all contribute to significant reductions in greenhouse gas emissions (GHGE) (>90%) and resource exergy consumption (>70%) compared to heat supplied by decentralised natural gas condensing boilers. However, to realise the full potential of hybrid energy systems, it is essential to ensure that the electricity consumed by them is provided by dedicated GHGE-free sources. The analysis has been carried out with the assumption that dedicated PV power will cover all the electrical needs of the energy systems considered.

Finally, an assessment of the strengths, weaknesses, opportunities, and threats (SWOT) of Hybrid Energy Networks, was carried out based on a literature review, qualitative input from experts, an extensive feedback and discussion phase with stakeholders and an online survey.

The results show that, in general, the positive characteristics are considered more relevant by the experts than the negative ones. The most relevant results voted for are:

- Strengths: a higher degree of system flexibility; the decarbonisation of DHC networks and a higher degree of freedom for planning/operation.
- Weaknesses: an increasing level of complexity; price signals that do not yet take into account the grid situation; and current electricity tariffs and taxes.
- Opportunities: digitalisation, as it can help manage complexity; more research, products, demonstration projects, training, etc.; and decarbonisation incentives that can support sector integration.
- Threats: The possible disruption of existing business models and the risk of stranded investments due to various uncertainties, i.e. the regulatory framework, the market design, the market evolution in terms of electricity prices and alternative flexibility providers as well as the medium- and long-term availability of waste heat as a source for HPs.

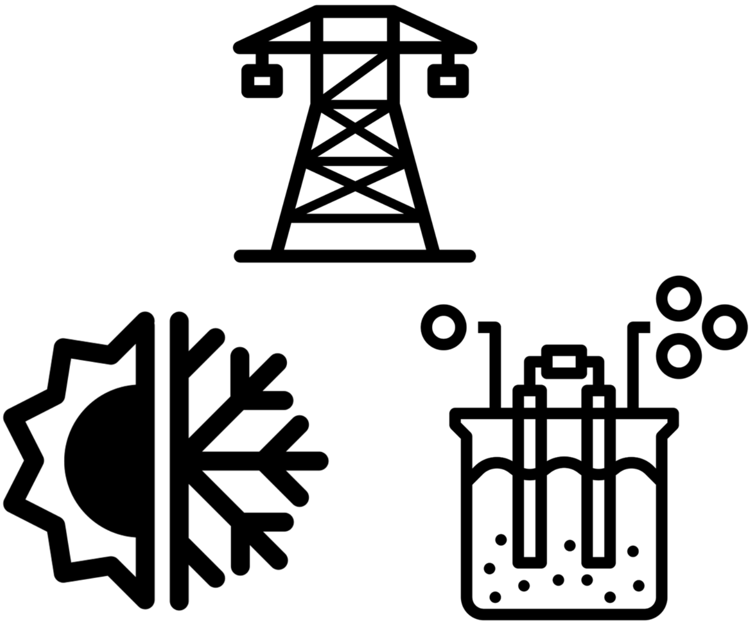
List of abbreviations

4GDH	4^{th} generation DH
4GDHC	4^{th} generation DHC
5GDHC	5^{th} generation DHC
aFRR	automated Frequency Restoration Reserve
AEL	alkaline electrolysis
ASHP	Air-source heat pumps
ATDH	Ambient temperature district heating
ATES	Aquifer Thermal Energy Storage
BL	Balancing market
BM	Business models
BMC	Business Model Canvas
BTES	Borehole Thermal Energy Storage
CAPEX	Capital expenditure
CCGT	combined cycle gas turbines
CCS	Carbon Capture and Storage
CEEP	Critical Excess Electricity Production
CHP	Combined Heat and Power
CCHP	Combined Cooling Heat & Power
CO_2	Carbon dioxide
COP	Coefficient of Performance
CPEC	Cumulated primary energy consumption
CTES	Cavern Thermal Energy Storage
DA	Day-Ahead
DC	District Cooling
DH	District Heating
DHN	District Heating Network
DHC	District Heating and Cooling
DHCN	District Heating and Cooling Networks
DHW	Domestic Hot Water
DSM	Demand-side Management
DSO	Distribution system operator
eB	Electric boiler
EC	European Commission
eff.	Efficiency
EMS	Energy Management Systems
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
ESCO	Energy Services Company
ETS	Emissions trading system
EU	European Union
FiT	Feed-in tariff
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential

H&C	Heating and Cooling
H2	Hydrogen
HEN	Hybrid Energy Network
HES	Hybrid Energy System
HOB	Heat-only boiler
HP	Heat Pump
HtP	Heat-to-power
HVAC	Heating, Ventilation and Air Conditioning
LCOH	Levelized Cost of Heat
LT	Low temperature
LTDH	Low-Temperature District Heating
MILP	Mixed-integer linear programming
MW	Megawatt
OPEX	Operating Expenses
PEMEL	PEM electrolysis
PSO	Public Service Obligation
PtC	Power-to-Cold
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy
REA	resource exergy analysis
REC	resource exergy consumption
RED	renewable energy directive
RES	Renewable Energy Sources
RHC	Renewable Heating and Cooling
SB-CHP	solid biomass CHP plants
SCGT	simple cycle gas turbines
temp.	Temperature
TES	Thermal Energy Storage
TPEC	Total primary energy consumption
TRL	Technology Readiness Level
TS	Task Sharing
TSO	Transmission system operator
TYNDP	Ten Year Network Development Plan
VHP	Virtual heating plant
WSHP	Groundwater heat pumps
WWTP	wastewater treatment plant

PART A - BACKGROUND

After the general introduction (section 1), the cooperation with the IEA international smart grid action network (IEA ISGAN) is described (section 2).



1 INTRODUCTION

Author: Ralf-Roman Schmidt (AIT)

1.1 MOTIVATION

Coupling the electricity and gas sector together with a closer integration with other sectors, i.e., heating & cooling, transport, industry, and urban infrastructure[1], is considered one of the key measures for decarbonizing the energy system. It is often referred to as “sector coupling”, “sector integration”, “smart energy system” or “hybrid energy system”.

District heating and cooling (DHC) networks are traditionally linking the heating & cooling (H&C) sector to the electricity and often also to the gas sector through widespread gas-fired combined heat and power (CHP) plants. However, the role of CHP plants will significantly change in the future since decarbonisation will make the use of fossil fuels almost impossible. For renewable fuels, there will be a growing competition with hard-to-decarbonise sectors such as air transport and certain industrial processes. Moreover, an increasing share of renewable electricity production from hydro, wind, and photovoltaics (PV) will drastically replace the amount of electricity produced from CHP plants. Consequently, other heat (and cold) sources will be needed for covering the heat (and cold) demand in DHC networks in the future; as well as other coupling points will be needed to provide flexibility between the different sectors and to increase the overall efficiency of the energy systems. Further on, hydrogen is playing an increasingly important role in the energy system, and synergies to other networks will be important to consider.

1.2 AN INTERNATIONAL COOPERATION

The IEA Technology Cooperation Programme on District Heating and Cooling (IEA DHC[2]) is dedicated to make both DHC and CHP powerful tools for energy conservation and the reduction of environmental impacts of supplying heat. The activities under the supervision of the IEA DHC are called Annexes.

The aim of the **IEA DHC Annex TS3 „Hybrid Energy Networks“**[3] was to promote opportunities and to overcome challenges for DHC networks in an integrated energy system context from a technical and strategical point of view. The IEA DHC Annex TS3 was running from autumn 2017 to early 2023, followed by a reporting and reviewing phase. During the

[1] including water and waste management, telecommunication etc.
[2] https://www.iea-dhc.org/home
[3] https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts3

project, several workshops, webinars, and special conference sessions were organized. The activities in the IEA DHC Annex TS3 were funded through a task-sharing approach, where various international participants contributed resources in-kind. In addition, some national funding was granted. The task-sharing approach allowed to connect existing national and international projects via the international platform and thus benefit from international experience and exchange.

The IEA DHC Annex TS3 was organized in the following sub-tasks:

A. Assessment of technologies and synergy potentials on a national level;

B. Available tools to plan, design and operate Hybrid Energy Networks;

C. Analysis of different case studies;

D. Business models, legal aspects, and political framework.

The coordination team of the IEA DHC Annex TS3 consists of Ralf-Roman Schmidt (AIT, overall lead); Dennis Cronbach (Fraunhofer IEE, Subtask D lead), Anton Ianakiev (NTU, Subtask C co-lead); Anna Cadenbach (Fraunhofer IEE, Subtask C co-lead); Daniel Muschick, (BEST, Subtask B co-lead); Peter Sorknæs (Aalborg University, Subtask A lead), Inger-Lise Svensson (RISE, Subtask C co-lead) and Edmund Widl (AIT, Subtask B co-lead). However, numerous stakeholders from research, industry and government organization were involved and were contributing.

To facilitate a better understanding of integrated energy systems, in 2018 the IEA DHC Annex TS3 established a cooperation with the IEA International Smart Grid Action Network (ISGAN), see section 2. Further cooperations were established with the IEA HPT Annex 47[4] and 57[5].

This guidebook is summarizing the overall work in the IEA DHC Annex TS3. Further publications can be found at https://www.iea-dhc.org/the-research/annexes/ts3/publications

1.3 AIM AND STRUCTURE OF THIS GUIDEBOOK

The aim of this guidebook on Hybrid Energy Networks is to highlight some of the key-opportunities and give recommendations to overcome the challenges for district heating and cooling (DHC) networks in an integrated energy system context, including both, the electricity and gas networks, where a special focus was put on hydrogen. Due to the complexity of the topic, this guidebook gives selected insights into the work and activities of the participants in the IEA DHC Annex TS3, related to some of the main aspects relevant when planning and

[4] https://heatpumpingtechnologies.org/annex47/
[5] https://heatpumpingtechnologies.org/annex57/

operating Hybrid Energy Networks, considering both technical (system configuration, operational strategy) and strategic aspects (business model, regulatory frame). The focus of this guidebook is on:

Part A Background: After the general introduction (section 1) the cooperation with the IEA international smart grid action network (IEA ISGAN) is described (section 2).

Part B Concepts and technologies: This part of the guidebook is introducing the definition and the concept of Hybrid Energy Networks (section 3), including the concrete connections between electricity and DHC networks (section 3.2); between electricity and gas networks (section 3.3) and between gas and DHC networks (section 3.4). Further enabling technologies are explained in section 3.5, including storages and energy networks. A special focus is out on large scale HPs in section 4. Finally, the double loop concept is introduced in section 5.

Part C System perspective: This part of the guidebook gives the system perspective on Hybrid Energy Networks, including the point of view of the transmission system operators from electricity and gas (section 6); the role of CHP plants and HPs from an European perspective (section 7), selected scenarios for Austria and Denmark (section 8), as well as the possible synergies between hydrogen and DH (section 9). Further on, reports for selected IEA DHC Annex TS3 partner countries (Austria, Denmark, Germany, Italy, and Sweden) were created, giving some more details on the situation and scenarios. This country reports can be found in the Appendix B to F.

Part D Implementation: This part of the guidebook analyses regulations and new roles and actors in energy trading as well as business models involving consumers and their individual choices including energy communities in selected countries, including a summary of results from selected projects (section 10). Further on, case studies for Hybrid Energy Networks are summarized (section 11).

Part E Evaluation: Here, different tools for modelling, simulating, and evaluating Hybrid Energy Networks are discussed (section 12), and a resource exergy analysis is performed (section 13). Finally, the strengths, weaknesses, opportunities, and threats of Hybrid Energy Networks are discussed (section 14).

2 COOPERATION WITH THE IEA INTERNATIONAL SMART GRID ACTION NETWORK (IEA ISGAN)

Author: Joni Rossi (RISE and leader of the IEA ISGAN Working Group 6 on Power Transmission and Distribution Systems)

With the increasing complexity of energy systems and their interconnections with industry, transport, land use planning, and urban design, the need to link technologies and processes across sectors becomes more urgent than ever. This calls for cross-sectoral technical solutions, aligned legislation, a supporting market and advanced ICT systems. However, even in a digitally interconnected system, the need for stakeholders to understand each other, to discuss each other's needs, and to work towards integrated solutions are key enablers for a successful energy transition.

To facilitate a better understanding of integrated energy systems, in 2018 the IEA DHC Annex TS3 established a cooperation with the IEA International Smart Grid Action Network (ISGAN) which supports the accelerated development and deployment of smarter, cleaner electricity grids around the world. The IEA ISGAN Working Group 6 'Power Transmission and Distribution Systems' focuses on the potential system-related challenges in the development of future smarter grids, including technologies, market aspects, and policies.

In ISGAN, we see the power grid as an enabler for energy efficiency and for achieving a sustainable energy system for all. Furthermore, we support solutions that maintain and improve the security, reliability and quality of electric power supply while facing challenges related to significant trends in the electricity sector and in society. Therefore, a holistic approach is needed, starting at the planning stage, and continuing throughout all phases of implementation, both vertically, along the different voltage levels of the grid, as well as horizontally and across sectors.

To meet sustainable development goals, new requirements for grid planning processes, such as decarbonization, energy security, and affordability have been added to the more traditional tasks of providing security, adequacy, quality of the service, resilience, and efficiency. By understanding electrification policies in countries worldwide, as well as technological developments across sectors and how they impact the limits of the system, new needs and opportunities can be integrated in the future power system planning process. Especially with decreasing reliance on natural gas, different sector coupling solutions between heat and electricity need to be explored to increase the efficiency of the different systems as well as the overall resilience. That also implies initiating proactive dialogue with all stakeholders from both electricity and heat networks early in the planning stage. Such dialogue can facilitate the integration of new loads and smart sector coupling solutions in the right size and location, the calculation of the potential for flexibility in demand and production, and the quantification of uncertainties. As such, a range of network and non-network options can be embraced and an optimal balance between risks and benefits can be struck in new market frameworks with maximum benefits to society.

When exploring and evaluating new opportunities in load and storage from the heating and cooling sector, a balance must be found between increased investments at the planning stage and increased implementation of flexibility at the operational phase. Here, flexibility needs are required in a timescale from fractions of a second (e.g., stability and frequency support) to minutes and hours (e.g., thermal loadings and generation dispatch) to months and years (e.g., planning for seasonal adequacy and planning of new investments). Examining the flexibility needs of the whole energy sector paves the way to a coordinated use of existing cross-sectoral flexibility solutions which reduce the overall need for investments. Next to a permissible regulatory framework and an innovative and transparent market environment, a tighter cooperation between stakeholders is again needed to manage the different future networks at maximum efficiency and to balance synergies and conflicts across sectors.

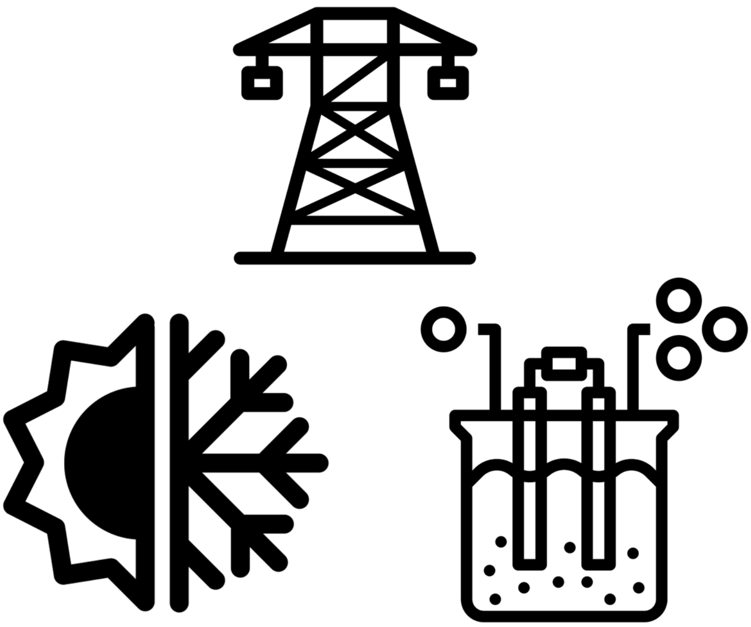
Flexible solutions need to be considered from the overall system perspective and from the more local perspective. There is an increasing interest in smart control of multi-energy systems, especially in urban systems with increasing electric loads driven by electrification of transport sector, cooling/heating technologies, various forms of energy storage technologies, advancements in distributed generation and demand-side response. Advantages of smartly controlled multi-vector systems include decreasing energy transfer losses, proximity of local assets / prosumers, and links between electricity, transport, and heating networks (which are always local). Local collaboration and understanding between incumbent and new actors, who all play an important part in the energy transition, will be important for the development of innovative business models at district scale.

Inter-stakeholder cooperation is therefore important in the integrated planning and operation of different energy and transport networks. But when we move from research and demonstration level to large-scale uptake of innovative solutions, it will also become crucial in the realization phase. This will increase the need for a robust and skilled workforce in all sectors, as well as for newly skilled people at the intersection of sectors.

ISGAN and Working Group 6 have been very pleased to be part of the discussions and workshops of the IEA DHC Annex TS3, and to broaden the discussions between stakeholders at different levels towards a more holistic understanding of integrated energy systems.

PART B - CONCEPTS AND TECHNOLOGIES

This part of the guidebook is introducing the definition and the concept of Hybrid Energy Networks (section 3), including the concrete connections between electricity and DHC networks (section 3.2), between electricity and gas networks (section 3.3) and between gas and DHC networks (section 3.4). Further enabling technologies are explained in section 3.5, including storages and energy networks. A special focus is out on large scale heat pumps in section 4. Finally, the double loop concept is introduced in section 5.



3 THE CONCEPT OF HYBRID ENERGY NETWORKS

Author: Peter Sorknæs, Rasmus Magni Johannsen and Iva Ridjan Skov (Aalborg University), Ralf-Roman Schmidt (AIT).

Increasing levels of variable renewable energy sources (RES) are being installed in energy systems to reduce costs and emission of greenhouse gases. The result is a continuous increase of electricity production from variable RES in the electricity system, as wind turbines and solar power technologies, mainly photovoltaics (PV), are being implemented in energy systems (IEA, 2020). However, the large-scale introduction of variable RES also means that the energy system, and especially the electricity one, needs to change to facilitate these new variable sources, which contrasts with the traditional dispatchable sources (Lund, 2014). Research has shown that such a change in the energy system is best addressed by holistically looking at the energy system, by identifying synergies between the different energy sectors and by identifying different flexibility options that can be leveraged within the system (Lund et al., 2016; Mathiesen et al., 2015). The change from an energy system based mainly on dispatchable generation to a system with a high degree of non-dispatchable generation means that the flexibility that once was on the generation side to a larger extent must be found in the rest of the energy system to allow for an energy-efficient and low-cost transition (Lund, 2014).

Different concepts have emerged within research addressing this issue, such as Hybrid Energy Networks, see Figure 1.

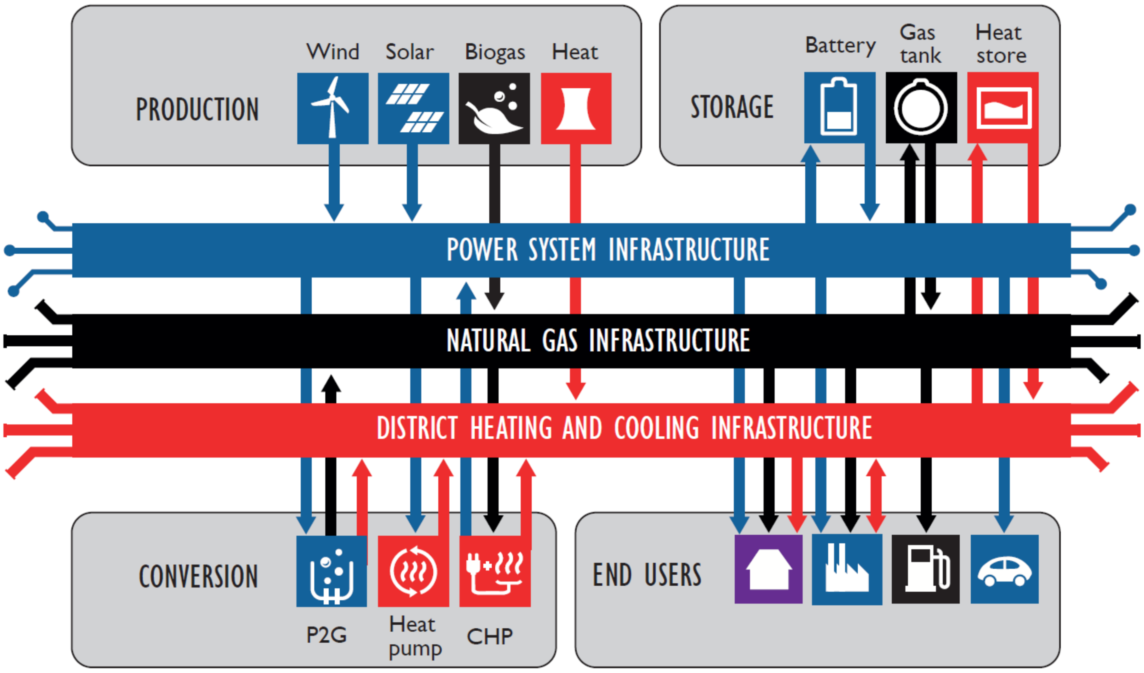


Figure 1: Example of a Hybrid Energy Network with some possible technologies and connections (source: Fraunhofer IEE)

In this section, the concept of Hybrid Energy Networks is briefly explained, and the main technologies required to connect different types of networks, namely the electricity, gas, and heating and/or cooling networks, are investigated, including enabling technologies.

3.1 DEFINITION AND CLASSIFICATION

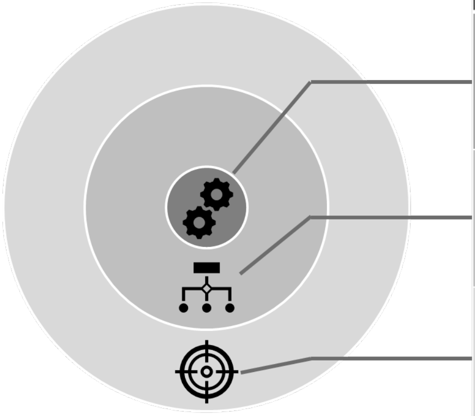
What is a Hybrid Energy Network, and how does it differentiate from concepts such as "smart" or "integrated" energy systems?

One of the first fundamental discussions within the IEA DHC Annex TS3 was the actual definition of a Hybrid Energy Network, since the various coupling points (heat pumps, electric boilers, power-to-gas processes as well as CHP plants, see below) can exhibit different integration levels, i.e. starting from traditional DHC networks, which are already integrating the electricity and the gas network via CHP plants, up to the concept of the 4th generation networks from (Lund et al., 2014), see section 3.5; and even "5th generation" or "cold networks", working with decentralized heat pumps, described e.g. in (Buffa et al., 2019), see also section 3.5.2.

Based on a literature review and a discussion within the Annex participants, the following definition for Hybrid Energy Networks has been established, adapted from the definition of a "smart energy system" from (Lund, 2014).

"A Hybrid Energy Network is an approach, in which electricity, thermal, and / or gas networks are combined and coordinated to utilize synergies between them, in order to achieve an optimal solution for the overall energy systems"

In order to allocate the different technology options such as coupling points, as well as the connected business models and strategies in the framework of a highly integrated energy system and to differentiate the levels of energy system integration, a more detailed classification approach of a Hybrid Energy Network was developed within the IEA DHC Annex TS3, see Figure 2.



Layer	Minimum	Maximum
Technology	Single coupling points, central controls of network and coupling points	Multiple and diverse coupling points, high operational flexibility, advanced controls, automation and analytics
Organization	Minimum permissible ownership of coupling points, traditional business models and services offered	Diverse ownership, high share of prosumers, innovative business models and services offered
Strategic	Central structures, integration of coupling points as a reaction to market pressure	Decentralized structures, integrated planning and design, optimized interaction and decarbonization

Figure 2: Classification of Hybrid Energy Networks based on different levels of systems integration[6].

Considering this set-up, the requirements for a "minimum" integrated Hybrid Energy Network are low, and many cases fall under this category. In contrast, a "maximum" integrated Hybrid Energy Network is more difficult to reach and far beyond the state-of-the-art[7].

A Hybrid Energy Network system can include a wide range of energy technologies that allow for connections between different energy networks. The technology types can be categorised based on which of the three networks they connect, namely the electricity network, gas network, and DHC network. The defined connections are described in separate sections, alongside a section about technologies that are not strictly Hybrid Energy Network technologies but enable a stronger and/or more flexible connection between the networks and are therefore considered as important in connection to Hybrid Energy Networks.

The division of technologies is based on the end-product that these technologies provide, so e.g., a combined cycle gas turbine that includes a steam turbine is only considered to produce heat if some of the produced heat is distributed in DHC networks.

[6] This classification differs from the concept of the 4th generation of DHC networks from (Lund et al., 2014), since the main characteristic of a Hybrid Energy Network is the integration between the different networks, and not the supply temperature or the time period where the different generations were dominating. I.e. a newly setup 4th generation DHC network can be realized with minimum system integration and a constantly adapted 2nd or 3rd generation DHC network can be a highly integrated solution in the overall energy system.

[7] However, the level of system integration does not necessarily correlate with system and/or cost efficiency due to the increasing complexity (see also section 14)

3.2 CONNECTING ELECTRICITY NETWORKS WITH HEATING AND COOLING NETWORKS

The connection between the electricity and DHC networks is for the most part one-directional[8]: Electricity is used to produce heating (and cooling).

Here, the predominant technologies are electrically driven **heat pumps** (HP) or mechanical chillers, using electricity to move heat from one place (a heat source) to another (a heat sink). Whereas mechanical chillers are designed to remove heat from a space or process stream, making it cooler and rejecting the heat to the environment (heat sinks are e.g., air, lakes, rivers), heat pumps are designed to extract heat from the environment and use it to provide useful heat (e.g., in district heating networks). Depending on the point of view, these technologies thus are referred to as Power-to-heat (PtH) or Power-to-cold (PtC). For district cooling applications, the most dominant technologies are not electricity but heat-driven absorption chillers, using heat from a district heating network as a driving energy (compression chillers are used mostly as back-up or for peak supply) and using the environment for rejecting the excess heat[9]. For district heating applications HPs have a high conversion efficiency of the used electric energy to useful heat, expressed by the Coefficient of Performance (COP). For HPs using ambient heat as a source, the COP is typically around 3-4 on a yearly basis (David et al., 2017), meaning that when 1 unit of electricity is used, 3-4 units of useful heat are produced. Since there is a high dependency of the COP on the temperature lift between heat sink and source (the lower, the better), a series connection where the HP provides the first part of the required temperature lift, and/ or reducing DH network temperature levels is beneficial, e.g. (Geyer et al., 2021). Additional, using a higher temperature heat source such as excess heat from cooling of datacentres or supermarkets can increase the COP significantly. See also section 4 for more details on the integration of large-scale HPs in DH networks as well as the results of the cooperation projects IEA HPT Annex 47[10] and 57[11].

Another power-to-heat technology are **electric boilers** (eBs). They have relatively low investment costs compared to HPs and enable generation of heat at high temperatures and very fast heating gradients. With the conversion method being based on electric resistance thereby heat-producing, the efficiency is close to 100%. Hence, their exergetic efficiency is much lower than HPs and the electricity demand per unit of heat is much higher (corresponding

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[8] Though some technologies allow for converting heat to electricity, operating at lower temperatures than traditional steam turbines, e.g. stirling engines and organic rankine cycle, conversion from district heating and cooling to electricity networks is generally limited due to low electrical efficiency (Padinger et al., 2019). Further on, the conversion efficiency is even lower when also accounting for grid loss and electricity for pumping in the DHC networks.
[9] However, more advanced DHC networks are reusing the excess heat by storing it and using it in winter times (see 4.4.2).
[10] https://heatpumpingtechnologies.org/annex47/
[11] https://heatpumpingtechnologies.org/annex57/

to a COP of about 1). These aspects make electric boilers typically useful for applications with limited operating hours (Danish Energy Agency and Energinet, 2020a), e.g., as a backup or a peak capacity in DH networks, or for participating in short term electricity balancing markets, e.g. (ISGAN, 2019).

Due to their higher investment costs compared to electric boilers, HPs require more operating hours than eBs to be economically viable (Danish Energy Agency and Energinet, 2020a). However, for an electric based heat supply, HP will provide significantly higher resilience to increases in electricity prices than eBs, due to their high efficiencies.

3.3 CONNECTING ELECTRICITY NETWORKS WITH GAS NETWORKS

Different Hybrid Energy Network technology options exist for producing gaseous products via electricity and using gas for producing electricity.

Historically, this has been dominated by going from gas networks to electricity networks, where natural gas has been used in gas-fired **Combined Heat and Power** (CHP) plants and power plants to produce electricity. Though the main role of CHP plants is to produce electricity, CHP technologies are also connecting electricity and DH by utilising the excess heat from electricity production. While the excess heat can be used to satisfy a heat demand in district heating, it may also be converted into cooling power using an absorption and absorption chillers, thereby operating as a **Combined Cooling Heat and Power Plant** (CCHP), sometime also referred to as trigeneration plants. While in the past CHP/CCHP technologies predominantly relied on fossil fuels (coal and natural gas), the technology does also allow for the usage of renewable fuels such as biogas / biomethane, synthetic fuels, electrofuels, or biomass to substitute natural gas, coal or oil as the primary fuel (Korberg et al., 2021, 2020). Technology-wise this can be achieved using traditional technologies such as simple-cycle gas turbines, combined-cycle gas turbines, and gas engines, or it could be using hydrogen in potential upcoming technologies such as fuel cells (Danish Energy Agency and Energinet, 2020a), see also section 9.2.1. CHP/CCHP can be dispatched when needed and could therefore provide much-needed flexibility for energy systems based largely on renewable energy production (Andersen and Østergaard, 2020), see section 6 and 8.

Going from the electricity to the gas network has historically only seen limited implementation. However, solutions for electricity to gaseous products i.e., **power-to-gas** (PtG)[12] processes could see increased utilisation, as it allows the production of fuels for sectors where direct

[12] Power-to-X (PtX) is often used as a combined term for power-to-gas (PtG) and power-to-liquid (PtL) (Korberg et al., 2021, 2020). However, since the focus here is on the connection with the gas network, PtL processes are not addressed further.

electrification is not possible and allows for production of fuels that can be stored over long periods of time at low cost and low storage losses. The products from these processes are often referred to as electrofuels (Ridjan et al., 2016). There exist a lot of different production pathways to go from electricity to gaseous products, though the main component for this is electrolysis that is used to split water into hydrogen (H_2) and Oxygen (O_2), where H_2 can either be used directly for energy purposes or injected into gas networks that are prepared for distribution of H_2. Alternatively, H_2 can be used as part of other processes where more complex gaseous products are generated, such as methane, which is also the main component of natural gas (Danish Energy Agency and Energinet, 2020b), see also section 3.5.2.

3.4 CONNECTING GAS NETWORKS WITH HEATING AND COOLING NETWORKS

The technologies connecting the gas and DHC networks mostly allow for a one-way connection, namely from gas to DHC. Though some technological options exist for utilising heat for production of gaseous products, the heat input is mainly used to reduce the need for electricity in the production and often the temperature levels in the DHC networks are too low to be used in such processes.

The most utilised direct connection from gas networks to DH is the production of heat via **gas-fired boilers** (i.e., heat-only boilers, HOB). Those boilers are mostly used in DH networks as backup and peak load units due to the relatively high cost of gas and the relatively low investment cost. Gas-fired boilers can achieve efficiencies upwards of 105-108%[13]. Further on, there are also technical setups where the gas is utilised as the main fuel to operate HPs, thereby utilising the higher useable heat output, similar to electrically driven HPs (Danish Energy Agency and Energinet, 2020a).

Besides these direct connections, utilizing **excess heat** from gas-fired CHP/CCHP technologies, gas-fired industrial processes, and different types of production of gaseous electrofuels including electrolysers ((Lester et al., 2020), see also section 9) also allows for the indirect connection between the DHC and gas networks.

3.5 ENABLING TECHNOLOGIES

While Hybrid Energy Network technologies are central in the connection of energy sectors, these are accompanied by other technologies that, despite not having any immediate sector connecting properties, do facilitate Hybrid Energy Network connection and the renewable

[13] Using lower calorific heat value for the fuel input

energy transition. This section will outline the most important technologies of this nature, focusing on energy storage technologies and energy networks.

3.5.1 ENERGY STORAGE

When going from one energy network to another, energy storage provides means for a temporal shift of the converted energy from when it is provided to when it can be used in the new network if there is no direct use for the converted energy.

Different storage technologies exist in electricity, gas, and DHC networks. However, the investment cost of electricity storage has shown to be higher and energy efficiency lower when compared with the storage solutions in DHC and gas networks. Especially large scale thermal energy storages and underground gas, and potentially H_2, storages in naturally occurring salt caverns have shown to have low investment cost per energy content stored (Lund et al., 2016). Though it should be noted that these technologies do not store the same type and quality of energy. However, being able to utilise lower cost and more energy efficient storage technologies are part of the argument for further sector integration.

The utilization of energy storages can be divided into a slew of time perspectives. Here the division is simplified into to two groups: Short-term storages that enable storage from down to seconds to 1-2 weeks, and seasonal storage that is used for long-term storage of energy between seasons.

Short-term storage makes it possible to shift energy production independently of demand for a few hours to few weeks, for example storing excess electricity production from variables RES on a weekend where the demand usually is lower. Short-term electricity storage can, however, also provide a range of ancillary services such as frequency regulation, or even back start grids after blackouts. Those storage can be realized by a broad range of technologies and storage mediums, ranging from chemical, electro-chemical, mechanical, thermal, to electromagnetic. Typical technologies include flywheel electrical storage, lithium-ion batteries, and flow batteries (also an electrochemical cell, but the electrolytes are stored in a tank (Zakeri and Syri, 2015). Mostly based on vanadium, but more ecologically sustainable solutions are currently under development, e.g., one based on the natural substance vanillin). Currently, short-term thermal storage options for DHC are dominated by sensible storage solutions, mainly hot water tanks, due to their relatively low-cost as well as simplicity and versatility (Danish Energy Agency, 2020).

Long-term (seasonal) storage makes it possible to exploit monthly or seasonal variances in renewable energy production. Within the electricity system, seasonal storage is most typical in connection to dammed hydropower and compressed air energy storage. Within the heating sector, seasonal storage is mostly done in pit thermal energy storages and borehole storages (BTES), also aquifer and cavern thermal energy storages (CTES and ATES) are an alternative especially in urban environments. They are mainly used for storing excess heat from solar thermal collectors, geothermal energy, heat pumps or waste heat produced during the summer. Finally, in the gas sector underground caverns are used extensively for seasonal storage of gas (Danish Energy Agency, 2020).

Short-term storages are generally of a smaller scale, whereas seasonal storages are somewhat larger in scale in relation to the serviced energy demand. This means that the same technology can in some cases be utilized as short-term storage and in other cases as long-term storage. Since the number of full charging cycles in long term storages is typically much smaller than in short term storages, the investment cost per stored energy unit for seasonal storage must generally be relatively low to be economically feasible[14].

While individual small-scale storage solutions may in some cases provide consumers economic benefits from reduced electricity bills depending on local electricity tax and tariff schemes (Zakeri et al., 2021), such solutions may not be beneficial in a socio-economic sense. Large-scale communal storage is required if the storages are to be utilised in a common sense and thereby also provide lower costs, greater system flexibility, and increased integration of RES (Lund et al., 2016).

Different types of **new energy storages** are emerging, such as thermo-mechanical energy storage technologies, where the electricity is stored as heat, generally at high-temperature levels, enabling it to return an amount of the stored heat to the electricity system again. Such systems have excess heat at the conversion from heat to electricity that can be used in local DH networks, thereby connecting the electricity and DH networks, though not being the main goal of the utilisation of the technology. Some concepts for this type of electricity storage also connects with cooling networks. Such electricity storages are known as Carnot batteries ("iea Energy Storage Task 36 – Carnot Batteries," n.d.; Lund, 2021).

3.5.2 ENERGY NETWORKS

When connecting different technologies, the availability of the networks is crucial. However, networks are no uniform entities, and these network variations can enable different Hybrid Energy Network connections, which, especially in future renewable-based energy systems, should be explored further.

[14] However, the economic feasibility of long-term storages can be improved by integrating them into short term operational optimization, e,g., by optimizing CHP or HP dispatch (Köfinger et al., 2018), (Totschnig et al., 2023).

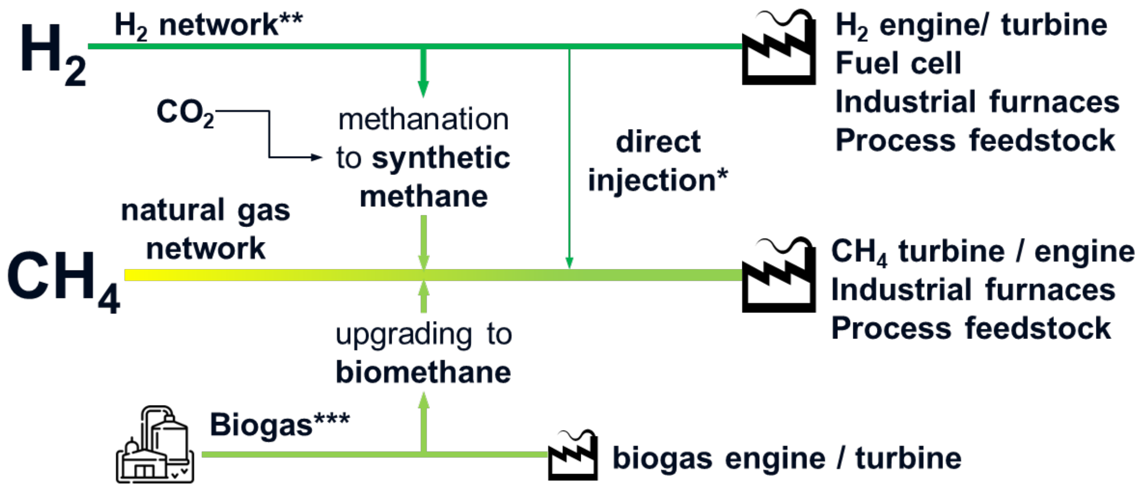


*Figure 3 Overview on different gas networks; *H2 injection into the natural gas network is currently only allowed to a certain extent; **H2 networks are currently in a planning stage; ***Biogas is usually used directly onside, without a regional network (source: AIT)*

For the **gas networks**, historically designed to transport natural gas (methane), biomethane upgraded from biogas or synthetic methane generated from renewable H_2 and CO_2 are renewable alternatives, that can directly substitute natural gas since they are chemically identical[15]. Discussions are ongoing about to what extent H_2 can be directly injected into existing gas networks, instead of first upgrading it to synthetic methane. However, due to H_2 having different physical and chemical properties from traditional gas, studies have found that there exists a limit to the amount of H_2 that can directly be injected into an existing network without the need of adaptions on the network or end consumer installations (Energinet et al., 2020). Therefore, discussions are ongoing about creating a separate H_2 network as a supplement to the gas network to transport H_2 from the place of production to the place of use, allowing intraregional H_2 trade and imports of H_2 in larger quantities ("EHB European Hydrogen Backbone," 2023).

The existence of **DH networks** is essential to the connection of the electricity, heat, cooling, and gas networks. Going forward, especially the DH networks are expected to see a change. This change is often discussed as the dominant DH technology in a 30–50-year period, due to identified historic generational changes and is expected to continue to develop going forward (Lund et al., 2014). This change has mainly been driven by the desire for increased primary energy efficiencies and diversity, which has led to a continuous reduction in temperatures in

[15] Technical challenges arise in the grid integration of renewable gases, as distributed generation and connection to low-pressure distribution grids implies a reverse flow from the distribution to the transmission level and thus detailed grid planning. Additionally, biomethane contains a higher level of oxygen, which must be taken into account, especially in the case of high shares of biomethane in the system, in order to remain within the specified regulatory framework (Nielsen, 2023)

the DH networks, which leads to lower grid losses, increased heat and power generation efficiencies in CHP plants and enables effective utilisation of more heat production technologies. Grid losses in DH networks vary significantly based on heat demand density, age, maintenance, and temperature levels, and can typically range from 5% to 35%, the latter applies for poorly maintained networks or networks in rural areas with very low heat densities (Frederiksen and Werner, 2013). Three generations have been identified since the start of the modern DH systems in the 1880s until around 2020. The next generation of DH networks is discussed as 4GDH (Lund et al., 2014), and it is expected to be characterised by supply temperatures of 50-60 °C and high shares of renewable and excess energy in the heat supply. This ongoing development of lowering supply and return temperatures in the DH network especially allows for more efficient use of, e.g., HPs and excess heat (Lund et al., 2018). In some DH network designs electric boosting units, e.g., HPs, are utilised at the residential level to boost the low supply temperature from the DH network to levels that can be utilised within the building. The reason can be, e.g., that the supply temperature at the residential level is below the levels needed for legionella-free hot water consumption (below 50-60 °C depending on installation), or the supply temperature can be so low that boosting is needed for using it for space heating (Tunzi et al., 2020; Yang and Svendsen, 2018). In cases where HPs are utilised for boosting, these boosting units can in some cases also provide cooling (Gudmundsson et al., 2022). Such systems allow for lower supply temperatures, thereby potentially allowing for lower grid losses and increased utilisation of excess heat, though a less flexible heat production would be experienced as electricity with limited flexibility will always be needed to satisfy residential heat demands. An overview of these four generations of DH can be seen in Figure 4.

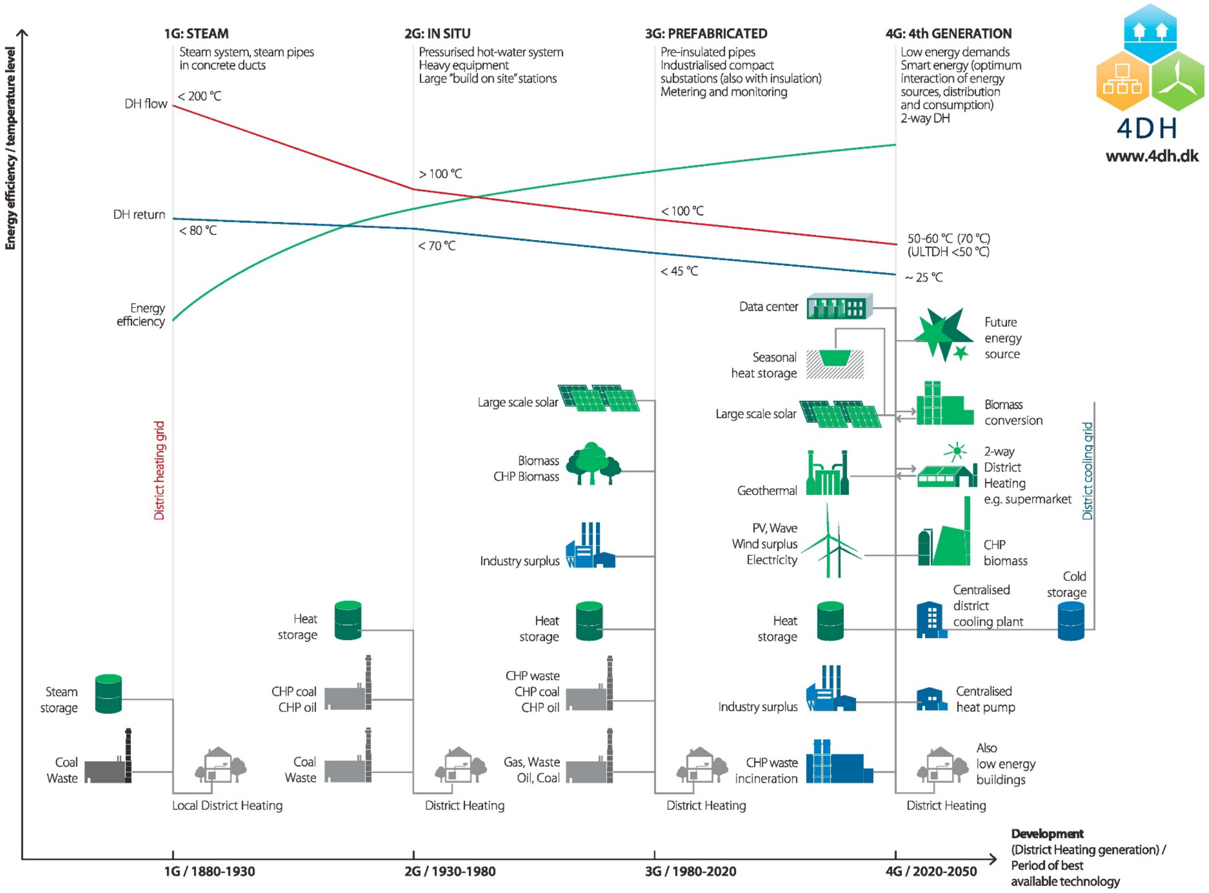


Figure 4: Overview of the first four generations of DH (Lund et al., 2018).

District cooling (DC) networks, while a mature and commercially available technology, are not as widely developed as DH networks (Werner, 2017). However, because of an increasing need for cooling world-wide (International Energy Agengy, 2018), district cooling networks are seeing increasing attention and implementations. For example, countries in southern Europe are increasingly establishing cooling networks, especially for the service sector and large-scale consumers such as hospitals and universities (Inayat and Raza, 2019). A recent publication (Østergaard et al., 2022) defines four generations of district cooling to make a similar framework as described for DH above. The first generation being pipeline refrigeration systems that were first introduced in the late 19th century, the second generation being mainly based on large compression chillers and cold water as distribution fluid, the third generation having a more diversified cold supply such as natural cooling, and the fourth generation combining cooling with other energy sectors sometimes into a renewable energy-based smart energy systems context, including combined heating and cooling.

One very much discussed **combination of DH and DC networks** has been described in the literature as "**cold networks**", "Anergy network"[16] or "5th generation" of DHC networks (short: 5GDHC), see also (Buffa et al., 2019). Those systems are operating around ambient temperatures, together with consumer-side heat pumps for boosting the network temperature to the demand side requirements. They allow bi-directional heat and cold supply and thus enable the integration of multiple prosumers. Very often, also seasonal storage is used to transfer the surplus heat from summer to winter times. Those properties make it an interesting option for Hybrid Energy Networks (see e.g., section 11.4). Although only a small number of cold networks have been built up to today (mostly in Switzerland and Germany (Wirtz et al., 2022)), there is an ongoing debate in the international DHC community on the role and definition of cold networks. I.e. (Lund et al., 2021a) is arguing, the nomenclature 5GDHC might lead to the perception such systems are a progression towards the 4GDH; and this is not always the case, e.g., those networks can require significantly more pumping power than 4GDH due to the low temperature difference between supply and return line. Further on, for single-source unidirectional systems without cooling, 4GDH can be economic superior towards cold networks, e.g. (Gudmundsson et al., 2022). Therefore, 5GDHC networks should rather be seen as a parallel development and therefore are referred to as cold networks in this report. On the other hand (Lund et al., 2021a) is recognizing that the cold network concept will become more suitable and competitive from a market and expansion perspective. Especially in places with heating and cooling demands of similar magnitudes, where end-users can trade heat without there being obvious and cheap sources. (Gjoka et al., 2023) argued, cold networks can be a viable alternative in mild and mixed-demand climates where traditional DHC systems remain uncompetitive. Therefore, a detailed assessment of each individual case is required for the best system design and there is no "one-size-fits-all" solution.

Another combination of DH and DC networks is the **double loop concept**, see section 5.

[16] this label ignores the fact that anergy is an outdated and far from universal concept, that can be misleading (Jentsch, 2010)

4 LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS

Author: Daniel Trier (PlanEnergi)

Large-scale heat pumps in district heating systems represent a straightforward existing and efficient link between the electricity and heating sector. In combination with thermal storages, they represent an option to integrate fluctuating renewable electricity in the energy system while enabling decarbonisation and substantial primary energy savings in the heating sector.

Figure 5: Flatbed air coolers of the 3 MW heat pump at Præstø Fjernvarme, Denmark; source: Daniel Trier (PlanEnergi).

Seven standalone documents have been developed on large-scale heat pumps in district heating. The general approach is to describe experiences relevant for a wide range of countries, though some parts are based on a Danish context. The topics include market development, incentives and policies, economics and electricity grid connection options, and operation experiences with air-source heat pumps in a relatively cold climate. Besides this, more general experiences are described such as pros and cons of various heat sources, suitable refrigerants, tendering process, and recommendations regarding the configurations and energy system integration.

A few key take-away messages can be derived from the documents:

- While synthetic refrigerants are causing concerns regarding undesired side-effects, the use of natural refrigerants has proven both suitable and reliable.
- The combination with a thermal storage to some extent enables the disconnection of supply and demand, thus reducing the need for peak production units while representing an option to prioritise hours where the electricity carbon footprint and/or prices are lowest. In many cases, this feature has shown to be well-worth the investment cost of the storage.
- It is worthwhile to consider how heat pumps can be physically and operationally integrated with other production units when the heat pump capacity is not sufficient. Instead of parallel operation (e.g., together with a boiler), a series connection where the heat pump provides the first part of the temperature lift, can increase the COP level thus representing a potential for operational savings.
- A trade-off between investment costs and efficiency should be considered to evaluate the feasibility of improving the COP by investing in a more complex heat pump system design, compared to a simpler, less efficient system. An additional value of high COP levels is a reduced impact from electricity price variations due to the lower electricity demand, thus making the final heat price more resilient.

The individual documents are joined in Appendix A.

5 THE DOUBLE LOOP CONCEPT

Author: Michele Tunzi (Technical University of Denmark)

A practical example of the electrification of the DH is presented in the double loop concept. The main idea of the double loop concept – see Figure 6 is to separately circulate the supply and return flows with a constant pressure difference and secure the displacement of heat and cool flows in all parts of the network. This has two advantages:

- Firstly, the summer flow can be circulated only in the supply lines, removing the necessity of having by-pass flows to keep the pipes warm during no-load periods or summer operations. It avoids unnecessary increasing of the return temperatures and the use of the return lines to deliver the cooling to the end-users, embedding heating and cooling in the same infrastructure.

- Secondly, it increases the possibility of augmenting the network operation's flexibility, allowing easier integration of any available local energy source. Then, local pumps ensure energy delivery to the local users and are hydraulically separated from the operation of the main distribution loops (Tunzi et al., 2020).

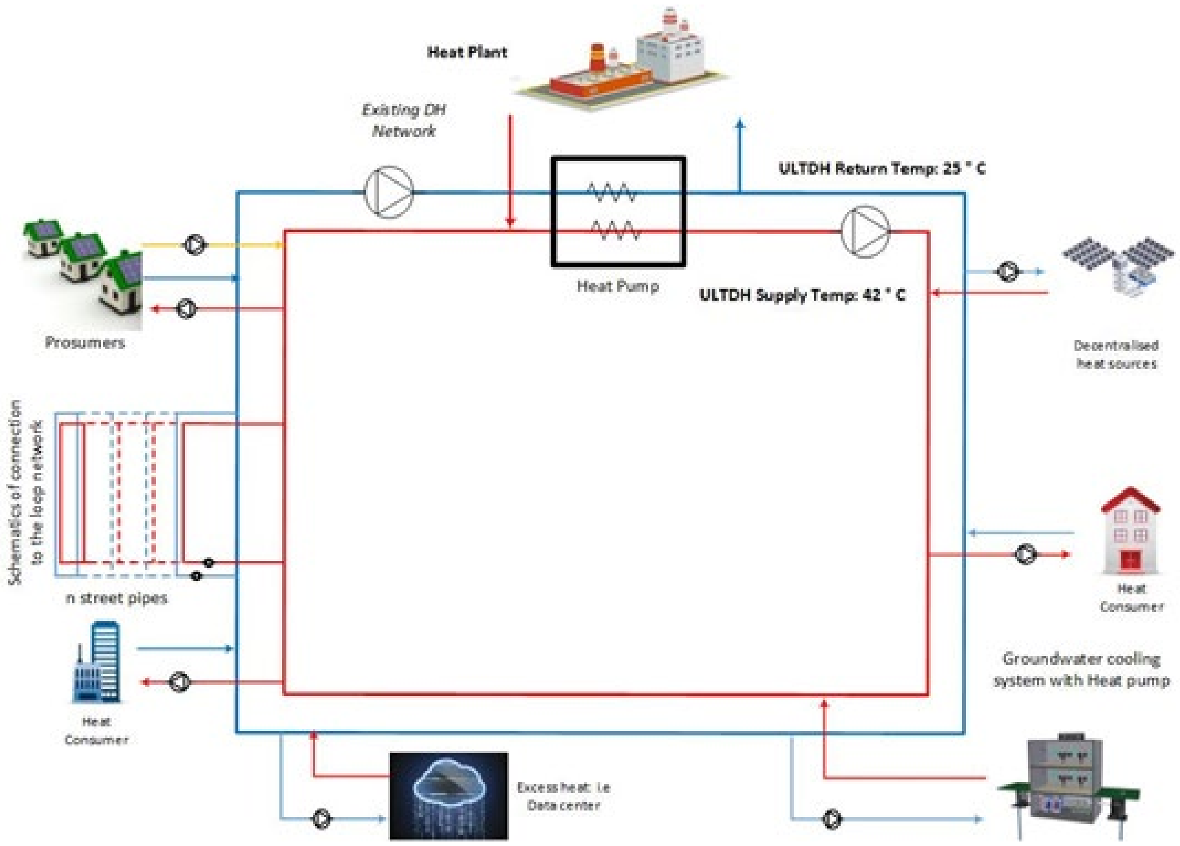


Figure 6: Schematic representation of combined heating and cooling double loop concept

An example is presented for this Danish case based in an urban area in the northern part of Copenhagen, illustrated in Figure 6. The site is composed of medium and large commercial buildings, recently built or renovated, requiring both heating (at low temperature) and cooling. Despite a local DH network available in this municipality, this specific area is among the few ones still using natural gas to cover the space heating and domestic hot water demand. Active cooling instead is provided by local cooling air conditioning systems. The local municipality is investigating a sustainable strategy, technically and economically, to expand the current network and replace the natural gas grid with district heating and cooling networks.

Figure 7: Commercial area in northern Copenhagen – the red point represents the excess heat available, while the yellow ones the consumers for the specific area

The estimated total heat consumption in the area is 11.3 GWh based on the buildings' real gas consumption and energy certificate. The cooling demand is 1.6 GWh, representing 14% of the heating demand based on the assumption of 30 kWh/m^2 for cooling in commercial buildings in Denmark (Persson and Werner, 2015). In addition, the commercial buildings highlighted in the red area of Figure 5 use process heat. According to the estimation, 2 MW of heat can be potentially recovered and used as the main heat source for the DH network. The investigation looked at five different scenarios, all using the 2 MW of process heat combined with large HPs to produce heating and cooling for the area, as summarized in Table 5. The last two scenarios used the traditional branched district heating network layouts (tree-network), covering only the heating demand in the area, and assumed individual cooling systems installed in each end-user.

Table 5: Summary of the scenarios investigated (WSHP = groundwater heat pump; ASHP = air-source heat pump)

Scenario	Network Layout	Process Heat High Temp (65 °C)	Process Heat Low Temp (35 °C)	WSHP (COP 6)	ASHP (COP 4)	Individual cooling
1	Double-loop	X	-	X	-	-
2	Double-loop	-	X	X	-	-
3	Double-loop	-	X	-	X	-
4	Tree-network	X	-	-	X	X
5	Tree-network	-	X	-	X	X

As the buildings in this area can be comfortably heated with supply temperatures below 55 °C for the majority of the heating season, the design of the network assumed supply/return temperatures of 55/25 °C for all scenarios. According to Danish building regulations, the design heat capacity was estimated to be 5 MW based on the outdoor design temperature of - 12 °C and no heat gains. For the cases where the supply temperature from the process heat was high enough to secure 55 °C in the network (Scenario 1 and 4), only a heat exchanger was considered; instead, for the scenarios where the supply temperature from the process heat was at 35 °C (Scenarios 2, 3, and 5), a HP of 2.4 MW was necessary to raise the temperature in the network at 55 °C. The rest of the design heat capacity was based on large HPs as summarized in Table 5, and the analysis evaluated, technically and economically, the impact of having groundwater heat pumps (WSHP) compared to air-source heat pumps (ASHP). The ground water is also used as cooling source for the scenarios with double loops. Furthermore, based on the Danish energy market, the potential local waste heat is not free, and an industrial price of 20 EUR/MWh was assumed to be paid by the district heating operator. This price may vary in the future and be different in other countries and energy markets, where the cost of surplus can be free of charge. The design flow was 38 kg/s, and the pipe diameters varied from DN 160 (mm) to 26 (mm); the total length of the main distribution pipelines is 1.3 km. All components' capital and operating costs were based on the Danish market, and the detailed cost breakdown can be found in the national energy catalogue (Danish Energy Agency and Energinet, 2020a).

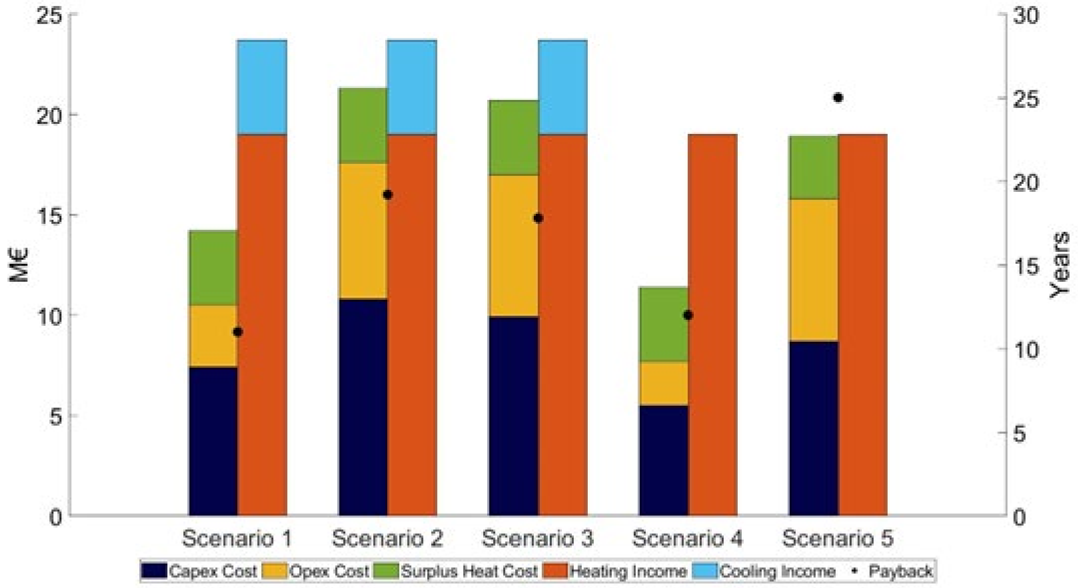


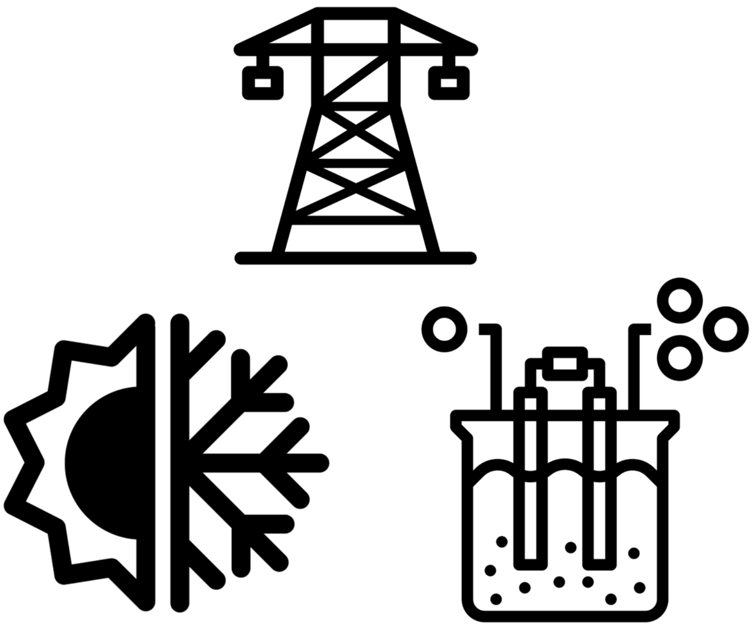
Figure 8: Economic assessment of the electrification of district heating and cooling network as an alternative to natural gas grids

The economic assessment was based on the net present value and assumed a project's lifespan of at least 30 years. The results, summarized in Figure 8, highlighted that the double loop concept, embedding heating and cooling in the same infrastructure, can secure the best return on investments for the DH operator. The analysis also showed that the capital and the operating costs increased consistently for the scenarios where the local surplus heat was at 35 °C due to the investment for the booster heat pumps – necessary to raise the temperature to 55 °C – and higher electricity consumption. On the contrary, Scenarios 1 and 4, where the surplus heat was assumed at 65 °C, had a payback period lower than 15 years. In the scenarios based on traditional branched DH networks – Scenario 4 and 5 – although only heating would be delivered to the end-users, the return of investment was below 30 years even for the case with the surplus heat at 35 °C. However, the commercial buildings in this area need active cooling, and the solution of having individual cooling systems in each building can be 25-30% more expensive and less efficient for the end-users. Finally, having individual HPs for both heating and cooling in each building could be a possibility; nonetheless, a district energy system should be the preferred option to replace the natural gas grid in a dense urban area as the one investigated. In fact, an integrated heating, cooling, and electricity networks can increase the security of supply – exploiting local availability of energy sources – and ensure lower costs compared to individual solutions (Tunzi et al., 2020), making the end-users less exposed to the volatility of the energy market.

PART C - SYSTEM PERSPECTIVE

This part of the guidebook gives the system perspective on Hybrid Energy Networks, including the point of view of the transmission system operators for electricity and gas (section 6**Fehler! Verweisquelle konnte nicht gefunden werden.**); the role of CHP plants and HPs from an European perspective (section 7), selected scenarios for Austria and Denmark (section 8), as well as the possible synergies between hydrogen and DH (section 9).

Further on, reports for selected IEA DHC Annex TS3 partner countries were created, giving some more details on the situation and scenarios regarding Hybrid Energy Networks on a national scale. This country reports can be found in Appendix B Austria; Appendix C Denmark; Appendix D Germany; Appendix E Italy and Appendix F Sweden.



6 THE POINT OF VIEW OF THE TRANSMISSION SYSTEM OPERATORS FOR ELECTRICITY AND GAS

Author: Olivier Lebois (RTE Expert and Member of the Steering Group of the joint ENTSO-E and ENTSOG (European Network of Transmission Operators for Electricity and Gas) TYNDP (Ten Year Network Development Plan) Scenario building process).

District heating combines on a single network several heat sources. Such sources are usually utility-scale equivalents of technologies that can be installed at household level (e.g., gas/biomass boilers, heat pumps, etc.). They provide a good potential to adapt to the heat supply to local resources (biomass in rural area, waste in urban area…).

Reaching carbon neutrality requires the highest standards in terms of energy efficiency. In the space heating sector, heat pumps offer the highest efficiency potential and district heating may facilitate their integration in very dense areas where the evaporator may be difficult to install. Sector coupling is another component aiming at a more efficient energy system. District heating offers a good potential to recover heat from a wide range of processes being directly or as a heat source for highly efficient heat pumps. With the expected development of electrolysis to provide low carbon molecules, heat pumps can help to compensate the energy losses of the conversion by recovering the associated heat.

Regarding the extent of the carbon neutrality challenge, it is important that energy modelling considers the energy efficiency and flexibility that could be offered by district heating systems. In their TYNDP 2022 scenarios[17], ENTSO-E and ENTSOG have used a specific load profile for heat pumps operating in district heating network to make sure that peak heat demand is met by a combination of heat pumps, boiler/CHP, and thermal storage. As a result, it limits the peak electricity demand thus facilitating the integration of RES.

[17] ENTSO-E and ENTSOG are developing the Ten-Year Network Development Plan (TYNDP) scenarios that will support the European Union plans for energy infrastructure and to achieve the objectives of the EU Green Deal as well as the Paris Agreement, and to ensure a fair, affordable and secure transition towards a clean and decarbonised energy system; see https://2022.entsos-tyndp-scenarios.eu/

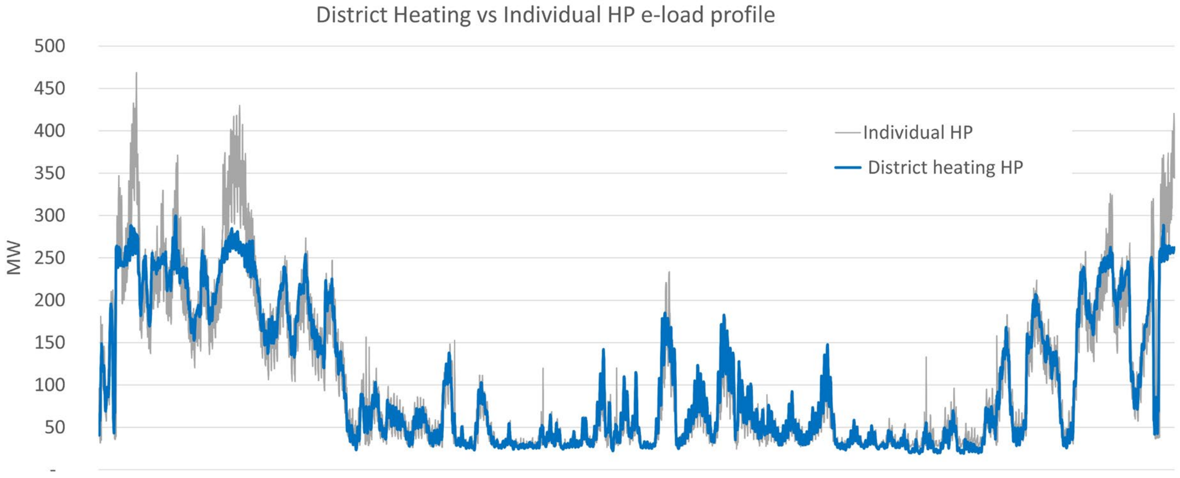


Figure 9: comparison of all electric individual and district heating heat pump load profiles (indicative data), source: ENTSO-E and ENTSOG TYNDP 2022 scenarios

Such modelling innovation was a first in the modelling of the European electricity system. In a near future, it is expected that district heating modelling is further integrated in a sector coupling perspective to consider both derived heat from electrolysers and the ability to dynamically adapt the merit order of heat sources to provide more flexibility to an electricity system dominated by variable RES.

7 THE ROLE OF CHP PLANTS AND HEAT PUMPS FROM AN EUROPEAN PERSPECTIVE

Authors: Lukas Kranzl, Mostafa Fallahnejad (TU Wien, EEG)

Climate and policy targets require a fundamental transition and full decarbonisation of the DHC sector. This is also reflected by the policy targets to increase the RES share in the district heating sector during the recast of the European renewable energy directive[18]. Still, the current supply structure of DHC in Europe is strongly dominated by fossil fuel-based heat generation, which accounts for ca. 73% of the total DHC supply (Commission et al., 2022).

In this context, it is important to understand that the economic and policy framework in the past two decades was, in general, strongly in favour of CHP plants, in particular Gas CHP.

Thus, the question arises, to which extent the heat generation mix needs to change in the coming years and decades and, in particular, how the interaction between the DH and the electricity sector needs to change. On the one hand, the main technologies under consideration in this context are CHPs that produce electricity and heat; on the other hand, heat pumps that consume electricity for heat generation.

As a key boundary condition, the transition of the sector to full climate neutrality is an important constraint, which needs to be considered in related analysis and policy conclusions.

In the following paragraphs, we will discuss the expected role of CHPs and heat pumps in future scenarios of the European DH sector by sharing selected results from three studies being carried for the European Commission (Braungardt, 2023; *ENER/C1/2019-481 – Potentials and levels for the electrification of space heating in buildings (preliminary results)*, 2023; European Commission. Directorate General for Energy. et al., 2022).

Moreover, we will complement this by discussing the required set of electricity and gas prices for allowing feasibility of CHP plants and thus derive conclusions regarding a viable mix of DH supply technologies.

The project ENER/C1/2018-494 developed scenarios with full decarbonization by 2050 (except baseline) and different technology focus. District heating generation largely follows economic optimization of the full energy system model Enertile. The results show high share of heat pumps in district heating in all decarbonization scenarios (~2/3). H2 boilers are used for covering peak load. Drivers and uncertainties are mainly open questions regarding the (partly

[18] When writing this report, the recast was still under discussion.

policy driven) resource constraints of biomass, biomass price developments as well as prices for H2 and e-fuel imports. Results are depicted in Figure 10.

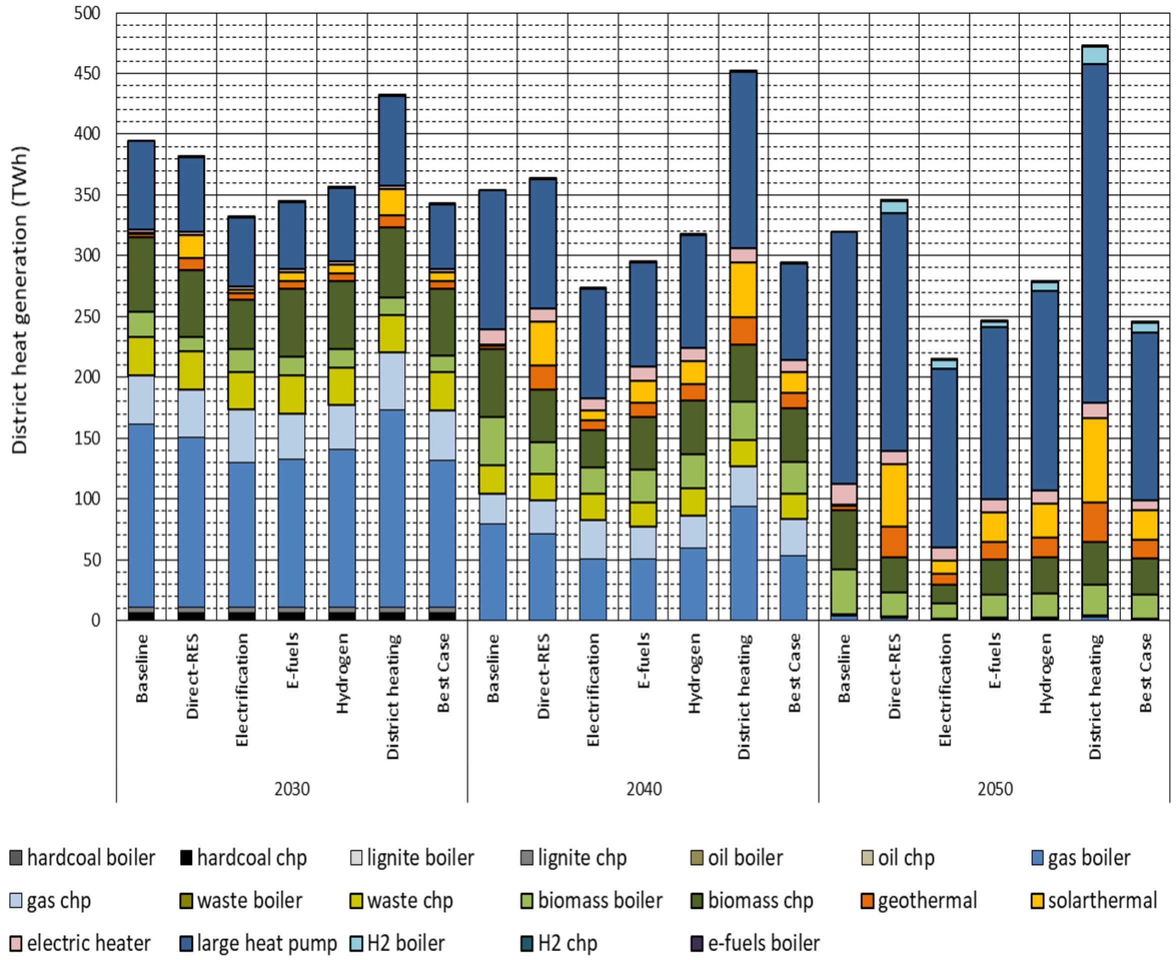


Figure 10: Scenario comparison of DH supply mix in different scenarios by 2050, EU-27 (European Commission. Directorate General for Energy. et al., 2022)

Figure 11 shows the DH supply mix under 13 scenarios with different type and levels of electrification by 2050. Besides the Reference scenario, other scenario names in the x-axis refer to a type of electrification (direct electrification (Elec), Hydrogen (H2) and E-Fuels) and the share of the floor area supplied by that supply technology. Similar to Figure 10, it becomes clear that district heating demand and district heating supply mix differs between scenarios depending on scenario specification. In all decarbonization scenarios, heat pumps have the highest share in the district heating generation mix in 2050. Drivers and uncertainties are the limitation and availability biomass in the (district) heating sector, biomass price developments and H2 and e-fuels import prices.

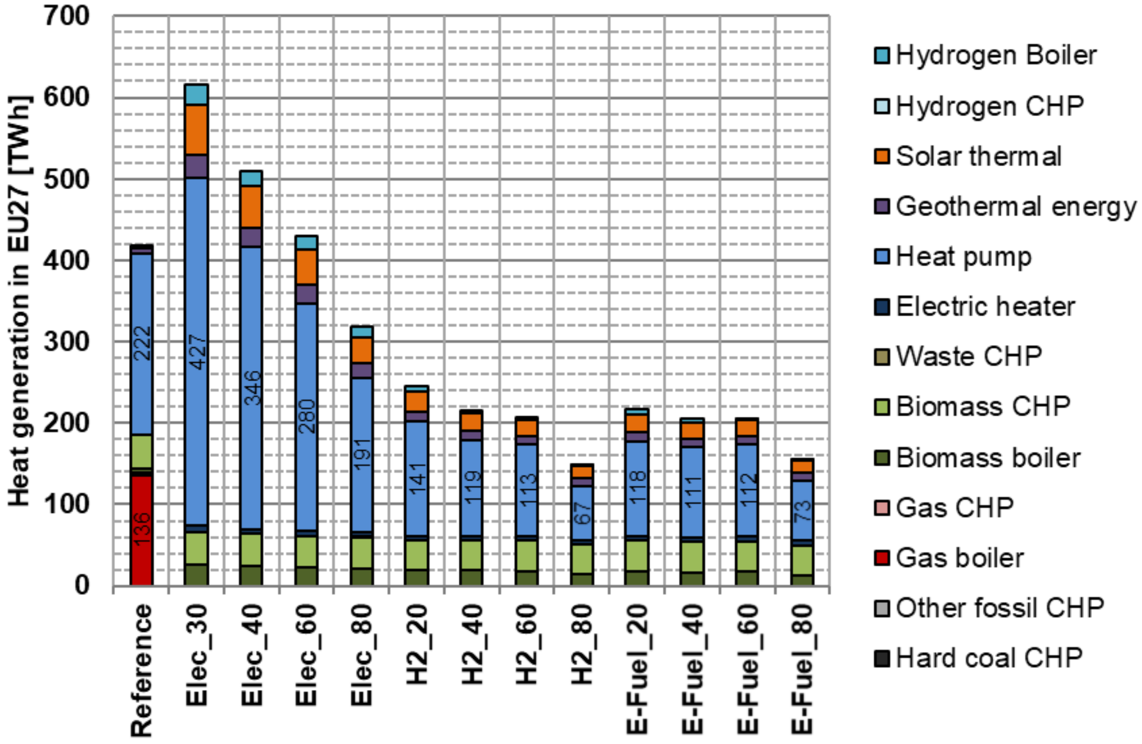


Figure 11: Scenario comparison of DH supply mix in different scenarios with different type and levels of electrification by 2050, EU-27 (Scenario names: direct electrification (Elec), Hydrogen (H2) and E-Fuels; and the share of the floor area supplied by their corresponding generation technologies) (ENER/C1/2019-481 – Potentials and levels for the electrification of space heating in buildings (preliminary results), 2023).

Policy-driven "decarbonization pathways" scenario vs. a baseline scenario, which does not meet climate targets, were developed in the project ENER/C1/2019-482 (see Figure 12). In the decarbonization scenario, heat pumps hold a share of more than 40%. Also, a significant share of geothermal is considered under this scenario (>30%). Main drivers and uncertainties are the potentials and costs for geothermal, solar thermal, potentials and costs of heat storage, potentials, and prices of biomass in the (district) heating sector and H2 and e-fuels import prices.

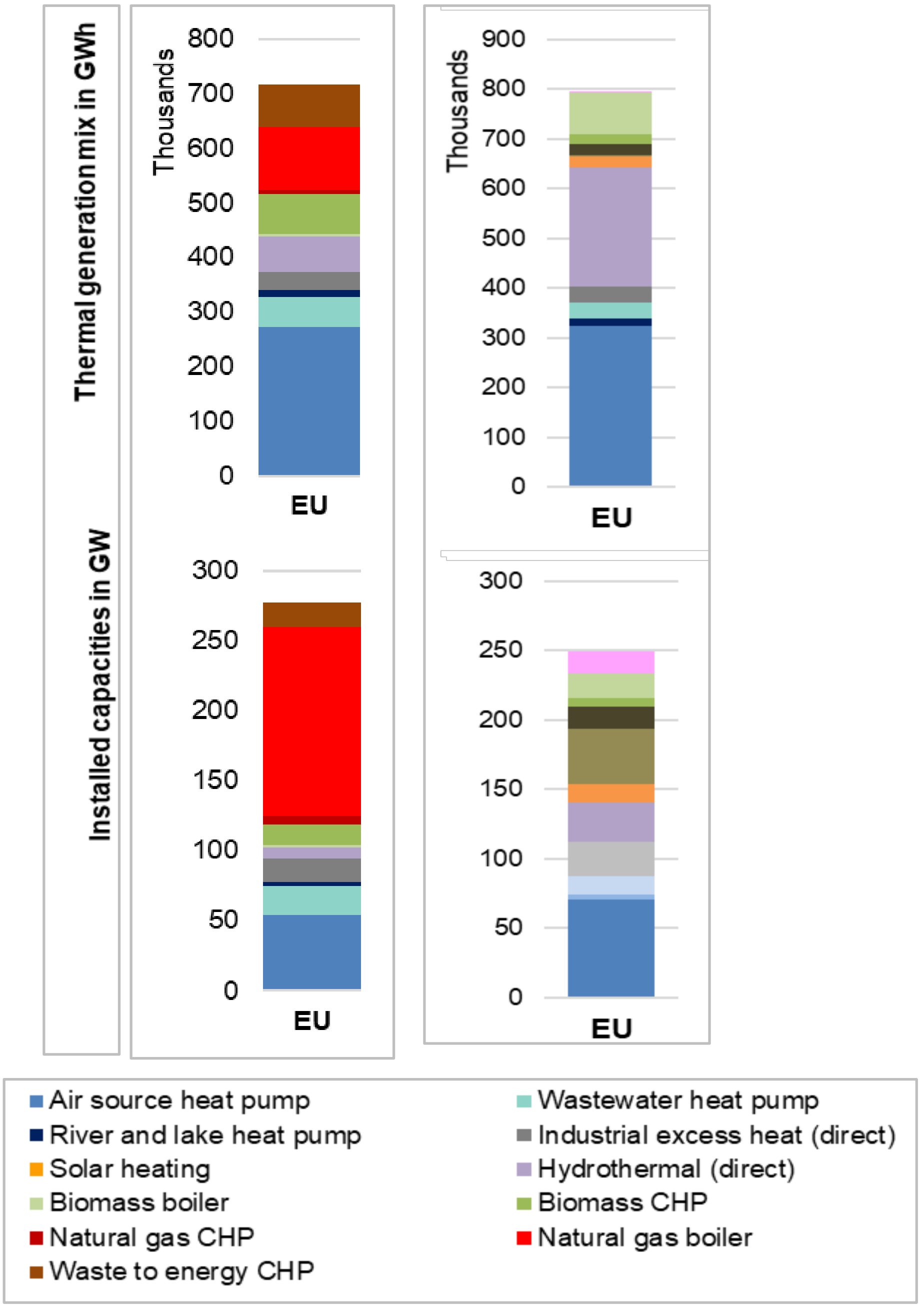


Figure 12: Scenario comparison of DH supply mix in a baseline scenario (left) and a decarbonisation scenario (right) by 2050, EU-27 (Braungardt, 2023)

So, we can draw following conclusions from these considerations:

1. The share of CHP in district heating generation in decarbonization scenarios 2050 is between 3-7%, with a certain share of it being biomass CHP, the remainder either biomethane, e-gas or H2

2. The share of HP in district heating generation in decarbonization scenarios 2050 is between 40% and 75%.

3. The role of H2 and renewable gases is mainly for peak load coverage and to a small share – and with low full load hours – for CHP.

Of course, one could argue that the insights and conclusions from these studies are driven by very specific assumptions of future gas and electricity prices. Therefore, it helps to depict the conditions under which the levelized costs of heat (LCOH) for CHP might be below the LCOH of heat pumps. Under standard technology assumptions of a gas CCGT and an air-source heat pump, assuming identical full load hours of both technologies and – a simplified annual/seasonal consideration, results as shown in Figure 13 can be derived. As expected, the gas CHP needs an electricity price above the gas price – even for very low seasonal coefficient of performance (SCOP) of the heat pumps – in order to result in lower LCOH as those of heat pumps. However, if in the long-run only gases can be considered which have been derived from renewable electricity, this condition (i.e., that electricity price > gas price) cannot be fulfilled in a durable and large-scale way.

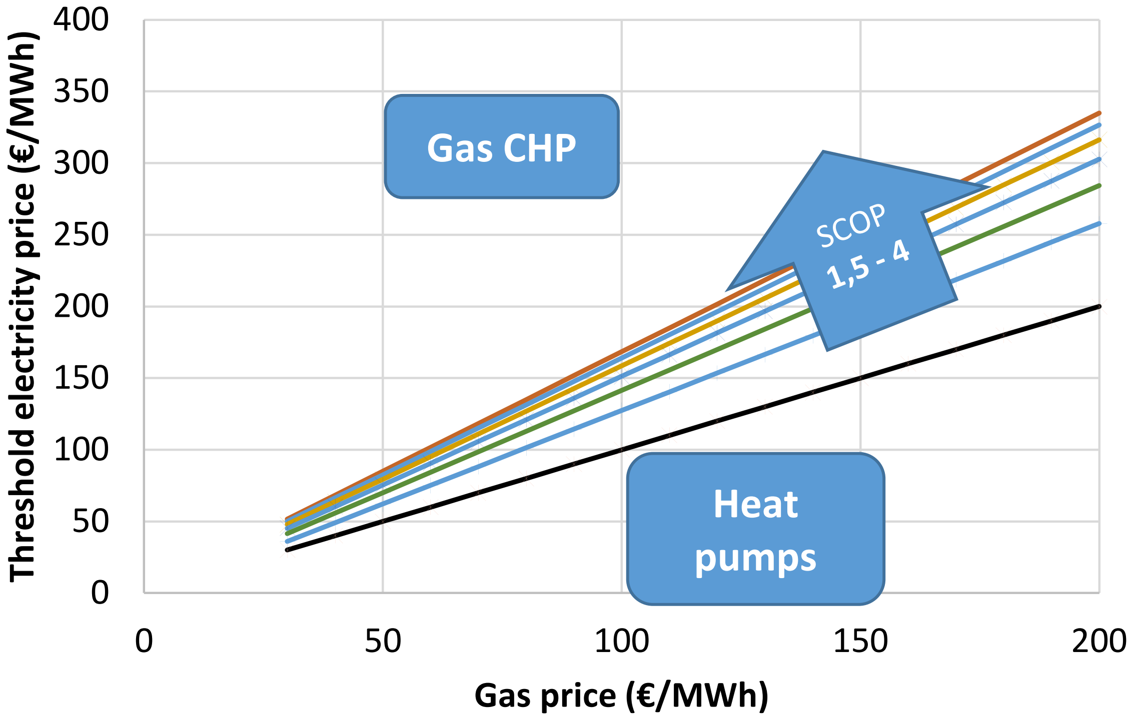


Figure 13: Threshold electricity price for different gas prices and SCOP for ensuring economic viability of gas fired CHP.

Limitations for these considerations mainly refer to following aspects:

1. Is H2 as energy storage so much more effective than thermal storage? The modelling results shown above indicate that this is not the case and that H2 might only be relevant for covering peak loads.

2. H2 and e-fuel imports might change the picture if import prices are considerably lower than the generation costs in Europe and if substantial quantities can be imported under these low prices. Considering the insights that have been gained recently with respect to dependencies from low-diversified energy imports, new geopolitical dependencies in particular from regions with non-democratic governments should be discussed very carefully, also considering the target of building a resilient energy system.

3. There are also renewable gases, which do not rely on electricity, such as biomethane. Indeed, they could play a role for peak load coverage in DH supply. However, the literature in general does not indicate very high quantities of these potentials at sufficiently low supply costs to allow large scale employment for heat supply with large full load hours (Ruiz et al., 2019).

Overall, current studies, scenarios and model results show that CHP is part of a cost-effective solution only as biomass CHP and to a limited extent in a decarbonized energy system for district heat supply. All scenarios point to a substantial increase in the relevance of heat pumps.

The question, whether CHP plants based on renewable gases are needed to ensure decarbonized district heating generation, based on our analyses can be answered with “no.” Depending on the size of thermal storage or generation mix, H2 boilers for peak load coverage may be reasonable.

The question whether gas CHP plants are needed to ensure decarbonized electricity generation based on the studies mentioned in this section also can be answered with “no,” at least not for the case of sufficient expansion of electricity grids, storage, and demand response activation. At least CHP will not play a role with high full load hours.

Uncertainties regarding the relevance of large-scale heat pumps lie less in potential competition with CHP, but rather in the following issues:

- Costs and potentials of other heat sources such as geothermal, waste heat, solar
- Availability, prices, political framework for biomass use in the energy sector
- Development, costs, and barriers of different large-scale heat storage systems
- Lowering of system temperatures in DH grids
- Stringency in the implementation of climate targets

Many of these questions will be discussed in follow-up sections.

8 NATIONAL SCALE ASSESSMENTS FOR AUSTRIA AND DENMARK

Authors: Peter Sorknæs (Aalborg University)

In this section, some of the most prominent energy conversion technologies that allow for Hybrid Energy Network are analysed further using different national energy system scenarios to identify their role in different national energy systems, using the example of Austria and Denmark. First the national scenarios used are described alongside the energy system tool utilised. Then the application of Hybrid Energy Network technologies is analysed. Lastly the findings of these national analyses are presented. This section is supplemented by Appendix G, where detailed results and discussions can be found.

8.1 ENERGY SYSTEM ANALYSIS TOOL

EnergyPLAN is a holistic energy system analysis tool developed for the simulation of hourly energy flows across all energy sectors, namely electricity, heating, cooling, industry, and transport. EnergyPLAN is primarily designed for the simulation of national and regional energy systems and has been used for a wide range of different energy system analyses in research. EnergyPLAN is developed around the concept of Smart Energy Systems, where all energy demands are included in the energy system alongside possible coupling points between the energy sectors. As such it is also useable for Hybrid Energy Network analyses that have a similar focus on flexibility and interconnections between different energy networks. (Lund et al., 2021b), see also section 12.

An overview of the energy demands, energy conversion units, energy storages and energy sources used in EnergyPLAN can be seen in Figure 14.

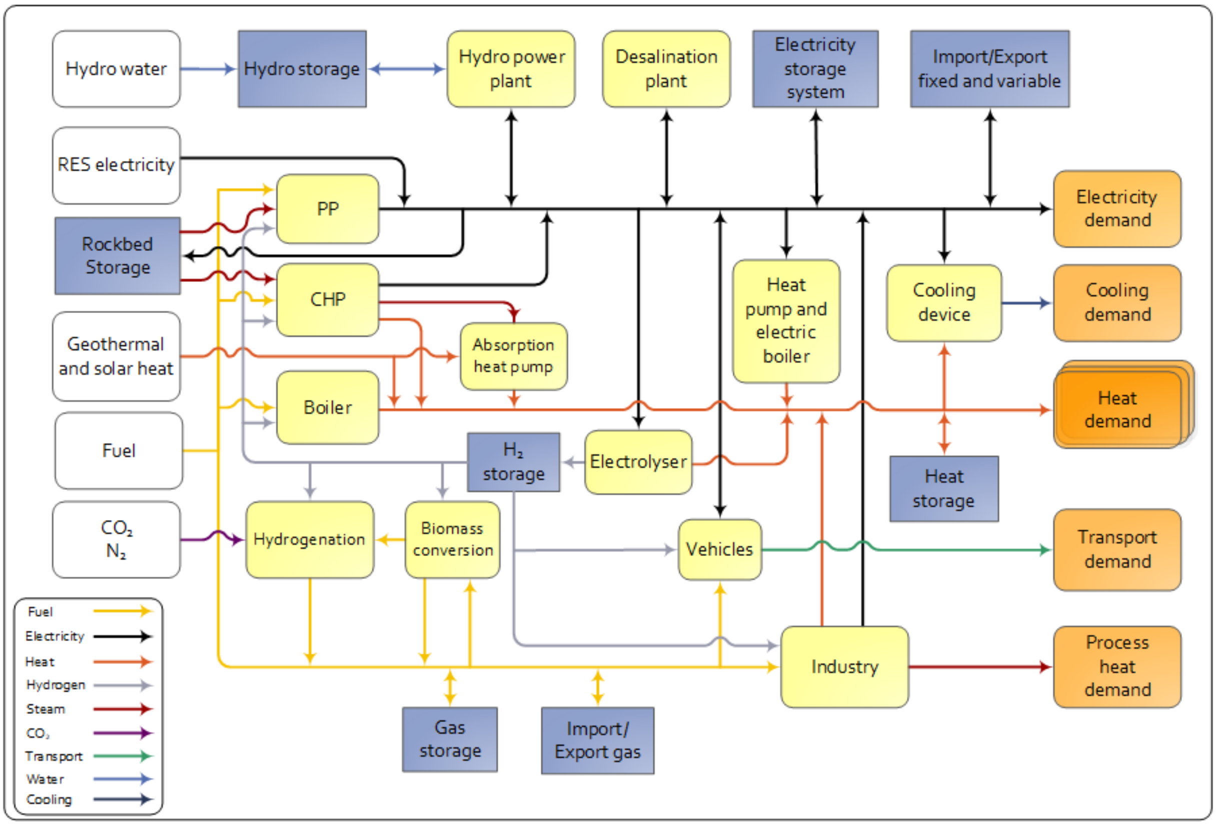


Figure 14: Overview of technologies and cross-sector integration in EnergyPLAN v16 (Lund et al., 2021b)

EnergyPLAN simulates the operation of each type of technology shown in Figure 14 based on different simulation strategies that can be chosen by the user. The simulation includes the possibility to utilise flexibility using energy storages and coupling points between different energy sectors. Different simulation options exist in EnergyPLAN; in this report, all results are based on a simulation approach that aims at reducing the fuel consumption of the entire energy system. (Lund et al., 2021b)

8.2 SCENARIOS

To understand how different Hybrid Energy Network technologies affect different national energy system scenarios, scenarios with different utilisation of RES were investigated. Some national energy systems will be highly reliant on variable RES in their energy supply, while others will have a larger share of dispatchable RES technologies, such as biomass-fired technologies and dammed hydropower. Such systems could act as hypothetical energy system scenarios; however, as different conditions, such as temperature and solar potential, also affect other parts of the energy system, such as energy demand, it has been chosen to highlight these differences by utilising existing energy system scenarios for two different countries where these differences are predominant. Likewise, as the focus is on Hybrid Energy

Network technologies and their utilisation in connection with DHC networks, the investigations are based on countries where DHC already exist, and potentials for expansion are identified and evaluated. The countries investigated are Austria and Denmark.

Both countries have existing DH systems; however, the DH market share in Austria is around 28%, compared to around 58% in Denmark (Persson et al., 2019). Previous studies have found that both countries have the potential to increase their DH market share while reducing energy system costs and fuel consumption, also when considering the potential for energy savings in buildings. For Austria the optimum DH market share has been found to be around 45-54% (Paardekooper et al., 2018a); for Denmark, it has been found to be around 63-70% (Vad Mathiesen et al., 2021). The two countries also have very different options for the integration of non-fuel-based RES into the electricity system. Austria has existing hydro power facilities with the potential to expand this capacity, and likewise have potential for geothermal generated electricity, onshore wind power and PV (Paardekooper et al., 2018a). Denmark has no significant potential for hydro power or geothermal electricity, instead mostly having a potential for offshore wind power, onshore wind power, and PV (Lund et al., 2021c). As a consequence, it is expected that the future Danish energy system will rely on electricity supply from variable RES to a larger extent than the future Austrian energy system.

Instead of developing new energy system scenarios, existing energy system scenarios are investigated for Austria and Denmark. Three different scenarios are used for each country, namely: a reference model for 2015, a low DH market share scenario for 2050, and a high DH market share scenario for 2050. Both 2050 scenarios are energy systems relying primarily on RES.

To emphasize the effects of different changes in the scenarios on the energy systems and their operation, it was decided to remove all electric interconnections to other countries from the scenarios. This was possible for all Austrian scenarios. However, all Danish scenarios originally included transmission capacities to surrounding countries. Therefore, the transmission capacity was removed from the Danish energy system scenarios, and instead additional power plant capacity was installed to allow the model to balance the electricity system. The details of this are described in Section 8.2.2.

All the chosen scenarios have been developed in EnergyPLAN v16 (see also section 12). The scenarios and any adjustments made are described in the following.

8.2.1 SCENARIOS FOR AUSTRIA

For Austria, scenarios from the study “Heat Roadmap Europe 4” (Paardekooper et al., 2018b) are used, where the 2050 HRE scenario represents the high DH market share with a DH market share of approx. 50%. The “Heat Roadmap Europe 4” also includes a 2015 model for Austria which will be used as the 2015 reference scenario. The technical setup of the Austrian

EnergyPLAN HRE and 2015 scenarios remain mostly unchanged. However, in this study the HRE scenario is changed so that the DH fuel boiler capacity is increased to be able to cover 120% of peak DH demand, as to allow for it to work as backup and peak load capacity, and DH grid losses changed from 15% to 10%, a value that was found to be more plausible for this DH level in the analyses in the Heat Roadmap Europe 4 study (Paardekooper et al., 2018b). The HRE scenario is used as a base for making an Austrian low DH market share scenario for 2050, where the DH market share is decreased from 50% to 42% while maintaining the same total heat demand. Therefore, the heat demand supplied by individual heating solutions are increased by the reduced DH heat demand (excl. DH grid losses), keeping the same share of different individual heating solutions of the total individual heating demand. The DH production units and storages have also been adjusted to fit this new DH demand. The details for this can be found in appendix G.

8.2.2 SCENARIOS FOR DENMARK

For Denmark, the IDA2045 scenario from the study “IDA’s Climate Response 2045” (Lund et al., 2021c), where a climate neutral Danish energy system based on 100% RES is proposed, is used as the high DH market share scenario for 2050, alongside the 2015 energy system model described by Sorknæs, et al. (Sorknæs et al., 2019). The IDA2045 scenario has been made based on the possibility to hourly import and export electricity, but with a yearly net exchange of zero. However, as it has been chosen to remove all possibilities for import and export of electricity to highlight the energy system effects, the IDA2045 model used here has been adjusted.

First the electricity transmission capacities to other energy systems have been removed. The power plant capacity has instead been increased to ensure that all electricity demands can be met in the system. Then the yearly Critical Excess Electricity Production (CEEP)[19] and gas exchange have been kept equal to the values in the original IDA2045 model by adjusting the gaseous electrofuels production, electrolysis capacity, H_2 storage capacity and the power production from offshore wind and PV. Ensuring the same CEEP and gas exchange ensures that the energy production in the two scenarios is comparable, so that there is a comparable correlation between the installed amount of variable RES and the consumption of energy. P2G, or gaseous electrofuels production by CO_2 methanation of recycled CO_2 emissions (CCU), is chosen as the main gas producing technology as it allows the production of renewable gas without the need for biomass in the process, and the biomass consumption in the IDA2045

[19] Critical Excess Electricity Production (CEEP) is electricity produced that cannot be utilized in the energy system, where in a real-world situation this production would either be exported or result in reduced production from variable RES units.

scenario is already at the expected sustainable limit. The electrolysis and H_2 storage capacities have been adjusted so that they maintain the same relation to the total H_2 demand, as this changes with the change in P2G production. The PV and offshore wind power are changed based on their relative capacities compared with each other. Different electrofuels are used for meeting the transport demand in the scenario, however these were not adjusted in the iterations. The IDA2045 scenario has been adjusted with the following:

- Gas and CEEP balance result in increased gas production via CO_2 methanation of 11.65 TWh/year. The maximum capacity of CO_2 for P2G production is changed from 400 to 1,048 tons CO_2/hour to accommodate the increased production. The additional demand for electrolytic H_2 means that the electrolysis capacity is increased from 4,800 MW to 8,091 MW and the H_2 storage is increased from 320 GWh to 539 GWh. The extra electricity demand means that the PV is up from 10,000 MW to 11,873 MW and offshore wind power is up from 14,075 MW to 16,711 MW.
- To ensure sufficient electricity production capacity in the energy system the power plant capacity is upped from 3.1 GW to 10.8 GW. The extra power plant capacity is set as 50% simple cycle gas turbine and 50% combined cycle gas turbine.

The IDA2045 scenario has a DH market share of 66% of the total heating demand. IDA2045 is used as a base for making a Danish low DH market share scenario in 2050, where the DH market share is decreased to 50% while maintaining the same total heat demand, and therefore the heat demand supplied by individual heating solutions is increased by the reduced DH heat demand (excl. DH grid losses), keeping the same share of different individual heating solutions of the total individual heating demand. The DH production units and storages have also been adjusted to fit this new DH demand. The details for this can be found in appendix G.

8.2.3 COMPARISON OF THE SCENARIOS

This section shows the comparison of the different energy system scenarios for Austria and Denmark. Figure 15 shows the primary energy supply of the entire energy system.

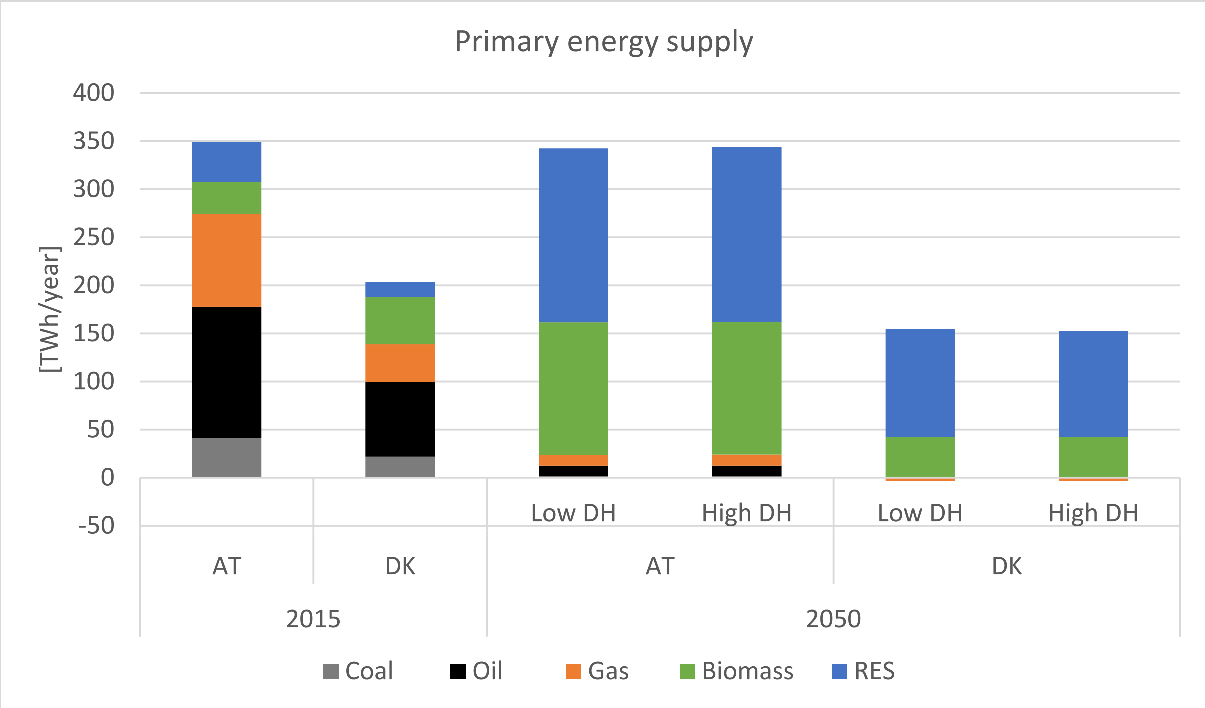


Figure 15: Primary energy supply of the entire energy system of each scenario modelled in EnergyPLAN

Figure 15 shows that the primary energy supply in the Austrian energy system scenarios is larger than in the corresponding Danish energy system scenarios. This is because the end-user demands in the Austrian energy system are larger. It is also clear that the primary energy supply is similar for the low DH and high DH scenarios, with a difference of 1.3 TWh/year in the Austrian scenarios and 1.6 TWh/year in the Danish scenarios.

The Austrian scenarios are built around a relatively large consumption of biomass, especially used for CHP and power plants. The Heat Roadmap Europe 4 scenario for Austria is not developed based on a limit to what could be a sustainable amount of biomass consumption, and as such, this scenario also represents a high biomass consuming scenario.

The Danish energy system scenario considers that the Danish energy system is only allowed to utilise what is assessed to be a sustainable amount of biomass. As Denmark has a relative high potential for biogas, due to a large agriculture sector, an export of biogas to the rest of Europe of about 3.5 TWh/year is also part of the model, which is why a gas export can be seen in Figure 15.

For the 2050 Austrian scenarios the RES category consists of about 45% onshore wind power, 27% PV, 26% hydro power, 2% geothermal and less than 1% solar thermal. For Denmark the same category in 2050 consists of about 68% offshore wind power, 15% onshore wind power, 13% PV, 4% solar thermal, and less than 1% wave power. Geothermal heat and low-temperature heat utilised via HPs are not included in primary energy supply.

Figure 16 shows the electricity supply in the different scenarios. It is visible from the figure that future energy system scenarios have significantly more electricity production than in 2015, due to increased direct electrification and PtX solutions for hard to abate sectors. It is also clear from the figure that the electricity production in Denmark is expected to be mainly provided by wind power, where the electricity production in Austria is more varied. Wind power and PV provide 53% of the electricity production in the 2050 Austrian scenarios and 90% in the 2050 Danish scenarios. It can also be seen that the scenario for Austria is much more reliant on electricity production from thermal plants, which are mainly based on biomass and green gases.

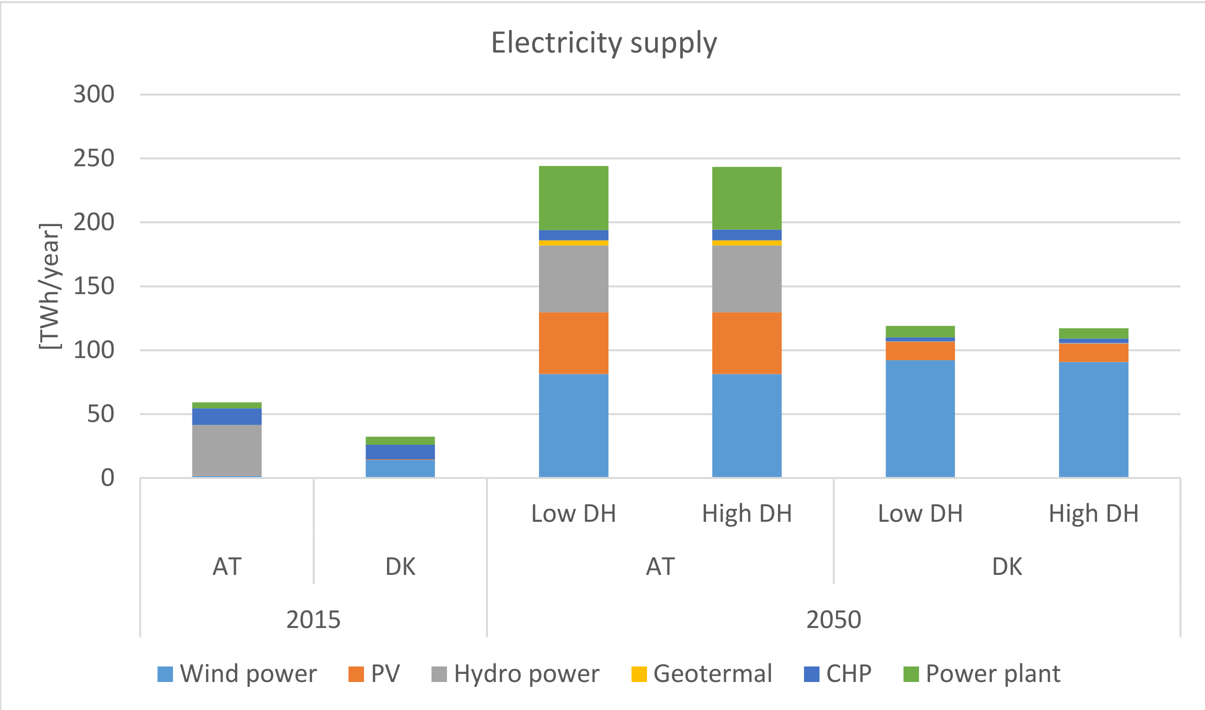


Figure 16: Electricity supply of each scenario modelled in EnergyPLAN

Figure 17 shows the DH supply for each of the scenarios. The figure shows a clear trend that the excess heat and geothermal are among the main sources of DH in the future energy system scenarios, where especially in Denmark these sources are expected to be dominant in the DH supply. The category heat pumps represent HPs that utilise ambient heat sources, such as air and rivers, as the low temperature heat source, and as such, do not include HPs used for being able to utilise excess heat or geothermal heat. HPs utilising ambient heat sources also see a significant, large utilisation in the 2050 scenarios compared with the 2015 scenarios, especially in the Danish energy system scenario. CHP has traditionally been the main supplier of DH in both countries, however, in the Danish future energy system scenarios this amount is reduced from around 58% of the supply to only 7-8%, where in the future Austrian scenario the reduction is only from 69% to 32-36% due to the higher utilisation of thermal plants based on biomass.

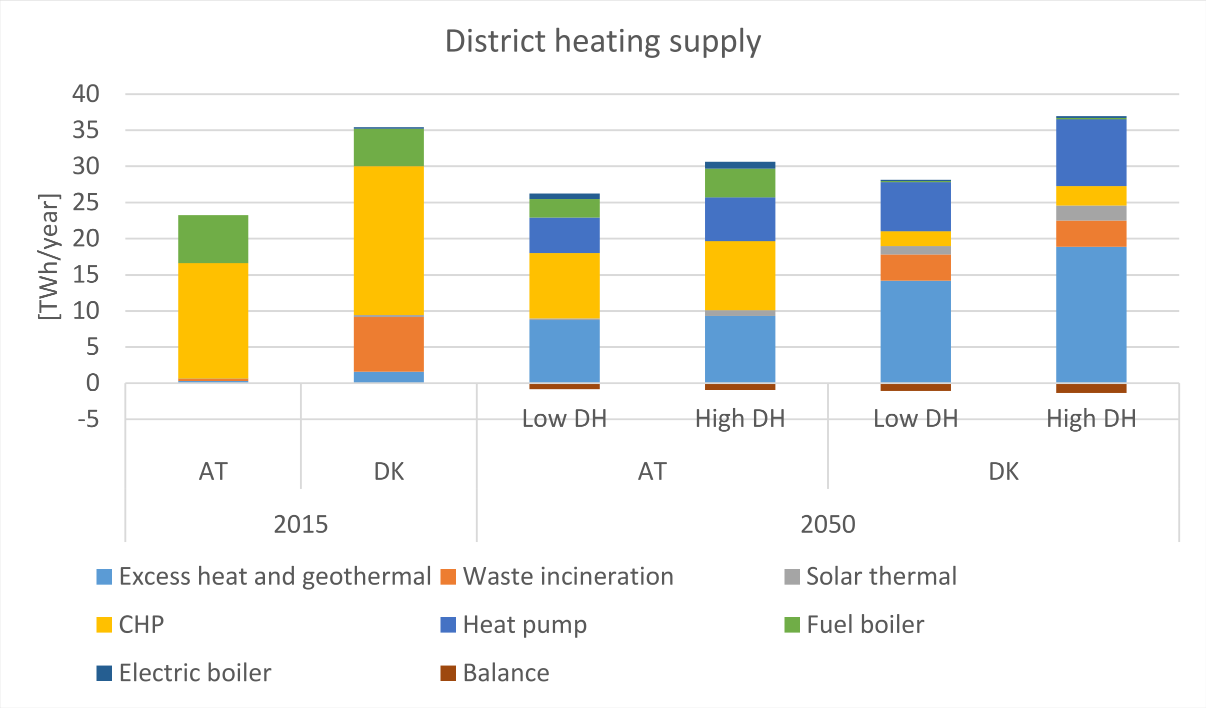


Figure 17: District heating supply of each scenario modelled in EnergyPLAN

8.3 APPLIED COMBINATIONS OF HYBRID ENERGY NETWORK TECHNOLOGIES

Here the different scenarios for Hybrid Energy Network technologies are described. The choice of scenarios is based on the general description earlier in this document and the technologies utilised in the national energy system scenarios. The changes are categorised in the following categories:

1. Direct electrification of DH
2. Thermal plant technologies
3. Excess heat from electrofuel production (incl. electrolysis)

The details of the different changes are described in separate sections. For all the Hybrid Energy Network scenarios the energy balance of the energy scenarios is maintained. For electricity this will be done by adjusting the marginal variable RES technology based on the change in CEEP identified in the EnergyPLAN simulations. Therefore, if a change in technology results in lower CEEP, then the capacity of the marginal variable RES capacity is increased until the yearly CEEP value is kept unchanged, and vice versa with a higher CEEP. For Austria it is assumed that the marginal variable RES technology is PV, and for Denmark it is assumed to be offshore wind power, as the technical potential for offshore wind power capacity in Danish waters could be up to 40 GW (Danish Energy Agency, 2019). Table 1 shows the capacities of the marginal variable RES technology and starting CEEP value in each scenario.

Table 1: Marginal variable RES capacity and CEEP in the different scenarios. For AT scenarios the marginal is PV and for DK scenarios it is offshore wind power.

Scenario	Marginal variable RES capacity [MW]	CEEP [TWh/year]
AT2015	103	0.0
AT-Low DH	47,000	7.4
AT-High DH	47,000	7.4
DK2015	1,271	0.0
DK-Low DH	17,004	7.2
DK-High DH	16,711	7.2

Besides adjustments to the respective marginal RES technology, thermal power plants will be introduced to ensure that the electricity demand can be fulfilled at all hours of the year if the electricity system needs more dispatchable power capacity to maintain electricity system balancing.

Besides the electricity system, balancing efforts are also made with respect to the gas system, which will be balanced so that the yearly net import of gas will be unchanged compared to the starting version of the scenario. If the gas consumption needs to be increased, then the default technology for balancing is biomass gasification. Biomass gasification has shown to be the potentially cheapest method for producing renewable gases except for biogas, which is limited by the agriculture sector (Korberg et al., 2021, 2020; Sorknæs et al., 2020), though it does increase the need for biomass consumption of the energy system. The biomass gasification is assumed to have a conversion efficiency of 80% and electricity consumption of 1.1% of the biomass input. For simplicity it is assumed that biomass gasification does not provide excess heat for DH. As there is uncertainty in relation to what the prevailing renewable gas technology will be going forward, and whether using biomass gasification is compatible with a sustainable consumption of biomass, for some results another gas producing option will be included to show the effects of choice of marginal gas producing units. This alternative gas production is by using PtG for production of gas to the grid via CO_2 methanation, where the gas produced does not directly consume biomass, but instead is reliant on H_2 from electrolysis and CO_2 capture and results in larger electricity demands and total energy system costs. When this option is used, the electrolysis and H_2 storage capacity will also be adjusted so that the capacity is kept constant relative to the need for H_2.

If the gas consumption instead is reduced by a change to the scenario, then for the AT scenarios this will be discussed, as there is no significant gas producing technology in the scenario. For the DK scenarios there is already CO_2 methanation due to the method used for creating a closed energy system model, as described in Section 8.2.2. Therefore, if a change results in reduced gas consumption, then the gas production from CO_2 methanation will be reduced until the same gas balance is found.

8.3.1 DIRECT ELECTRIFICATION OF DISTRICT HEATING

Direct electrification of DH is understood as utilising Hybrid Energy Network technologies that use electricity for the sole purpose of producing DH. As described, there are two types of technologies that can be used for this purpose, electrically driven HPs, and electric boilers. Though more DH production can be achieved via HPs compared to electric boilers, HPs have significantly higher investment costs, meaning that there is a trade-off for the more energy efficient conversion of electricity to heat. For this reason, it is relevant to investigate the effect of HPs and electric boilers in the DH system in the different national energy system scenarios. The following tests are performed:

- Varying levels of electric boiler capacity in DH
- Varying levels of HP capacity in DH
- Replacing HP and electric boiler capacity in DH

The HP and electric boiler capacities vary greatly from scenario to scenario. To make the results easier to compare, the ranges investigated are set to 0-200% of the existing capacities in the 2050 high DH market share scenarios for each country. The DH HP has in the 2015 scenarios a COP of 3 for both countries, and in the 2050 scenarios the COP for Austria is 4, and 3.9 for Denmark[20]. Table 2 shows the capacities of the DH-based electric boilers and HPs in each of the six national scenarios.

Table 2: Electric boiler and HP in DH capacity in the different scenarios.

Scenario	Electric boiler [MW_e]	HP [MW_e]
AT2015	0	0.7
AT-Low DH	1,027	1,027
AT-High DH	1,200	1,200
DK2015	522	3.8
DK-Low DH	1,142	1,781
DK-High DH	1,500	2,300

[20] The difference in COP is related to differences in heat sources utilized and expectations on lower DH grid temperatures in 2050.

8.3.2 THERMAL PLANT TECHNOLOGIES

Though the yearly production of electricity is expected to be reduced from thermal plants, such as CHP, the need for capacity will likely still be important for the energy system for periods where other sources are not sufficient as discussed in section 6. It is therefore relevant to identify what type of thermal plants bring most benefits to the energy system. This is both the question of whether CHP is relevant for a future energy system, where its yearly production is expected to be relatively low, but also with respect to what type of RES-fuel-based thermal plants could be relevant. Here the question is related to solid biomass, but also to renewable gaseous fuels, such as biogas and gaseous electrofuels. Consequently, the following variations for thermal plants are investigated:

- Change all existing large-scale CHP to combined cycle gas turbines (CCGT)
- Change all existing large-scale CHP to simple cycle gas turbines (SCGT)
- Change all existing large-scale CHP to solid biomass CHP plants (SB-CHP)
- No large-scale CHP, change existing to only gas-fired power plants

The installation of the new technologies is done so that the electric condensing capacity remains unchanged. The assumptions used for each of the technologies are shown in Table 3. It is assumed that there is no cost difference between the CHP and power plant implementation of each technology. The efficiencies are based on lower heating value for the input fuel and includes the possibilities for flue gas condensation.

Table 3: Overview of input parameters for the three different types of large-scale thermal plants

	Conden-sing eff.	CHP electric eff.	CHP heat eff.	Investment [M EUR/MW-e]	Yearly fixed OM [% of inv.]	Lifetime [Years]
CCGT	63.0%	60%	27%	0.80	3.25	25
SB-CHP	44.8%	35%	67%	1.90	2.58	25
SCGT	45.0%	45%	45%	0.52	3.46	25

8.3.3 EXCESS HEAT FROM ELECTROFUEL PRODUCTION

It is expected that large parts of the future energy system can transition to RES via electrification and solid biomass sources, though it is also expected that there will still be sectors where gaseous and liquid fuels are needed, though the exact extent of this need is not yet known. Parts of this demand can be met by non-electricity intensive sources, such as biogas, though if the biomass consumption for energy should be kept at sustainable levels it is expected that a share of these fuel demands should come from electrofuel production, where electricity is used to produce H_2 via electrolysis (see also section 9) and combined with a carbon or nitrogen source to create a gaseous or liquid fuel. These electrofuels are especially expected to be needed for long-haul trucks, international shipping, and international aviation, but also to a minor extent in other sectors, such as for use in thermal plants for peak load power production. The production of these fuels will have conversion losses that could be utilised for DH, though the potential for this both depends on the used technologies and the placement of these technologies. If they will largely be in rural areas, far from areas with potential for DH, then the potential DH utilisation will be greatly reduced.

The energy system effects of utilising the excess heat from these processes for DH are investigated. This is done simply by testing three different utilisation rates of the existing excess heat potential in the scenarios, namely 0%, 50% and 100%. As no electrofuel production exists in the 2015 scenarios, these analyses are only performed for the 2050 scenarios. In the 2050 scenarios for Austria the total utilised excess heat from electrofuel processes incl. electrolysis is 6.6 TWh/year and in the 2050 scenarios for Denmark the total utilised excess heat from these is 2.9 TWh/year. As the widespread implementation of hydrogen production with electrolysis is still in the ramp-up phase, the expectations of installed capacities are subject to high uncertainties. Therefore, these figures differ from the calculated waste heat potentials from electrolysis processes in section 9.3.2.

To address the issue of the technology choice effects, it has been chosen to investigate the effect of different types of electrolysis and their effect on the energy system. Generally, three types of electrolysis exist, namely Alkaline (AEC), Polymer electrolyte membrane (PEM) and Solid Oxide Electrolysis Cell (SOEC), see also section 9.2.2. These technologies have different efficiencies for conversion of electricity to H_2, but also different operating temperatures, meaning that they also have different potential for excess heat that could be utilised for DH. The energy system effects of utilising these are tested by completely changing the existing electrolysis capacities to each of these technologies. It is assumed that a variation of these technologies will be utilised in the future energy system, based on time of installation, etc.

The used data are shown in Table 4. The efficiencies used include losses in system connected to the electrolysis, such as losses related to compression of hydrogen, and are based on lower heating value. It should, however, be noted that there are uncertainties related to these numbers. For example, the electric efficiencies for AEC and PEM are quite close in the table, and some sources state AEC as potentially being more efficient than PEM (International Energy Agency, 2019), while others state PEM as potentially more efficient (Mathiesen et al., 2013). This uncertainty will be considered in the summary of the results and is also reflected in different assumptions for the calculation conducted in section 9.3.2.

Table 4: Technical and cost assumptions for different types of electrolysis in Denmark in 2050

Type	Electric efficiency (based on lower heating value)	Excess heat potential	Investment cost [M EUR/MW-e]	Technical lifetime [years]	Yearly fixed O&M [% of investment]
AEC	65%	8%	0.4	30	5
PEM	68%	10%	0.45	20	5
SOEC	75%	5%	0.5	20	3

The starting point for all the 2050 scenarios is that they utilise SOEC electrolysis.

8.4 RESULTS

Here the main findings from the national energy system analyses are summarised. Details are given in appendix G.

8.4.1 DIRECT ELECTRIFICATION OF DISTRICT HEATING

The national energy system analyses seem to show that electric boilers allow for a potentially larger installation of variable RES without creating increased levels of unusable electricity production. However, using electric boilers for transforming electricity to heat require significant more variable RES to produce the same amount of heat then this solution is both more expensive and less energy efficient than with HPs, thus HPs should be prioritised for the electrification of district heating. Electric boilers are chosen by the model only because the integration of variable RES into the DH system is limited by the total heat demand, so due to the relative lower efficiency of electric boilers more electricity is used to produce the same amount of heat when compared to HPs. However, this does not mean that large capacities of electric boilers provide an efficient use of the electricity generated from variable RES, as electric boilers have a low exergy efficiency.

Additionally, HPs have a larger potential to reduce the biomass consumption of the energy system compared to electric boilers. The reason being that HPs will be able to produce more heat than electric boilers with the same amount of electric energy, and this larger DH production will reduce the DH production from other units. Though again this potential is limited by DH demand, as the biomass consumption reduction only is seen as long as the HPs can replace biomass-based DH production units.

Looking at the total energy system costs, the costs of the energy system are mostly affected by the installed capacity of HPs, compared with the electric boilers. Due to the relative high investment costs of HPs the optimal installed level of HPs is especially dependent on the full load hours it can operate, as well as the production cost of the DH production units that it replaces. Therefore, the cost optimal capacity of HPs is dependent on available thermal storages as well as on what other DH production facilities are installed as well as the total DH demand of the energy system. For electric boilers, the effect on the costs is mostly related to the potential to integrate more variable renewables into the energy system, as more electric boilers do allow for increased levels of variable RES without increasing the amount of non-useable electricity production.

8.4.2 THERMAL POWER PLANT TECHNOLOGIES

For renewable-based energy systems, highly electrically efficient gas-fired thermal power plant technologies utilising renewable gases, such as biogas or synthetic gas from biomass gasification, provided the lowest costs, primary energy consumption, and biomass consumption for the energy system. This is regardless of whether the energy system is based on a large share of variable RES or dispatchable RES. In the national energy system analyses these highly electrically efficient thermal plants are represented by combined cycle gas turbines. Biomass-fired thermal plants showed the highest energy system costs due to their relatively low electric efficiency and relatively high investment costs.

Though the role of thermal plants will change to produce significantly less electricity, instead serving mostly as a backup for the renewables in the electricity system, utilising the excess heat from these still provides important energy system benefits, by reducing the energy system costs and primary energy consumption of the national energy system, as well as the demand for installation of variable RES.

8.4.3 EXCESS HEAT FROM ELECTROFUEL PRODUCTION

Utilising electricity as part of the production of gaseous and/or liquid fuels is expected to become increasingly relevant to allow utilisation of variable RES to produce fuels for hard-to-abate sectors, such as long-haul transport and international aviation. Such processes are expected to have excess heat potentials, and therefore can be relevant to consider in relation to DH systems (see section 9).

The national energy system analyses showed that utilising excess heat from electrofuel production provides lower costs, primary energy consumption, biomass consumption, and reduces the need for variable RES for the energy system as a whole.

Electrolysis is the most important part of converting electricity to fuels, as it allows to produce H_2 that can either be used directly, be injected in grids for utilisation elsewhere, or be used as part of production of more complex gaseous and liquid fuels. The results show that having a higher electric efficiency is more important from an energy system perspective than being able to utilize larger amounts of excess heat from the electrolysis.

8.5 MATRIX OF TECHNOLOGIES

The findings are summarized in Figure 18.

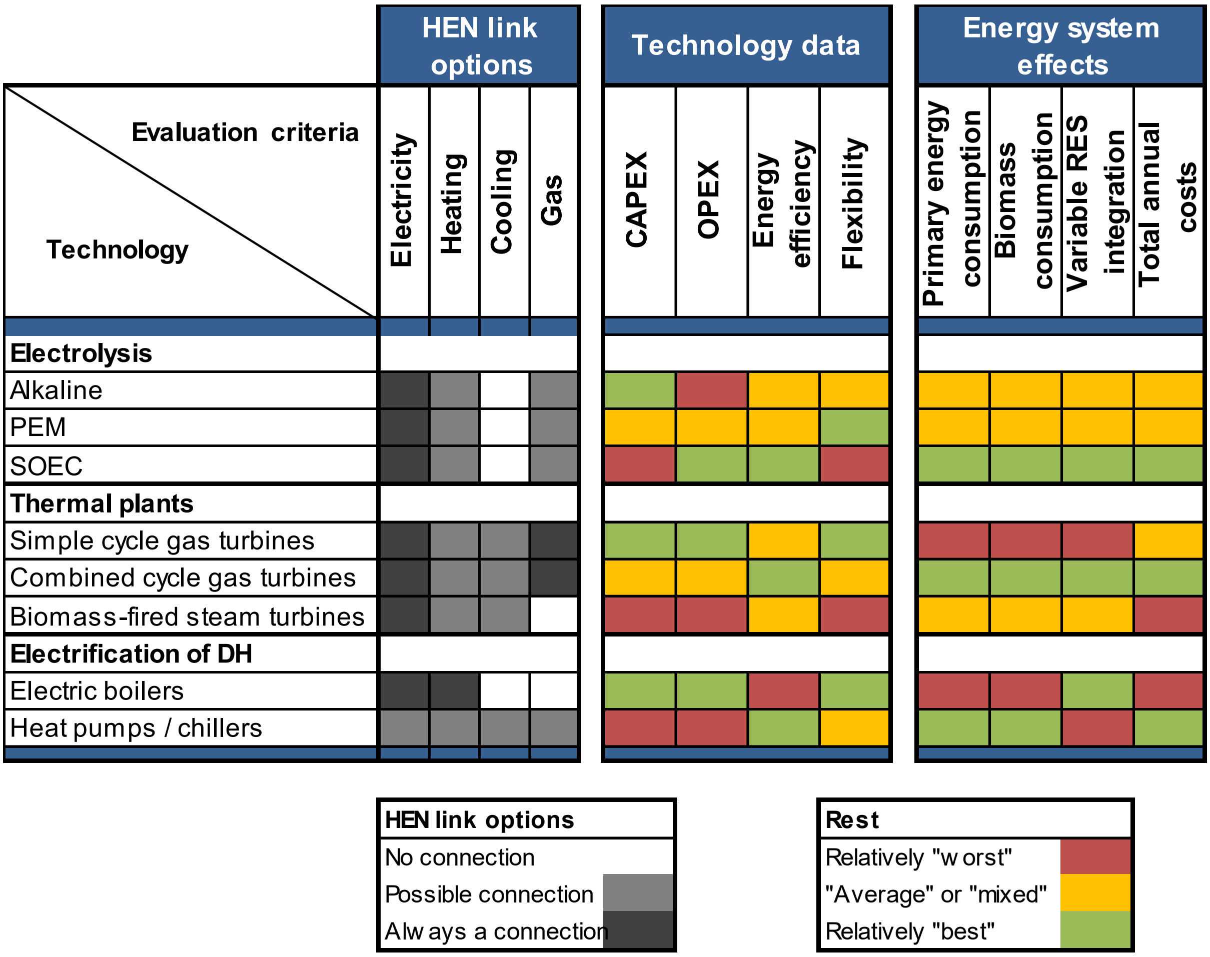


Figure 18: Matrix summarising the findings for the investigated Hybrid Energy Network (HEN) technologies. "HEN link options" are possible connections for each technology.

The technologies are ranked in three different categories:

- "**HEN link options**" shows possible connections to grids. Here a dark colour means that there is always a connection to this network, grey means that it is possible to have connections to this network (e.g., an absorption chiller connected to a CHP allows thermal plants to connect to district cooling networks), and white means that there is typically no direct link to this network.

- "**Technology data**" shows the ranking of technology data for the types of technologies. The scale is relative within each technology category and is based on the expected future performance of the technologies. Green means relatively "best" (e.g., green in CAPEX means lowest CAPEX and green in Energy efficiency means most efficient), yellow means that it is average for the category or that it is mixed depending on specifics of the technology, and red means relatively “worst”.

- “**Energy system effects**” summarise the findings of the national energy system analyses presented in this section. The same colour scale is used as for “Technology data”.

It is important to note that the ranking for the technologies does not always result in similar findings in the energy system effects. E.g., a technology on its own might have the lowest costs, but not the lowest total annual costs for the energy system, which can be due to other aspects, such as energy efficiency.

This is, e.g., the case for SOEC electrolysis, where energy efficiency was found to be the most important aspect in the national energy system analyses, and thereby this technology showed to provide lower total annual costs even though having the highest CAPEX. It should also be noted that for comparing Alkaline and PEM there are uncertainties related to which of these technologies will become more energy efficient, as the expected electric efficiencies are very close. Therefore, these technologies have been given the same categorization for energy efficiency and for the energy system effects, as it was found that electric efficiency is the most important metric for these technologies.

9 HYDROGEN AND DISTRICT HEATING

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As hydrogen and district heating are seen as two essential pillars of a sustainable and fully renewable future energy system, this section is discussing the technological synergy potentials of hydrogen-related technologies and district heating systems more in detail compared to section 3. Considering current state of the art and expected future developments, it is meant as a systemic overview presenting potential infrastructure-related or system-inherent barriers and opportunities.

9.1 RELEVANCE OF HYDROGEN

Hydrogen is expected to be considerably important in the transition to renewable energy systems, both, as renewable energy carrier and as feedstock material for renewable synthesis processes. Accordingly, various national governments have elaborated and announced appropriate intentions to integrate hydrogen and power-to-gas as part of their energy and climate strategies (IEA, 2021). Also, the European Union announced a hydrogen strategy in 2020 towards a climate-neutral Europe. The EU roadmap targets on implementing up to 40 GW electrolysis capacities within the EU borders by 2030, along with additional capacities of 40 GW in the Eastern and Southern neighbourhood dedicated for hydrogen imports to EU countries (European Commission, 2020a).

From a current perspective, the main applications of hydrogen are expected to be in the decarbonization of industrial processes, where it is rather to be applied as a substitute to present fossil feedstock materials for reduction and synthesis processes than as a dedicated energy carrier. Therefore, renewable hydrogen is not only considered to replace current fossil supply (e.g., for ammonia production) but overall industrial demand is also expected to increase by additional use – e.g., in the chemical industry to produce renewable hydrocarbons and fuels as well as metallurgical processes, such as steel production, as an emission-free reducing agent. Furthermore, hydrogen is expected to be of considerable relevance to provide long-term storage capabilities regarding excess production of renewable energy sources (RES), such as wind and PV. In the context of a decoupled supply and demand of renewable energy, the use of renewable gases is also expected to retain a certain importance in terms of flexible and controllable supply of power and heat. Consequently, it becomes clear that hydrogen, along with the corresponding production and conversion processes, will be of considerable relevance in our future energy systems and play a significant role in sector

[21] Most of the elaborated results have also been published in (Böhm et al., 2021) and (Reuter and Schmidt, 2022).

coupling and integration. Thus, its potential relevance regarding the development of todays and future district heating (DH) networks must not be neglected in this regard.

9.2 HYDROGEN TECHNOLOGIES

Regarding the integration with district heating, two hydrogen technologies are most relevant: fuel cells and electrolysis[22]. Their respective characteristics with certain relevance to the topic are thus discussed in the following.

9.2.1 FUEL CELLS

Fuel cells allow a direct conversion of chemical energy to electrical energy, in contrast to thermal engines, which usually have an intermediate conversion to mechanical energy and therefore added complexity and potential energetic losses. Thus, fuel cells can reach electric efficiencies of about 60% as of today, depending on cell type and mode of operation (cf. Table 5). Additionally, using low-carbon (methane, synthesis gas) or carbon-free (hydrogen) fuels, direct CO_2 emissions can be reduced or avoided in the conversion (Staffell et al., 2019).

The availability of various cell types allows for a broad range of potential applications of the technology. Besides mobile application in fuel cell electric vehicles (FCEV) of all types (passenger cars, trucks, busses, military and space crafts), fuel cells are mainly used in stationary applications for power technologies (Lindorfer et al., 2020). Stationary fuel cells are used as power sources for backup supply or decentralized plants not connected to the grid (Dodds et al., 2015). In this regard, combined cycle power plants, cogeneration, and residential generation are currently in a well-developed state (Choudhury et al., 2013).

Despite being incompatible for mobile applications by reason of their elevated temperature levels, solid oxide fuel cells (SOFC) are a promising technology for power generation due to high electric efficiencies of about 60%. Furthermore, the high operating temperatures of 600-1,000 °C allow for an appropriate utilization of waste heat (e.g. in current cogeneration systems) increasing overall efficiencies of CHP systems up to 90% (Radenahmad et al., 2020). In addition, SOFC technology provides high fuel flexibility and can be powered with H_2, CH_4, CO, hydrocarbons, and mixtures of those. Novel solid oxide cells also allow a reversible operation, thus either operating in electrolysis mode producing hydrogen from electricity or in fuel cell mode generating electric power from gaseous fuels.

[22] From all fuels, the resource exergy efficiency of converting hydrogen in boilers is one of the lowest. (North and Jentsch, 2021a). Therefore, the use of hydrogen in individual and district heating boilers should be only considered as an exception or to cover rare peak loads.

Besides SOFC, polymer electrolyte membrane fuel cells (PEMFC) are the most common fuel cell technology (by number of units shipped) (E4tech, n.d.). With typical capacities in kW range, they are dominant in residential micro-CHP systems providing high efficiency, durability, reliability, rapid start-up and shut-down, part-load capability and operating temperatures of around 80 °C. Despite slightly lower electric efficiencies, they offer higher flexibility due to shorter start-up times compared to SOFC-based systems and their operating temperatures allow an integration in individual buildings (Staffell et al., 2019).

Table 5: Comparison of key characteristics of fuel cell technologies. Based on (Coralli et al., 2019; E4tech, n.d.; Lindorfer et al., 2020)

Technology	**Polymer Electrolyte Membrane (PEMFC)**	**Solid Oxide (SOFC)**	**Phosphoric Acid (PAFC)**	**Molten Carbonate (MCFC)**	**Alkaline (AFC)**
Technology status	Commercial Stationary, portable and transport applications	Commercial Stationary and portable applications	Commercial Stationary applications	Pre-Commercial (R&D) Stationary applications	Pre-Commercial (R&D) Stationary applications
Electrolyte	Perfluorosulfonic acid	Yttria stabilized zirconia	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane
Operating temperature	< 120 °C	500–1,000 °C	150–200 °C	600–700 °C	< 100 °C
Typical stack size	< 1–100 kW	1 kW – 2 MW	5–400 kW	300 kW – 3 MW	1–100 kW
Electric efficiency (LHV)	60% direct H_2; 40% reformed fuel	60%	40%	50%	60%
Advantages	High load flexibility; Reduced corrosion and electrolyte management	CHP applicability; High efficiency; Fuel flexibility	CHP applicability; Tolerance to fuel impurities	CHP applicability; High efficiency; Fuel flexibility	Low component costs; Start-up time
Disadvantages	Expensive catalysts; Fuel sensitivity	High-temperature corrosion and breakdown; Start-up time and load flexibility	Expensive catalysts; Start-up time; Sulfur sensitivity	High-temperature corrosion and breakdown; Start-up time; Power density	Sensitivity to CO_2; Electrolyte management / conductivity

For larger scale stationary applications phosphoric acid (PAFC) and molten carbonate (MCFC) fuel cells are available technologies, however, their uptake in number of shipped units is rather limited over recent years (E4tech, n.d.). They are operated at temperatures levels of 150-

200 °C and 600-700 °C, respectively, and provide electric efficiencies of 40-50%, while their long start-up times only allow limited flexibility in operation (Lindorfer et al., 2020).

9.2.2 ELECTROLYSIS

From a current perspective, electrolysis of water is seen as the major technology to produce carbon-neutral hydrogen from RES at large scale in the foreseeable future. To supply the abovementioned demands, total electrolysis capacities in TW-range will be needed (Böhm et al., 2020) with individual system capacities at multi-MW or GW scale, depending on the actual centralization of renewable hydrogen production. In that context, these applications are expected to represent a relevant part of the energy system, which must not be left unconsidered in terms of sector coupling and integration. Therefore, their thermal integration in future energy systems is an obvious target, even though a corresponding heat integration is widely dependent on the given temperature levels and thus the underlying electrolysis technology and mode of operation. An overview of current state-of-the-art electrolysis technologies is summarized in Table 6.

Table 6: Key characteristics of state-of-the-art water electrolysis technologies (Böhm et al., 2021)

Technology	**Alkaline (AEL)**	**PEM electrolysis (PEMEL)**	**Solid Oxide (SOEL)**
Technology status	Commercial (mature) TRL 9	Commercial (mature) TRL 8-9	Pre-commercial (R&D) TRL 5-6
Electrolyte	Aqueous potassium hydroxide	Perfluorosulfonic acid	Y_2O_3–ZrO_2, Sc_2O_3–ZrO_2, MgO–ZrO_2, CaO–ZrO_2
Operating temperature	60–90 °C	50–80 °C	650–900 °C
Operating pressure	10–30 bar	20–50 bar	1–15 bar
Typical stack capacity	< 10 MW	< 5 MW	< 100 kW
Electric efficiency (LHV)	63–71%	60–68%	100%[a]
Load flexibility	20–100%	0–100%	-100% / +100%
Cold start-up time	1–2 h	5–10 min	Hours
Warm start-up time	1–5 min	< 10 s	15 min

[a] Operation at thermoneutral voltage

<u>Low-temperature electrolysis</u> describes technologies supplied by feeding liquid water and operating at temperatures usually below 100 °C. These include alkaline and proton-exchange-membrane (PEM) electrolysis, which represent today's most mature and commercially available technologies. Low-temperature electrolysers are operated above their thermoneutral voltage[23] to compensate high internal losses and overvoltage (Buttler and Spliethoff, 2018).

[23] Thermoneutral cell voltage describes the minimum voltage required for electrolysis in an ideal cell without heat integration.

Thus, the stack is generating waste heat during operation, which requires external cooling and could therefore be utilized. Due to the low temperature levels, options for waste-heat recovery are limited. Taking additional losses of heat transfer and transportation into account, spatially close applications and direct integration are considered to be the preferred paths.

In contrast to low-temperature electrolysis, steam or high-temperature cells can be supplied with steam and thus reduce the total energy demand for the conversion by the heat of evaporation. Beyond that, high-temperature electrolysis offers to replace significant parts of the electric energy input by thermal energy and therefore allows for external heat integration (Buttler and Spliethoff, 2018). Depending on whether the cell is operated below or above thermoneutral voltage, it either acts as a heat sink or source. However, typical operating temperatures of 650–1,000 °C are significantly above common district heating temperature. Therefore, a primary utilization of potential waste heat from these processes may be found in reintegration (e.g., to preheat feedstock) or processes at elevated temperature levels rather than common DHN regarding exergetic efficiency.

9.3 INTEGRATION IN DISTRICT HEATING NETWORKS

9.3.1 TECHNICAL CONSIDERATIONS

An increasing demand for renewable hydrogen as a feedstock to decarbonize industrial production processes will be accompanied by the installation of electrolysis and therefore raise the question of utilization of corresponding waste heat potentials. At waste heat temperature levels of low-temperature electrolysis (AEL, PEMEL), direct integration into today's common district heating systems is currently possible primarily in the return flow. Alternatively, it can be a source for heat pumps that upgrade the waste heat temperature level and feed into the DH supply line. Continuously decreasing temperature levels in future DH networks (Köfinger et al., 2017, 2016; Volkova et al., 2020) are expected to improve these utilization potentials (see section 3.5). With regards to high-temperature electrolysis, the increasing demand for hydrogen and electrolysis in energy-intensive industries, as mentioned above, encourages an endothermal operation (i.e., as heat sink) and appropriate heat integration in industrial use cases for this technology to maximize the electric efficiency of the hydrogen production. However, with the further processing of hydrogen in terms of power-to-X, corresponding downstream conversion processes (e.g. methanation, Fischer-Tropsch) could take advantage of DH for utilization of their waste heat, often at temperatures of 200–400 °C (Bargiacchi et al., 2019). Nonetheless, the supply potential of thermal energy from electrolysis processes is estimated with 56–84 TWh_{th} related to the European electrolysis capacities as stated in the EU hydrogen strategy. Considering these EU distribution plans within the European borders, 6–10% of the EU DH demands could be covered by electrolysis waste heat utilization (Böhm et al., 2021).

Apart from the integration of waste heat from power-to-gas processes, these processes are also expected to play a major role in sector coupling between energy networks. By "greening the gas" (Tichler and Zauner, 2018), i.e., by (partially) substituting natural gas by SNG or hydrogen, power-to-gas applications allow to store seasonal excess electricity production from renewables in gas infrastructure (grids and storages). Thus, today's gas-fired CHP plants would then use power-to-gas products from the gas grids to provide heat and electricity in times with lacking production from other renewables. Though, for a transition to pure hydrogen or hydrogen-dominated gas grids, a modification of existing CHPs will be necessary due to changed combustion properties. In future energy systems fuel cells could hence replace today's CHPs, providing heat and power with higher combined efficiencies (Staffell et al., 2019). This accounts for commercial large-scale as well as residential applications. Furthermore, given the achievable efficiencies of hydrogen production and its subsequent utilization for heating, such applications will be primarily driven by demands and security of supply aspects (see also section 9.4). However, since the operational hours of CHP plants might decrease in the future (see section 6) the evaluation of the cost-benefit ratio for new investments into CHP infrastructure needs to be carefully done.

As discussed, hydrogen technologies available as of today allow numerous ways of sector integration in future energy systems. A potential design of heat integration in a future energy system with heavy usage of hydrogen is shown in Figure 19.

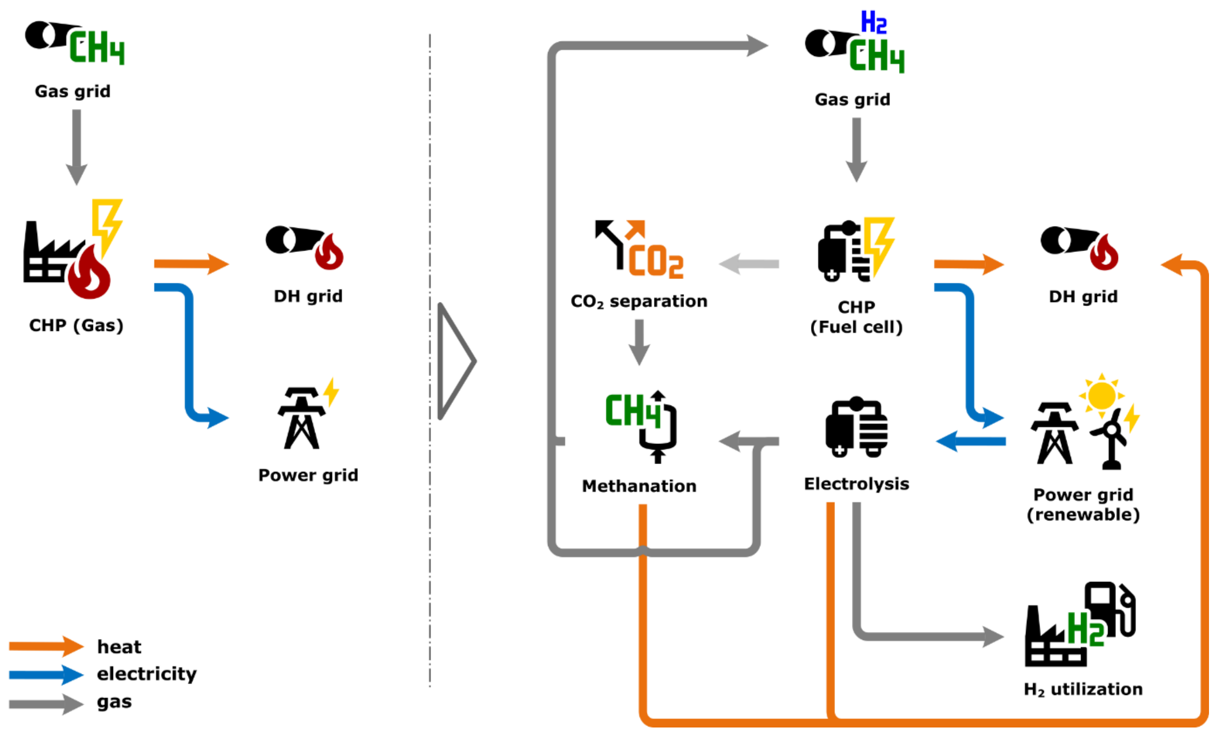


Figure 19: Potential integration of hydrogen technologies in the transition from today's (left) to future (right) heat supply networks

9.3.2 QUANTITATIVE ANALYSIS OF THE ELECTROLYSER WASTE HEAT UTILIZATION POTENTIAL IN DISTRICT HEATING

The focus of this section[24] is on the potential of waste heat from the two main relevant electrolyser technologies AEL and PEMEL (Ozturk and Dincer, 2021). However, most of the current installations are still demonstration projects that are not suited for the utilization of waste heat from the production. Additionally, it is difficult to obtain comprehensive data regarding their location and sizes. Therefore, the waste heat potential of electrolysers is assessed based on scenarios for their expected capacities by the years 2030 and 2040: On a European level, relevant data is available on a national level from the scenarios of the TYNDP 2022 (ENTSO-E and ENTSOG, 2022a). This data is combined with data on the global installed capacity from the Net-Zero Emissions scenario from the IEA (IEA, 2019). To analyse the waste heat potential, assumptions on the technology share and waste heat share are required. A value of 3,500 full load hours is taken from (Böhm et al., 2020). The chosen parameters for the assessment are summarized in Table 7.

Table 7: Parameters for the calculation of the waste heat potential of electrolysers (Böhm et al., 2021, 2020; Danish Energy Agency and Energinet, 2022; ENTSO-E and ENTSOG, 2022b; IEA, 2019; Li et al., 2019).

	Waste heat share, WHS (%)	**Waste heat temperature (°C)**	**Technology share, TS (%)**		**Presumed electrolyser capacity (GW)**	
			2030	2040	2030	2040
AEL	20	70	80	52	55.7	141.4
PEMEL	25	70	18	40	12.5	108.7

The waste heat potentials were calculated by following equations:

$$E_{total} = P_{total} * FLH \quad ; \quad E_i = E_{total} * TS_i \quad ; \quad WH_i = E_i * WHS_i$$

with *P* being the installed capacity, *E* the electricity demand, *WHS* the waste heat share, *WH* the waste heat potential and *i* denoting the different technologies (AEL, PEMEL).

The resulting aggregated waste heat potentials are depicted in Figure 20. The global waste heat potential from electrolysers is around 440 TWh and 2,200 TWh for 2030 and 2040, respectively. Considering only the EU27 + UK, the waste heat potentials are estimated to 35 TWh and 250 TWh for the years 2030 and 2040, respectively[25].

[24] this section is an extract from (Reuter and Schmidt, 2022)
[25] The calculated European waste heat potential for 2030 is lower than the range presented in section 6.3.1, mainly due to different electrolyser capacity estimations.

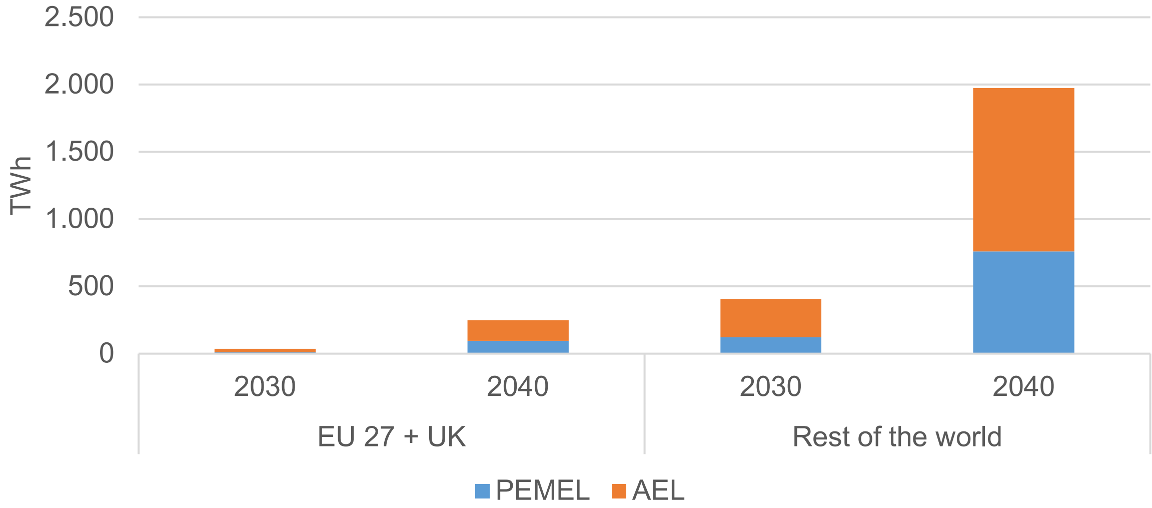


Figure 20: Waste heat potentials from electrolysers. Own calculation based on input data from (ENTSO-E and ENTSOG, 2022c; IEA, 2019).

Comparison to heat demand: In order to understand the magnitude of the waste heat potential, a comparison of the estimated waste heat potential for European countries for 2040 and the projected heat demand from district heating (DH) networks in 2040 has been performed based on data from (Lukas Kranzl et al., n.d.), see Figure 21.

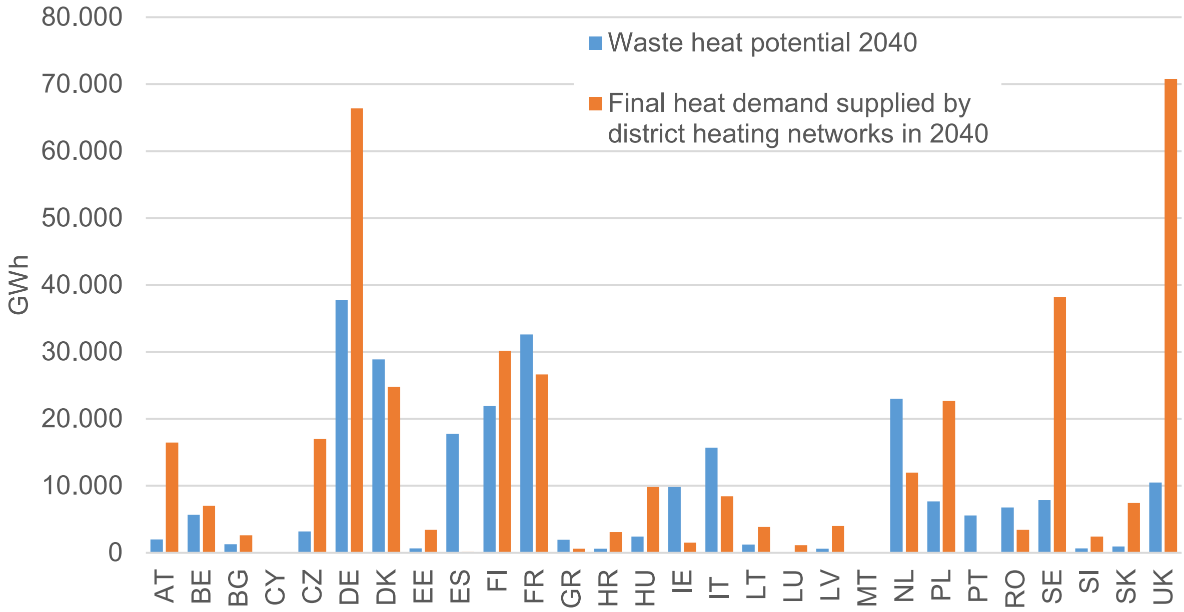


Figure 21: Comparing the estimated waste heat potential from electrolysers for 2040 and the projected final heat demand supplied by district heating networks in 2040 (Residential and non-residential buildings, space heating and hot water without industry (Lukas Kranzl et al., n.d.), heat losses in the network not considered).

Overall, the maximum theoretical waste heat potential could cover up to 64% of the final heat demand supplied by DH in 2040 (sum of all countries, not considering potentials above 100% coverage of the national DH demand). In warmer countries (Cyprus, Greece, Italy, Portugal, Romania, Spain), the waste heat potential can cover 100% and far beyond of the projected heating demand in DH. This also applies for Denmark featuring a high heat demand with a high share of DH as well as high waste heat potential. Additionally, in countries with medium heat demand and lower shares of DH (France and Netherlands) the waste heat potential exceeds the projected DH demand. Other countries with high heat demand, and low share of district heating reach about 10-80% of coverage.

9.4 DISCUSSION

Besides technical concepts and considerations, the practical feasibility of integrating hydrogen technologies in DH networks depends on several external variabilities. These variabilities include, among others:

- Seasonality of hydrogen demand and supply
- Positioning of the electrolyser and fuel cells related to district heating
- Security of heat and power supply
- Technologies used regarding the primary application (prioritization of hydrogen production vs. heat supply)

The SWOT analysis presented in Table 8 summarizes the corresponding opportunities and expert positions regarding the integration of renewable hydrogen technologies within todays and future DH systems. A detailed analysis related to the integration of electrolysis technologies was published by (Böhm et al., 2021).

While the importance of using the waste heat from electrolysis processes to achieve high macroeconomic primary energy efficiency is highlighted, its use in the implementation of power-to-gas plants has hardly been considered so far, as recent studies show (Böhm et al., 2021). Regarding the current technology status and implemented project sizes of electrolysis and fuel cells, waste heat is not yet a criterion for the positioning of electrolysers. However, positioning electrolysers far away from potential heat sinks inevitably involves significant investment costs for pipeline infrastructure and thermal losses if waste heat recovery is implemented at a later stage. Therefore, effective macroeconomic positioning is desirable, but further research is still required to promote the integration of waste heat. Effective planning tools could be developed to help mapping the expected demand for hydrogen and heat (and oxygen) as well as the availability of renewable electricity and water as input to the process (Böhm et al., 2021). Opportunities for technological developments that shall enable the integration of hydrogen and (district) heating system relate to larger-scale fuel cells (for use as a CHP plant in the district heating network) and the availability of waste heat from electrolysis at economically utilizable temperatures.

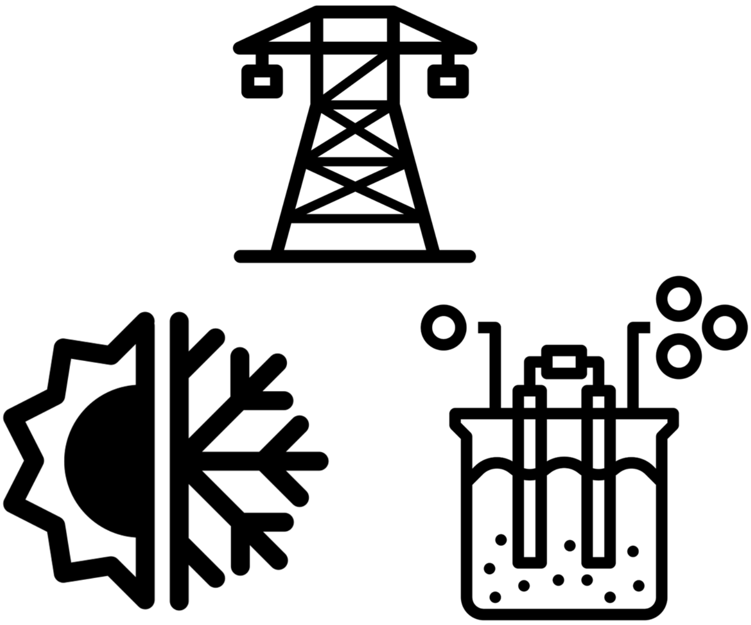
The quantitative analysis shows that in countries with low heat demand, electrolysis waste heat could theoretically decarbonize the complete district heating sector and far beyond. In fact, in some countries, the available waste heat potential far exceeds the final heat demand supplied by district heating networks, resulting in huge losses in waste heat potential if the waste heat is not utilized elsewise. Even if the theoretical potential cannot be fully exploited due to temporal and spatial mismatch of hydrogen production and heat demand, the integration of waste heat from electrolysis processes can provide an important basis for the decarbonization of district heating networks in Europe.

Table 8: SWOT-oriented summary of technology and system aspects on the synergies of hydrogen technologies and district heating, based on (Böhm et al., 2021)

Strengths Technology-specific advantages • Waste heat from electrolysis processes offers sufficiently high temperatures to feed into low temperature DH network, into the return line of high temperature DH networks or act as a source for a heat pump. • There is some degree of freedom on the final position within an area and thus electrolysers may be potentially located close to DH sites. • High-temperature electrolysis is likely to become an integral part of future industrial processes, envisioning a good (at least company-internal) use of their waste heat.	**Weaknesses** Technology-specific disadvantages • From a market perspective, waste heat temperature, especially from low-temperature electrolysis, might be too low to compete with other alternative or conventional sources. • The operation of electrolysers and the demand in DH networks could diverge seasonally. • Electrolysis is one source of waste heat among others – they compete with other sources and cannot really offer better characteristics (e.g., due to volatile production, potential relocation).
Opportunities System advantages • Electrolysis will be indispensable in a sustainable energy system and demand will be enormous. Hence, the waste heat potential will exist, and DH operators (facing goals towards renewable energy) may actively strive to integrate such sources. • The integration of industrial sites in DH networks already before electrolysis is installed will ease the feed-in of its waste heat. • Seasonal heat storages can be a summer heat sink and thus an advantage for some hydrogen technologies.	**Threats** System disadvantages • Infrastructure (electricity grid) limitation may enforce the allocation of electrolysers near renewable power generation and away from heat sinks. • Oxygen as another by-product of electrolysis could be given more weight for positioning than heat sinks. • Some DH system may not manage to decrease flow/return temperatures, decreasing techno-economic feasibility to feed in the waste heat.

PART D - IMPLEMENTATION

This part of the guidebook analyses regulations and new roles and actors in energy trading as well as business models involving consumers and their individual choices including energy communities in selected countries including a summary of results from selected projects (section 10). Further on, case studies for Hybrid Energy Networks are summarized (section 11).



10 BUSINESS MODELS AND BOUNDARY CONDITIONS

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This section highlights some of the key boundary conditions for Hybrid Energy Networks and emphasizes some of the recently developed business models and services. Section 10.1 provides an overview over European policies and regulations and section 10.2 an analysis of selected countries. The projects and business models contributed to this subtask are described in section 10.3. of this document. It establishes a closer connection between the partner contributions and the contents of the first chapter. The last section contains recommendations and conclusions derived from the study.

***Remark**: This chapter focusses on regulations and new roles and actors in energy trading as well as business models involving consumers and their individual choices including energy communities. Regulations and business aspect for an optimal Hybrid Energy Network are only partly addressed.*

10.1 INTRODUCTION

The share of volatile renewable energy sources (RES) in Europe is constantly growing. As an example, the net capacity of wind power increased from 179,062 MW in 2018 to 204,814 MW in 2019. The share of different RES must expand even further if the EU wants to fulfil its goal of a 32% share in 2030 (Komusanac et al., 2020). On the other hand, DH plays a vital role in contributing to the decarbonization goals. Consequently, both the EU, as well as national and local policies set the framework for this development.

In 2016, the EU formulated its *Heating and Cooling Strategy*. It identifies areas where policy adaption is crucial to deliver for the *Energy Union* goals from 2015, which are security of supply, sustainability, and competitiveness (ECEEE, n.d.). It aims at decarbonizing highly fossil-fuel dependent DH networks, as well as also highlights the importance of linking heating and cooling to the electricity sector (European Commission, 2016). The Energy Union goals set the basis for the direction of DH business models, whereas supply-security and the inclusion of renewable energy sources is the focus. However, DH in the EU, and in Austria and Sweden in particular, is not operated in a highly competitive manner. This is due to DH systems constituting natural monopolies.

The *Clean Energy for all Europeans package* (2018/2019) consists of 8 legislative acts and overhauled the overall EU energy policy framework. The *Renewable Energy Directive*, the *Energy Efficiency Directive* and the *Energy performance in buildings Directive* set directions for sustainable heating, whereas the *Electricity Market Directive* and the *Electricity Market*

Regulation set out consumer empowerment in the electricity sector (European Commission, n.d.).

The *European Green Deal*, published at the end of 2019, aims at transforming all sectors to reach carbon neutrality by 2050 (European Commission, n.d.). It puts pressure on DH systems that include heat generation from fossil fuels and enhances investments in renewable generation. As part of the European Green Deal, the *EU strategy for energy system integration* came into place (July 2020) which aims for a more circular economy and sets out the goal to increase biomass utilization and accelerate the use of renewable electricity (European Commission, 2020b). To meet GHG reduction target, the EU published its *Fit for 55 package*. (Bundeskanzleramt, 2021). It also proposes to further amend, among others, the *Energy Efficiency Directive,* and the *Renewable Energy Directive* to meet the targeted goals.

The draft of the Renewable Energy Directive (RED III), aims at making EU energy systems more flexible, making it easier to integrate renewables (European Commission, 2021). It also provides sustainability criteria for bioenergy, which can have major impact on current DH networks. This draft therefore puts pressure on biomass-based DH networks and could stipulate a shift in generation technologies and fuel utilization.

Market

The tax share of electricity and gas prices varies throughout Europe. Figure 22 shows a comparison of the tax and levy share of the electricity and gas price in different European countries.

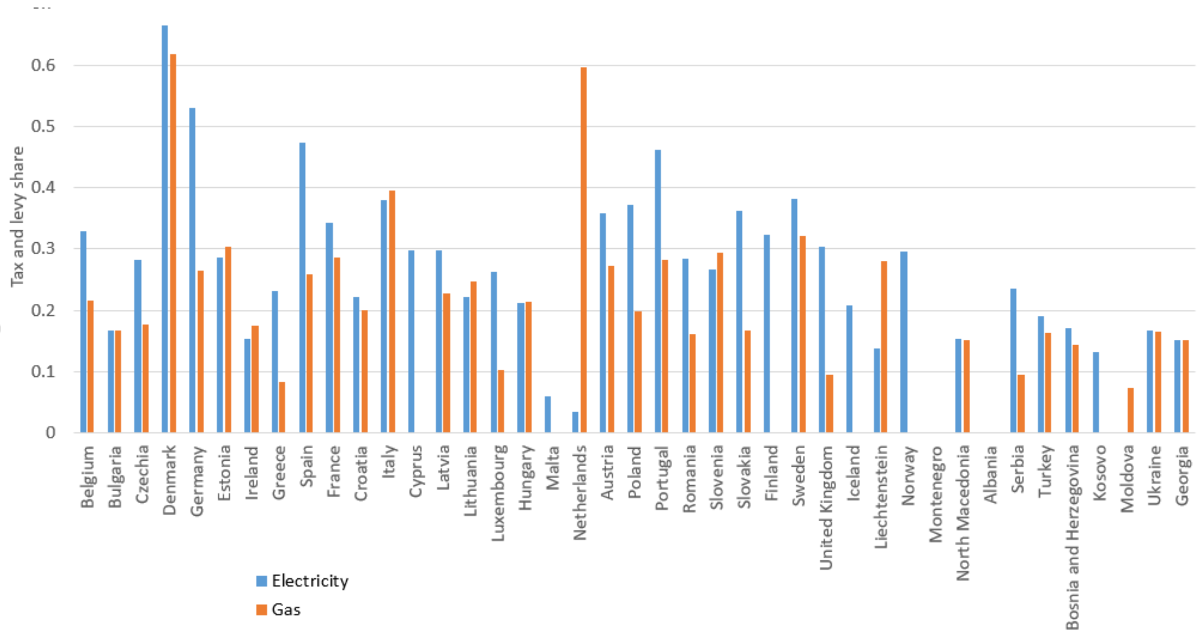


Figure 22: Comparison of Tax share of electricity and gas prices for European countries in 2020 (Eurostat, 2020)

Denmark has the highest share of taxes and levies, but also other countries, like Germany, have high levels. Interestingly, the Netherlands have the highest share of gas taxes while the tax for electricity is quite low. This is probably a result of the "Klimaatakoord" policy in the country. To fulfil the national climate goals, the price of gas was increased, while the price for electricity was decreased at the same time in 2019. Additionally, new incentives were created in order to make the acquisition of heat pumps more attractive (Klimaatakkoord, 2019).

In general, the gas price has a lower share of taxes compared to the electricity sector. Due to this discrimination, the operation of a heat pump might be economically inefficient if the operator had to pay the complete electricity tax.

Besides gas and electricity, there are of course other fuels used for heating purposes, especially biofuels. Unfortunately, no statistics for all of Europe could be found.

10.2 ANALYSIS OF SELECTED COUNTRIES

This section highlights some of the challenges and boundary conditions for selected countries from IEA DHC Annex TS3 partners.

10.2.1 AUSTRIA

In Austria, 30 % of the total final energy consumption is used for heating (including warm water and air conditioning). The market share of (local) DH in Austria's total heating demand (including warm water) was about 24 % in 2015 and has roughly tripled since 1990. The use of highly efficient CHP plants for DH in urban areas has succeeded in significantly reducing Austria's CO_2 emissions. However, currently, these plants are under severe economic pressure due to the development of gas and electricity prices (BMK, n.d.). The current share of renewable energy in DH constitutes just nearly 50% (Energy Monitor, 2020) with bioenergy as the biggest renewable energy sector in Austria with currently 53.10% (Biomasseverband, 2021). In the electricity sector, the increasing share of renewable energy sources leads to higher grid congestion (Ester et al., 2020). The wind and PV energy plants supply a power of 2800 MW. In combination with the stochastic nature of these energy sources, there is a high demand of balancing flexibility.

In 2018, the *Austrian Climate and Energy Strategy* (#mission2030) was decided. To reduce the dependence on fossil fuels, other sources such as solar thermal and ambient heat should be further expanded until 2030; and biomass should also play a vital role in the achievement of 100% renewable electricity (BMNT, 2018). The Austrian *Government's Program* of 2020 envisages climate neutrality for Austria already by 2040. The program also sets the target for 100% renewable electricity in 2030, for which measures are defined in the *Renewable Expansion Act* (energiezukunft, 2020). Furthermore, oil and coal heating systems for buildings shall be forbidden for new buildings by 2020 and forbidden when changing the heating system in existing buildings by 2021. Also, there will be a compulsory replacement of oil and coal heating systems older than 25 years and the replacement of all oil and coal heating systems. From 2025, no gas heating systems will be allowed in new buildings (Bundeskanzleramt, 2020). The federal and state governments are currently negotiating a *Renewable Heat Act* (*Erneuerbares-Wärme Gesetz EWG*). This act shall guarantee a renewable heat supply in Austria by 2040 through a gradual phase-out of fossil energy, called *Austrian Heat Strategy* (*Österreichische Wärmestrategie*) (Adensam, 2021) (BMK, n.d.).

The newly enacted *Renewable Expansion Act* (*Erneuerbaren-Ausbau-Gesetz EAG*) is the current basic legal document for defining subsidies for all green electricity generation technologies, including biomass and biogas CHPs. Furthermore, the Renewable Expansion Act defines that operators of DH or district cooling plants with more than 250 customers or 3 GWh of heat sales per year must publish on their website at the end of each year a breakdown of the type of fuels they use in heating and CHP plants as well as the share of waste heat or cooling fed into the grid (RIS, n.d.) (RIS, n.d.). This part of the law imposes a significant certification burden, but it also provides transparency regarding the extend of renewable energy inclusion in DH.

With the help of subsidies under the *Heating and Cooling Pipeline Expansion Act* (*Wärme- und Kälteleitungsausbaugesetz*), the expansion of the infrastructure is stimulated (BMK, n.d.). Amongst other key points, the act focuses on the integration of renewable energy sources for the expansion of small-scale regional heat supply in rural areas. This shall be achieved through promotion by means of investment subsidies. In this context, the additional expansion of heating and cooling networks may only be subsidized if the additional generation demonstrably leads to less use of primary energy sources and causes fewer CO_2 emissions. The subsidy amounts to a maximum of 35% of the total investment costs (RIS, n.d.).

In addition to national regulations, federal state- and municipality-specific legal requirements also come into play. Especially spatial planning (*Raumordnung*) can make an important contribution to the use of sustainable heat generation systems. Within spatial planning, zoning (*Flächenwidmung*) is the basis for the generation and distribution of renewable energy. Vienna, for example, as a federal state, issues its own spatial energy plans (*Energieraumpläne*), which serve the sustainable development of energy provision and use of heating and hot water generation systems in Vienna (see Vienna Building Code (RIS, n.d.)). Both spatial planning and building regulations (*Bauordnungen*) are not the responsibility of the Austrian national government (ÖROK, n.d.) (RIS, n.d.).

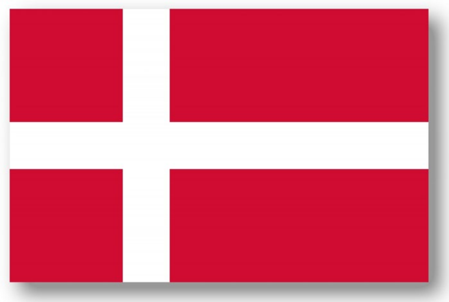
10.2.2 GERMANY

As can be seen in Figure 22, Germany has a tax and levy share of more than 50% on electricity. Included is a subsidiary to support RES integration, the EEG levy, which has a share of ~20% of the total electricity price. The electricity price in Germany is analysed in (Fraunhofer ISI et al., 2020). The authors conclude that the price policy has to be modified in order to be prepared for future emission free energy systems. They basically use the same argumentation as the authors of (Hvelplund et al., 2017). In (Fraunhofer ISI et al., 2020), different scenarios for a new price structure are investigated. They are based on new distributions of the electricity tax and the EEG levy on other energy sectors as well. This means that other technologies such as gas boilers also have to be considered by the renewable energy policies. The study contained scenarios where energy taxes and levies were in part or completely moved to the heating or gas sectors. In summary, it turned out that small heat pump systems could be profitable only if a part of the taxes and the EEG levy was moved to the heating sector. In case of bigger systems, a complete movement of these price parts would make them profitable.

Although not a shift regarding taxes and levies, the price for gas and oil for heating systems increased in the beginning of 2021, because a carbon dioxide tax was introduced. This is not a classical tax, but instead suppliers have to purchase certificates for fuels. Corresponding costs are forwarded to the customers. The intention is to make technologies based on electricity more attractive. As mentioned in the German country report, only an energy tax was part of the price for heating oil before the introduction of the carbon dioxide tax (NIBE Systemtechnik GmbH, 2022).

The Renewable Energy Sources Act (Eneuerbare-Energien-Gesetz, EEG) is a set of laws which were meant to provide a feed-in tariff concept for renewable energy sources. For an operator of a renewable energy power plant, this guaranteed a grid connection, preferred dispatch and a constant feed-in tariff for the next 20 years. The distribution system operators pay the feed-in tariff and in turn sell the power at the electricity stock exchange for typically lower prices. To close this gap, the electricity price a consumer pays contains the EEG levy. The EEG has been continuously revised. Currently, the final discussions for a third revision are ongoing. In 2022, the German government is going to phase out the EEG levy.

10.2.3 DENMARK



In Denmark, wind power production accounted for 43.6% of domestic electricity supply (2021), but there is a growing resistance among residents against more wind power parks (especially from projects where there are no significant local ownership/advantages), and also the reduction of subsidies is problematic (Maxwell et al., 2015). The Danish energy policy is designed to support new wind power plants with those subsidies. Until recently, there was the Public Service Obligation (PSO) which was paid to operators of wind power plants on top of market prices. It was decided to reduce the PSO and to finally remove it by 2022. Without replacing this subsidy, wind power plant operators depend on market prices for electrical energy. Because of their volatile nature, wind power plants do not guarantee a consistent income compared to conventional power plants due to imbalances between generation and consumption[26].

A way forward to reduce the imbalance that is discussed in Denmark is to utilize flexibilities of the electricity demand to aim for more dynamic adaptation of the demand to the generation, especially when there is a lot of wind power available. Other energy sectors, like the heating, gas, or e-mobility sectors, provide the flexibility to increase demand in a controlled manner, thus stabilizing market prices and providing ancillary services to the power grids at the same time. This kind of sector integration requires suitable coupling points between the sectors. In the case of the heating sector, heat pumps and electrical heaters represent possible coupling points (Wang et al., 2017), see also section 3. For the latter, economic control strategies have already been examined in (Zong et al., 2017).

Although possible and beneficial from a technological point of view, policies, regulatory frameworks, and market actors are not yet prepared for sector integration. Subsidies like the PSO were invented with the scope of the electricity sector only. Synergies between different sectors have not been thought of (Hvelplund et al., 2017).

The focus on the electricity sector regarding high taxes and levies for renewable energy integration today is regarded as an obstacle to further sector integration efforts (see also section 14.3.4). In (Hvelplund et al., 2017), the authors state that wind power will account for

[26] However, there is also an increasing interest in PPAs as a market mechanism for wind and PV, providing the required financial safety for most new installations. On the other hand, fossil-based technologies should have taxes added that reflect the true cost of fossil-based energy generation. This would push up the market price and give a healthier RES development.

a major share of the primary energy supply and electricity will function as an energy-system-internal energy carrier, which connects the heating, transportation and conventional electricity system. They also analysed the feasibility of heat pumps compared to biogas plants. It is emphasized that the operation of heat pump systems is charged with the taxes and the PSO, where in comparison a biogas plant has to pay only a small amount of extra tax.

10.2.4 SWEDEN

The electricity production in Sweden has a large share of RES, with 39% hydropower and 12% wind power in 2019. In addition to this, nuclear power and conventional thermal power has 39% and almost 10% share of the production in 2019, respectively. The wind power generation has seen a large increase in the last 15 years (SCB, 2019). The Swedish government has defined a goal of 100% renewable electricity production by 2040 (Government Offices of Sweden, n.d.). At the same time there is also an increase in electricity demand due to electrification of different sectors, such that both transportation and industrial processes get more and more electrified. One of the largest electrification initiatives in Sweden, HYBRIT, a collaboration between different actors to create fossil free steel, is expected to increase the electricity demand by 15 TWh, almost 10 % of the electricity use in Sweden today (LKAB et al., 2020). With electrification of transport and industry it is not only the electricity demand that increases, but also the power demand. The increasing share of RES in the electricity system and reduced amount of controllable production have shed light on the importance of power balance and available capacity, especially in the transmission grid in Sweden.

A large part of the electricity production is located in the north of Sweden, the electricity regions SE1 and SE2 with hydropower, while nuclear power is located in SE3 closer to a large part of the electricity demand which is congregated in the larger urban areas in SE3 and SE4. The capacity of the transmission grid is therefore of great importance to be able to match supply and demand continuously and instantaneously (Nordling, 2017). The restricted and congested grid capacity is one of the issues widely discussed in Sweden during the past years.

Heating in Sweden is primarily based on electricity, biofuels and district heating (DH). Electricity is the most common energy carrier for houses which use heat pumps, electric boilers and direct electricity heaters, followed by biofuels and district heating, while multi-family houses and non-residential buildings are mainly heated by DH (Swedish Energy Agency, 2020a). DH has over 50% market share for heat supply in residential and service sector buildings in Sweden, with more than 90% of all dwellings in multi-family houses connected to DH (Swedish Energy Agency, 2020a). District heating production is mainly based on biofuels, solid municipal waste, waste heat from industry and heat from heat pumps as well as a small share of fossil fuels (SCB, 2019). In the agreement of Swedish energy policy, it is stated that *"A competitive district heating sector and reduced use of electricity for heating are prerequisites if we are to be able to deliver renewable electricity and warmth on cold winter days."* (Government Offices of Sweden, n.d.).

The DH market is one of the largest energy markets in Sweden, but compared to the electricity market, which is a cohesive market, the DH market consists of several local energy players with certain conditions, similarities, and differences. In Sweden, 72% of the companies are municipal or state-owned, whereas in Germany, a majority of DH companies are owned by the private sector (Magnusson, 2016).

The DH sector and market of Sweden is governed by the District Heating Act (DHA) which became law in 2008 (Regeringskansliet, 2008). This law has undergone some revisions and investigations in order to strengthen consumer rights. This is because the DH market is considered a natural monopoly (Boney et al., 2020). To support the uptake of renewables and stimulate competition in the DH sector, the EU has proposed to open DH infrastructures to third parties, known as third party access (TPA). There are many aspects to consider in the design of the TPA, i.e., how access is granted (mandatory or voluntary, negotiated or regulated), the level of freedom of choice for customers (retail or production market), how and/or if end-user price should be regulated etc., which increase the complexity of regulation. This needs to be justified by the benefits achieved by the TPA (Bürger et al., 2019).

Policies

The Swedish carbon tax was introduced in 1991 and it is levied on all fossil fuels in proportion to their carbon content, as carbon dioxide emissions released in burning any fossil fuel are proportional to the carbon content of the fuel. The tax was introduced at a rate of 250 SEK (EUR 24) per tonne CO_2 emitted and it has gradually been increased. In 2021 the rate is 1200 SEK (EUR 114), based on an exchange rate of SEK 10.49 per EUR. Industry outside the EU ETS has historically been charged a lower tax rate while industry covered by the system is entirely exempt from carbon tax. But things have changed and as of 2018, the industry rate outside the EU Emissions Trading System (ETS) is the same as the general rate. Combustion of sustainable biofuels is not subject to carbon taxation (Government Offices of Sweden, 2021).

The power and heating sector in Sweden was affected by the removal of tax exemptions in August 2019. Firms are required to pay 91% carbon tax and full energy tax for fuels used in CHPs and other thermal power plants included in the EU ETS, which is a large change, especially for CHPs which previously paid only 11% carbon tax and 30% energy tax. The CHPs not included in the EU ETS pay full carbon and energy taxes (Swedish Energy Agency, 2020b, 2020c).

In 2003 green certificates for renewable electricity production was introduced. The system is market based and since 2012 this market is shared with Norway. The green certificates are awarded to producers of renewable energy from wind power, some hydropower, some types of biomass, solar energy, geothermal energy, wave energy and peat in CHP. The system is constructed in a way that producers are awarded one certificate per MWh electricity produced. They can then sell the certificates and increase the profitability of their production. Retailers of electricity on the other hand are required to buy a certain quota of certificates in relation to how much electricity they sell, creating a market for the certificates. The quotas are adjusted annually.

10.3 SELECTED STUDIES AND PROJECTS

During the last years, the IEA DHC Annex TS3 partner institutions participated in different projects, which directly or indirectly also addressed related aspects. Some projects suggested new business models to support RES integration, others proposed regulatory modifications which have to be made by the countries to make RES economically feasible.

10.3.1 ECOGRID 2.0: MARKET FOR FLEXIBLE USE OF ELECTRICITY IN PRIVATE HOMES

There are several Danish research projects which propose alternative approaches to public incentives like the PSO and the current taxation system for electricity. The project Ecogrid 2.0 was finished in 2019 and its main purpose was to influence the balance between electricity production and consumption. Thus, also market prices were affected resulting in an improved feasibility for RES technology. The balancing was created by sector integration: On the island of Bornholm, 2000 households were asked to participate in a new electricity market design, where each consumer can provide flexibility to the market. Flexibility refers here to the activation of electrically powered heat supply units like heat pumps or electrical heaters.

Data from these customers was collected using smart meter systems. The general concept for flexibility trading was based on a new real-time market approach, where consumer equipment can react to market prices. This approach is a new concept, but it was designed to fit into the existing market structure. As depicted in Figure 23, the Ecogrid market aligns itself between the balancing power markets and the frequency-controlled reserves. The Ecogrid market can thus be used for short-term, intra-hour balancing, but also for day-ahead trading.

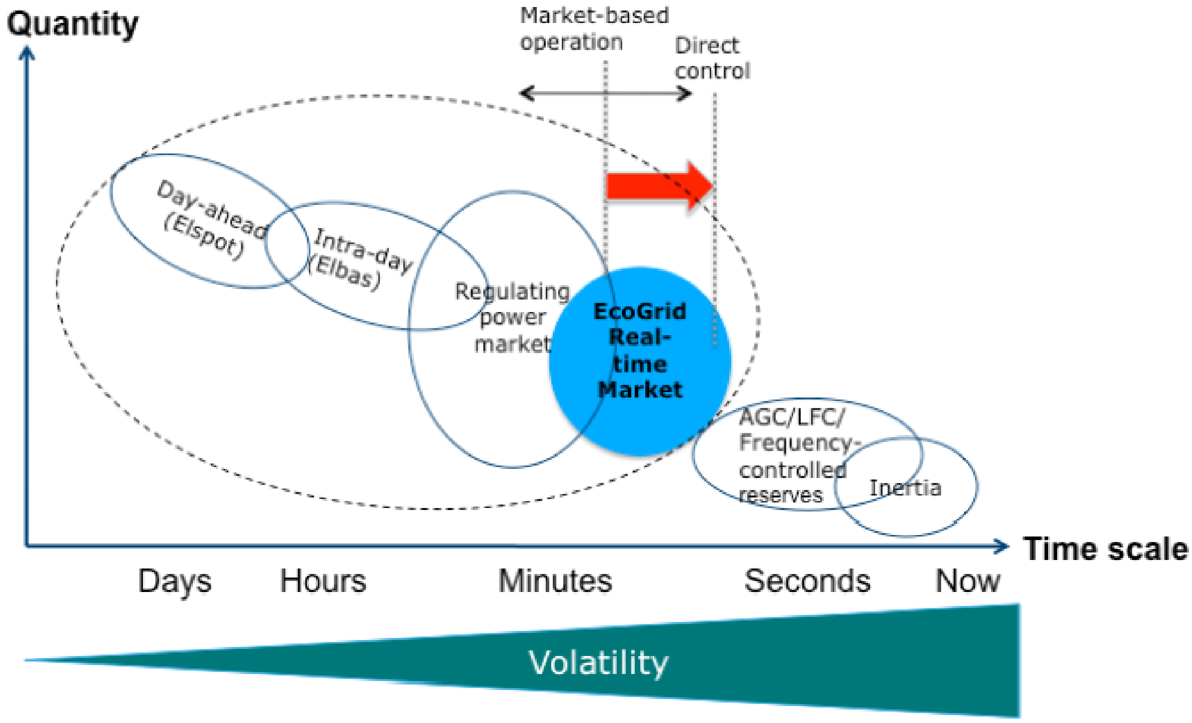


Figure 23: The Ecogrid market in the context of the existing market system. Figure from (Jorgensen et al., 2011)

The price of the Danish Elspot market is used as a forecast of the real-time price. It is sent directly to the consumers and updated every 5 minutes. If there is an imbalance in the system, the price signal will deviate from the day ahead prices. The real-time price is set by the real-time market operator, which can be the TSO. He chooses a price based on the need for balancing between production and consumption.

For the market concept to work, system operators, prosumers and retailers must work together. An ICT infrastructure must be created, as the market price signals must be delivered to the consumers. However, because the devices only react to the price signals, the communication lines do not have to be bidirectional. (Jorgensen et al., 2011) also argues that a consumer has the choice to either take part in the new market approach, or to choose traditional contracts for energy consumption. This shall lead to more competition between energy suppliers and accelerate the development of new business models.

Overall, the following advantages have been identified:

- The concept extends the current electricity market to a shorter time horizon and smaller assets.
- Improved system operation
- Indirect support for new RES integration
- Simple usage for customers
- No bidirectional communication necessary

Table 9: Business model canvas for Ecogrid

Key Partner TSO Market Households	**Key Activities** Aggregation of consumers Market-driven device control	**Value Propositions** Educational services Contribution to sustainable Energy supply	**Customer Relationships** Customer education regarding energy markets and sustainability	**Customer Segments** Households, which may provide flexibility to the power grid
	Key Resources	Economical incentives	**Channels** ICT infrastructure	Heat supply and vehicles
Cost Structure ICT infrastructure		**Revenue Streams** Reduced costs for network extension		

As can be seen from the business model canvas in Table 9, a part of the business model aims at the education of potential customers. This is necessary because customers typically want to have control of their own energy supply devices. It is necessary for new customers to understand the advantages of the proposed model and how to avoid higher costs. An additional effort is necessary because the appropriate ICT infrastructure must be installed and understood by the household owners. Of course, installation costs will have to be carried by the TSO. The main goal of the model is to reduce costs necessary for extension or strengthening of the network. (Energiteknologisk Udviklings- og Demonstrationsprogram, 2019; Jorgensen et al., 2011).

10.3.2 ENERGY LAB NORDHAVN

Another Danish project which has been finished recently was the Energy lab Nordhavn. The origin of this project was the need to better integrate fluctuating energy sources into the electricity grid. The project utilized a part of Copenhagen, called Nordhavn, as a demonstrator for innovative energy supply solutions. Compared to Ecogrid EU, the demonstrator is thus located in an urban area. This district was equipped with different new devices meant to provide sustainable, flexible, and integrated energy supply. For example, booster heat pumps have been installed in ultra-low temperature district heating substations for the preparation of hot water. Operation strategies for heating devices were also tested to provide services for the electricity network. The integrated operation of a centrally aligned heat pump fed by a battery was also part of the project. From a regulatory point of view, several recommendations are given:

- The economic performance of the heat pump is significantly reduced as long as the heat pump operator had to pay the normal tariff for operating the electrical network.

- The possibilities for activating thermal flexibility should be enhanced. Heat pumps can support the management of electricity grids
- It was also proposed to adjust the tax structure for coupling points between energy sectors and for batteries.

The corresponding report mentions that prosumer communities will play a more important role in the future and that involving prosumers might raise new business models from which district heating companies, retailers and end users can benefit. The structures they propose are based on a peer-to-peer exchange of energy between consumers and prosumers. There is no dictated price structure for generated electricity. Instead, customers negotiate directly with the operator of a power plant. There are not many details given on how the negotiation process might work. It is only stated that this kind of energy trading might lead to problems, but also advantages are named:

- A direct sale of energy between customer and producer may result in benefits for the grid operator, because, if he is aware of the energy trades and the corresponding stakeholders, the state of the grid can be better predicted. This might lead to less congestions. In addition, grid charges can be calculated individually, because the distance between consumer and producer, and thus the length of utilized grid lines, is known.
- Customers are currently not aware of the power plants which produce the consumed energy. With a P2P approach, each customer must show more interest in his energy consumption, leading to a more sustainable behaviour. This is called democratization of energy use.
- Prosumers may benefit directly from the produced energy and can act more independently.
- A revolution of the trading system with a closer interaction between customers and producers may also lead to a more transparent and simpler regulatory framework.

On the other hand, the Energy lab Nordhavn provided the opportunity to test and demonstrate different technical setups based on the combined operation of power and heating supply devices. However, as stated in (Greisen, 2019), the regulatory framework provided different obstacles for the system.

10.3.3 THE ISLE OF AERO

Both the Ecogrid EU and Energylab Nordhavn projects have in common that they try to increase the role of the energy customer. This is probably also because there is a growing resistance against more RES like wind parks in the communities (Maxwell et al., 2015). Besides the two mentioned projects, there is another one which tries to let inhabitants of a community directly profit from newly established wind parks. The isle of Aero has a clear vision of an emission free energy system. For that, it will have to build new wind parks. To increase the acceptance of these wind parks, the government of Aero decided to let inhabitants benefit from generated profits in different ways. One idea is to use a part of the wind park income to support the procurement of electric vehicles for the citizens of Aero. According to (Maxwell et al., 2015), this project is called Winds of Change.

10.3.4 INNONEX: INNOVATIVE CONCEPTS OF LOW-TEMPERATURE DISTRICT HEATING GRIDS

The Innonex project investigated innovative concepts of low-temperature district heating grids applied to a new housing estate "Heinrichsheim-Mitte-West" in Neuburg an der Donau (Germany). The housing estate will consist of 32 buildings with ~140 inhabitants. All buildings were meant to be supplied by a centrally aligned heat pump connected to the planned district heating grid. The heat pump utilizes the low temperature waste heat of a dairy, so it was also planned to install electrical heaters in the domestic hot water storage of each building to raise the temperatures to the legally required level.

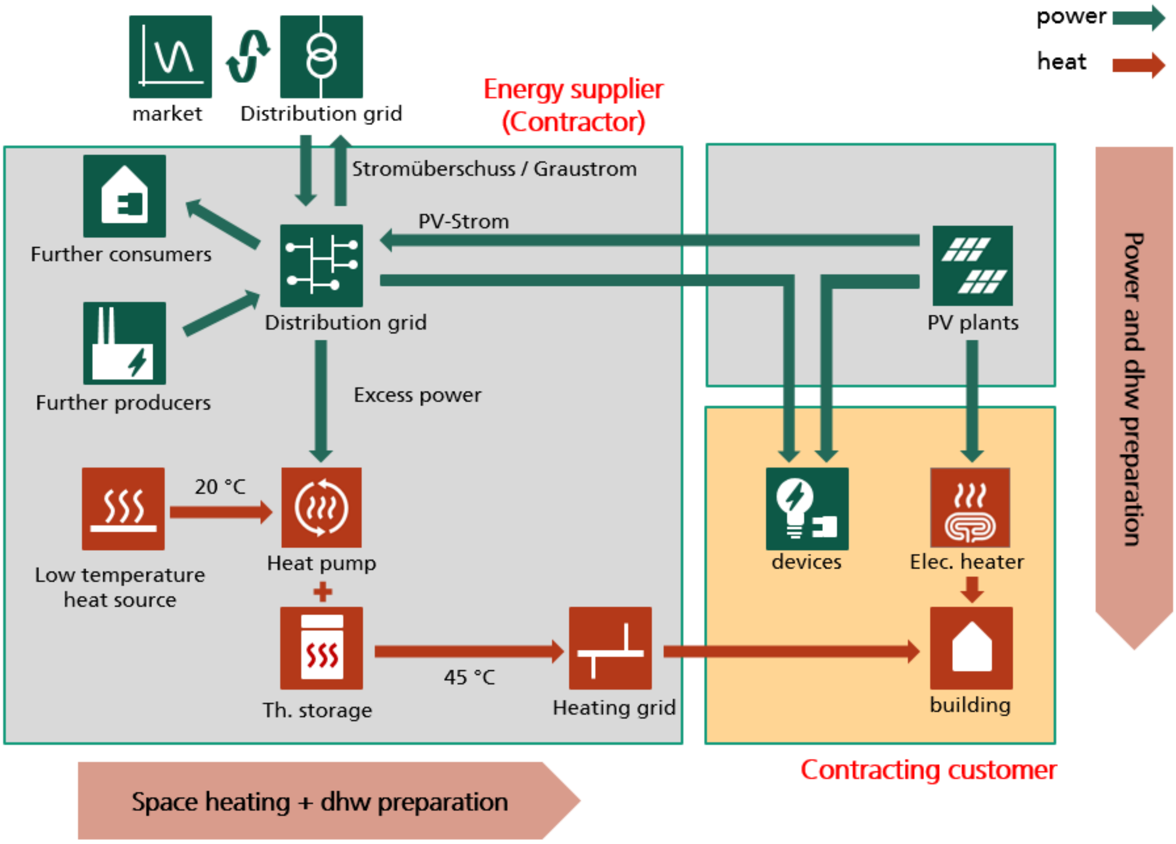


Figure 24: Basic supply setup created for the Innonex project.

As the heat supply devices rely on electrical power an important part of the project was to investigate if excess power generated by solar power plants could be shifted to the thermal sector to avoid a waste of energy. Thus, control strategies for the electrical heaters and the heat pump were implemented. The basic technical setup is shown in Figure 24. The stakeholders which interact with each other are also shown: On the one hand, the local public services company owns the supply devices (grey boxes), and on the other hand, there are the house owners who must supply electrical devices and use, besides the connection to the district heating grid, electrical heaters to raise the temperature level inside water storages.

The Innonex project identified several crucial regulatory obstacles (Ventury GmbH et al., 2020): The public services company emphasizes that it is important to take all stakeholders into account already at the beginning of the planning process of a new district heating system. If the municipality owns all estates, the public services company can easily decide to create a district heating system. Additional costs are added to the estate prices and every building gets connected to the grid. However, in case of Heinrichsheim-Mitte-West, the estates are owned by many estate owners and each of them can decide if he wants to be connected to the grid. Although generally possible (according to §16 EEWärmeG), the public services company did not require the estate owners to connect to the district heating grid. In this case, it is very difficult for the public services company to estimate the economic feasibility of the grid. The public services company made efforts to convince the estate owners that a district heating supply would bring economic benefits for them, nevertheless, conflicts of interest between the different parties remained.

Since the property developers in the planning phase are not the residents who were going to buy these estates and build homes, they considered to have no benefits from investing in a district heating grid connection. On the contrary, the district heating grid connection would have led to higher estate costs, making this option unattractive for the owners.

Due to this conflict, instead of the demonstrator simulations were carried out based on the originally planned district heating grid. Sector coupling aspects were also examined using the assumption of an existing heating grid in the mentioned settlement. While setting up possible control strategies for the heat pump and electrical heaters in combination with assuming available solar excess power, the participating stakeholders were identified. Because most of the buildings are not owned by the municipality, different incentive models were proposed to make the installation of a PV power plant attractive for the inhabitants of Heinrichsheim-Mitte-West.

One of the suggested approaches was a contracting model, where the public services company was able to rent the available rooftop areas to build their own PV power plants (also shown in Figure 24). Additionally, it was assumed that the electrical heaters inside the water storages are controlled by the public services company. Based on this setup, it was planned to use available solar power to

- supply household devices without considering the electrical heaters
- supply the electrical heaters in the storages
- and, if more power is available, use this power for the centrally positioned heat pump

As it turned out, it was not possible to use this strategy because of regulations in the electricity sector: Although the Stadtwerke Neuburg an der Donau are responsible for operating the electric grid and own electricity and heat supply units as well as existing or planned district heating grids, they have to be treated internally as different companies (EnWG §3, 38). The reason is that the electricity sector is regulated, while there are no regulations for the heating sector in Germany. Besides, the Stadtwerke Neuburg company is a vertically integrated company, as it operates the electricity grid and the electricity generating units. If the company also owns electrical heaters and the heat pump system, the following regulatory aspects must be considered:

- If the different devices and plants are operated with a strategy that is beneficial for the grid, it may be that economic advantages are generated which are not available to other system operators. This is prohibited in Germany.
- On the contrary, vertically integrated companies must guarantee transparency and a discrimination free system operation. (§§6a – 10e Gesetz über die Elektrizitäts- und Gasversorgung, EnWG).
- In case of the introduced settlement, Stadtwerke Neuburg an der Donau must separate the heat supply devices from the electricity supply and the operation of the electricity grid. Any kind of information, which could be used as an economical advantage, must not be transferred between these different parts of the company.
- Thus, the signals meant to control the electrical heaters and the heat pump system based on the availability of solar power could not be sent across the electricity grid, and the operating strategy invented in the Innonex project was not applicable.

Interestingly, only one of the project partners (IKEM) knew about these regulatory restrictions at the beginning of the project. This can be seen as an indicator that the legal framework needs to be communicated to the different stakeholders. Clearly, these regulations are an obstacle even for very basic sector coupling approaches. What is possible for a single household, leads to problems as soon as even small grids are optimized.

During further discussions in the project, an attempt was made to circumvent the regulations. In some situations, regulations do not apply to very small electricity grids. These are called “Kundenanlagen” (customer plants) or “Arealnetz”. Small housing estates can be defined as such with the consequence that they are exempt of the grid fees and no unbundling regulations do apply.

However, the concept of a “Kundenanlage” is restricted to very small areas and is typically meant for industrial areas. As described in (Ventury GmbH et al., 2020), a power plant may be defined as a “Kundenanlage”, if

- the plant is situated on a delimited area
- the plant is connected to a distribution network or to an energy generator
- the plant is not big enough to have an influence on market competition

Clearly, these conditions do not apply to a housing estate of a city.

10.3.5 FED (FOSSIL-FREE ENERGY DISTRICT)

In the FED (Fossil-free Energy District) project (Lagerfors, 2019) a digital marketplace for energy was built and operated at the campus area of the Technical University of Chalmers in Gothenburg, Sweden. The local market included more than 50 buildings at the campus and was also connected to the external district heating and electricity grids.

The idea behind the development of the local energy market was that it would be possible to trade smaller amounts of energy than in the existing energy markets. By managing the energy demand and supply locally, less energy would have to be transmitted over larger distances and demand peaks as well as the cost of infrastructure could be reduced. The main aims for the FED market were:

- the energy produced locally should be fossil free
- the amount of energy from the external grids should be reduced at peak demand hours when the CO_2 emissions are the largest
- through energy recovery, energy efficiency measures and local generation, the total input of energy from the external grids should be reduced

The market was created to enable the partners to trade an electricity and district heating/cooling surplus between buildings, and to balance the energy need and decrease the need of primary energy/fossil fuels in the area. The trading platform utilizes the flexibility of the electricity, heat and cold customers and storage operators to enable demand response and aggregated flexibility to be used for peak load management.

The trading system collects information regarding use of energy in district heating- and cooling devices, produced surplus energy from district heating and cooling devices, information from electricity meters, from photovoltaic production units and energy available in short-, mid- and long-term storage. All the energy-related data is connected and integrated to a cloud-based Metatech Marketing system based on Ericsson’s Service Enabling Platform, SEP. The platform enables small-scale trading with energy loads, surplus energy, and energy balancing actions down to the single building level. LORA (Low Power wide area network) is integrated and implemented in the system. LORA is a wireless telecom network that allows long range communication at a low bit rate among connected objects such as sensors or meters. Through LORA several additional sensors and meters (water, CO_2, wind etc.) are available for the trading system. This increases quality, resolution and usability of the data flow and creates business opportunities regarding energy services in the trading system.

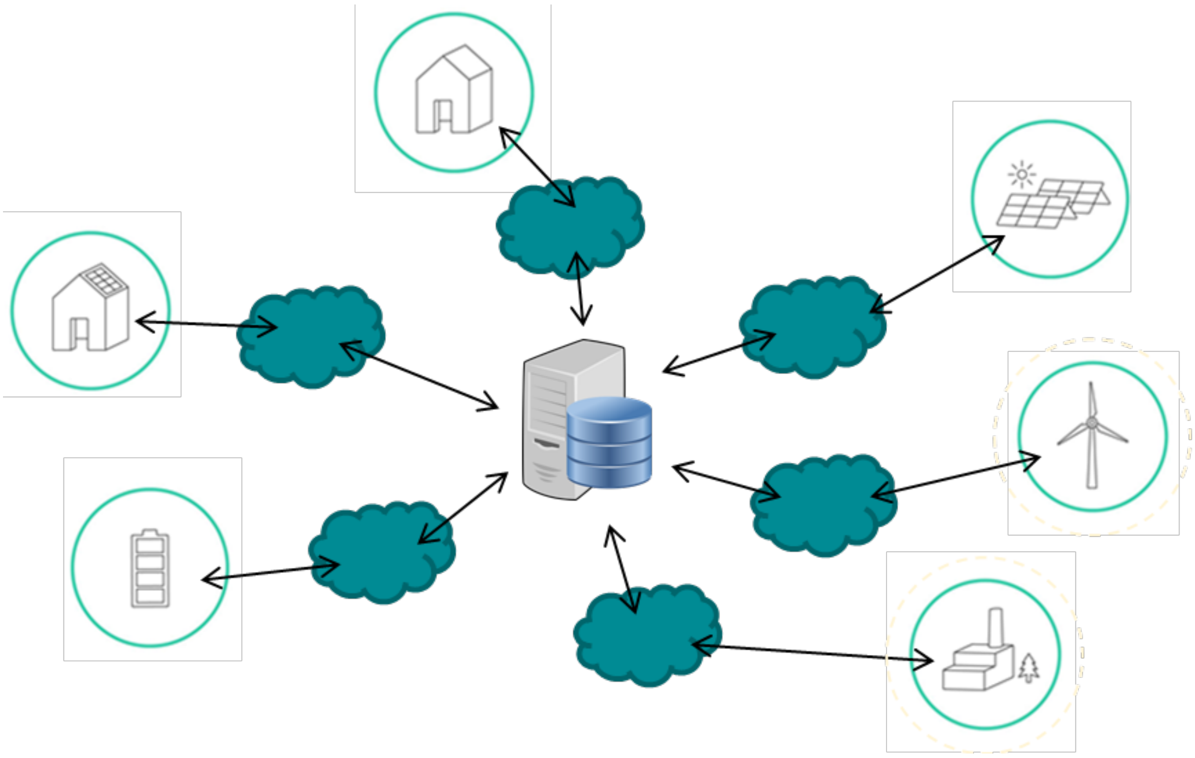


Figure 25: Structure of the energy market platform in the FED project.

The local prosumers, storage operators and customers trade excess energy with each other, sell excess energy to retailers and purchase energy from local producers in the energy market platform. Important market components included were:

- Environmental impact forecasts –primary energy factors and CO2 equivalents for different types of energy were part of the forecasts, allowing the actors to plan their energy use to minimize environmental impact.
- Peer-to-pool trading – through a local pool for energy the customers have access to local micro-generation as well as larger producers and retailers. The pool also provides market access for local production units or prosumers for their excess energy.
- Peer-to-peer trading – allows customers to choose producers of energy based on preference

The two main business models identified in the project are the ESCO (Energy Service Company) business model and the aggregator business model. In the case of the ESCO business model, the ESCO provides solutions such as energy efficiency measures, energy deliveries, or forecasting to the energy market actors and customers. In the FED project this would mean that the ESCO could provide advanced system optimization of the energy use of the customers (based on, e.g., environmental impact) or system services to improve the operation of grids and networks. The aggregator business model typically means that the aggregator coordinates many individual resources. In the FED context the aggregator could use the market platform to coordinate the resources in the system and provide this aggregated flexibility to the overlying systems (e.g., electricity or district heating grids) for peak load management.

The FED project did not fully develop business models for the local energy market, but an important factor identified in the project was the need to clarify which actor fulfils the role of the market operator or owner. A complete business model for the local energy market needs to include the costs and revenues associated with this role, as well as a fully functional price model, including how to set the price for CO2 emissions and how to set the prices to make the market attractive for both market actors and market owners.

10.3.6 FLEXI-SYNC (FLEXIBLE ENERGY SYSTEM INTEGRATION USING CONCEPT DEVELOPMENT, DEMONSTRATION AND REPLICATION)

In the Flexi-sync project, enabling technologies such as storage solutions, control optimization, increased usage of renewable energy sources and waste heat have been used in optimization modelling and eventually to form a new service. The new service accounts both for the demand and the supply side of the district heating (DH) system allowing for unprecedented levels of flexibility in DH and electricity sectors. Different use cases in Austria and Sweden have been analysed (Yang et al., 2022), in which the optimal operation of the supply-side system (the DH network comprising Combined Heat and Power (CHP) plant, central heat pump (HP), and heat-only boiler (HOB)) and the demand-side system (building-level HPs and thermal storage) are integrated into one system to provide flexibility to DH and electricity systems. Amongst the non-academic partners, the unprecedented combination of the demand and supply sides into one service is an important innovation that will allow increased flexibility by means of digital solutions. The new service is yet to go to market.

In the case of **Austria**, two types of business models are proposed:

1. The first new business model adds new cross energy domain components (i.e., a central CHP and an HP) and therefore links the system to the electricity grid, which is not common for rural DH systems in Austria. This inclusion enables additional flexibility to the existing DH network.

2. The second innovated business model is an extension of the first one and comprises the Day-Ahead and/or the aFRR balancing electricity market participation of the CHP and HP, because their combination turns out to be a profitable option.

Table 10. Business model canvas (BMC) showing the current and the two innovated business models ("new").

<table>
<tr><th>Key Partners</th><th>Key Activities</th><th>Value Propositions</th><th>Customer Relationships</th><th>Customer Segments</th></tr>
<tr><td rowspan="3">Chamber of Agriculture, forest associations, biomass associations, auditing associations, machine ring, farmers, wood owners, planners/installers, other cooperatives
New: Electric utility companies
New: power exchanges or aggregators</td><td>Contracting (plant and energy saving), construction of the systems, support & maintenance, repairs, local fuel procurement, accounting & invoicing, knowledge transfer
New: Electricity sales to utility companies
New: sale on electricity markets</td><td rowspan="3">Local heat supply, technical solutions/services, know-how transfer between plants, good price for biomass, workshops for users (planners, installers,...)
New: CHP/HP: Safer heat supply (redundancy), renewable local electricity supply, more attractive prices through provision of flexibility</td><td>Local, renewable experts for heat supply with a focus on integrating local value creation</td><td rowspan="3">Customers from the private living area, housing cooperatives and other property developers, public authorities, companies, churches
New: Electric utility companies
New: buyers on the electricity market</td></tr>
<tr><th>Key Resources</th><th>Channels</th></tr>
<tr><td>Fuel (biomass), know-how, infrastructure (heat generation plants, network...),
New: electricty, flexibility infrastructure</td><td>Heat supply contracts, information events, word of mouth, website, other cooperatives, wood chip supply contracts,
New: flexibility contracts</td></tr>
<tr><th colspan="2">Cost Structure</th><th colspan="3">Revenue Streams</th></tr>
<tr><td colspan="2">Fuel costs (biomass), infrastructure
New: Electricity costs (HP)
extended infrastructure costs (also for flexibility),
Costs possibly reduced by CHP (cushion off-peak periods),
New: market participation costs, costs for price optimization</td><td colspan="3">Ongoing: heat costs or contracting rate (CR);
One-time payments: connection costs (if no CR), membership fee for cooperative
New: Additional income through the sale of electricity possible (CHP), new income structures (new contracts) due to flexibility provision of buildings
New: volatile income due to direct electricity market participation</td></tr>
</table>

Those business models are consolidated by the fact that the use cases of electricity market participation show increased revenues. The cases including operational or investment support for the additional generation technologies are most profitable. This indicates the additional generation technologies and possible electricity market participation are economically viable to utilize flexibility options. In DH systems, the usage of building flexibility is profitable as well (especially for DH networks without existing thermal storage tanks). And when considering network densification, flexibility from the thermal storage mass of buildings can be economically viable. Furthermore, the business model modifications are also analysed. The stakeholder workshops and a questionnaire are also conducted to receive feedbacks which prove to be in favour of the innovated business models.

In the case of **Sweden**, two representative business models are developed and elaborated, i.e., the business model of connected product and of the performance contract. The main difference between these two business models is the investment arrangements and operation modes of HPs. Based on this, different blocks of the BMC are modified. Since Business Model Canvas is a widely used method to visualize existing business models for a company and create a visual roadmap of a business model's evolution. The risks perspective to business models is proposed in this analysis which is rarely considered in other studies. Trust issues between DH company, aggregator, and property owners, possible failures to respond to flexibility signals, and investment risks are proposed to DH companies before they proceed with any new business model. From a product-oriented mindset to better product offering and service-oriented mindset is the prerequisite to adapting to the changing business environment. To achieve a Win-Win situation, DH companies shall consider adjusting their conventional business logic, designing better offers, establishing dialogue- and trust-based customer relationships, involving new partners, developing innovative activities, channels (such as optimization solutions, installation, and maintenance) and price models.

The policy risks, technical risks, financial risks, and organizational risks are put forward to safeguard future new business models, based on the analysis of business models, policies, and regulations.

10.4 COMPARISON & CONCLUSIONS

This section compares the projects introduced in section 10.3 with each other, draws parallels and emphasizes differences. The contents of the sections 10.1 and 10.2 are also discussed, to create recommendations for future applications.

Remark*: This chapter focusses on regulations and new roles and actors in energy trading as well as business models involving consumers and their individual choices including energy communities. Regulations and business aspect for an optimal Hybrid Energy Network are only partly addressed.*

The recommendations and conclusions given in the final reports and publications of the contributions can be divided as follows:

1. Recommendations on regulatory boundary conditions. This involves the operation of sector coupling points, but also the configuration of taxes, subsidies, and grid charges.
2. New actors and roles evolving in energy trading. This point is because it gets easier for consumers of energy to also act as a producer (prosumers). This is the main driver for the creation of new business models.

Since the introduction of new market actors affects both existing business models and regulatory boundary conditions, these topics are discussed separately in the following. In the frame of the contributed projects, both topics do not depend on each other. However, interconnections between regulatory boundary conditions and future business models are created where necessary.

10.4.1 REGULATORY BOUNDARY CONDITIONS

With the Energylab Nordhavn and the Innonex project, it is obvious that different European countries are investing resources to increase demand flexibility through sector coupling applications. The mentioned projects of section 10.3 focus on coupling the same energy sectors: Power and heat using heat pumps and electric heaters as coupling points. An important topic is the development of operation strategies to switch the coupling point state in dependence of the requirements of the connected networks. Ecogrid EU, Innonex and Orpheus shared the idea to operate a large set of decentral aligned devices. Besides sharing the general scenario, Orpheus and Innonex also had in common that the creation of operation strategies was only theoretically possible. The regulatory framework in Germany (Orpheus investigated the city of Ulm, while Innonex investigated the city Neuburg an der Donau), proved to be a major obstacle for the integration of sector coupling technologies.

Only one project partner was aware of the regulatory details preventing the introduction of these strategies in the case of Innonex. This indicates that the German regulations are not prepared yet for sector coupling applications. However, institutes like the IKEM already realized the existence of legal obstacles. The major problem preventing to use the operation strategies was that the DSO was at the same time operating the grid and responsible to produce electricity and heat. With this configuration, a DSO is not allowed to control the state of coupling points, because it must guarantee a discrimination free supply of all consumers. From an electrical point of view, the coupling points between the power and heat sector are consumers. This rule makes sense from an unbundling point of view but does not respect requirements necessary for modern sector coupling applications. This is clearly shown by the efforts made during the Innonex project to somehow circumvent current regulations by building a parallel infrastructure to connect producers and consumers or trying to define the mentioned "Arealnetz". IKEM proposed therefore a new power plant concept, which is called "Anlagenkopplung" (plant coupling). The idea of the plant coupling is to remove the requirement to have a direct connection between the RES plant and the coupling point. Instead, RES plants and coupling points are connected virtually. This makes it possible to introduce operation strategies, although the participating plants are spatially decoupled. It must be emphasized that the plant coupling is meant to support RES, because the coupling point must consist of power created by sustainable sources up to at least 80%.

Interestingly, the final reports of the Danish projects did not mention similar problems, although the set of used devices was comparable. In case of the Ecogrid EU project, the reason for this might be that only market price information was sent to the consumers. The final decision to switch devices on or off was made by the device owners.

Besides this general obstacle regarding the introduction of operation strategies, the partner contributions argued that regulations regarding grid charges and taxes in the electricity sector could restrict the economic feasibility of sector coupling applications. This is also confirmed by (Hvelplund et al., 2017), where it is highlighted that in contrast to the electricity taxes and levies, nearly no taxes must be paid for biomass in Denmark. Even gas and diesel fuels have a lower tax share compared to electricity taxes, which is a clear incentive for heating technologies introducing a significant amount of carbon emissions. This imbalance is already known, but it seems that it is only in the last few years European governments have started to think about an integrated tax and levy system covering all energy sectors. As an example, in 2020 the Fraunhofer ISI institute suggested for an alternative distribution of energy taxes, including the amount of emitted carbon dioxide (Fraunhofer ISI et al., 2020).

Additionally, an article published by IKEM (Doderer et al., 2020) argues that the high taxes and levies a customer has to pay to operate a heat pump or an electrical heater prevent the invention of new and innovative business strategies and slow down the energy transformation in the heating sector. The following changes to charges and taxes are proposed in this article:

Grid charges: According to the German §118 Abs. 6 EnWG, electrical storages do not have to pay grid charges, as long as the stored energy is fed into the same network again at a later time. In 2011, the law was extended by a paragraph which also covers Power-to-gas plants. A new suggestion by IKEM is to expand the law even further, so that all plants which convert energy from one form to another are liberated from grid charges.

Alternatively, the removal of grid charges for PtG plants could be removed so that all energy converters have to pay the same price for electricity. In this case, additional incentives and subsidiaries could be created to support these technologies.

The removal of grid charges for coupling points and especially batteries was also suggested in the Danish Energylab Nordhavn project.

Reduced costs for plants providing flexibility: If a power plant can act as a flexible load, it should pay reduced costs for electricity. As an example, again the grid charges were mentioned. Another option would be to reduce the costs by a certain fraction for the times when ancillary services are provided. This is especially useful if the network operator could send signals to the plants as soon as there are congestions in the grid which shall be reduced by decreasing the electricity demand of the sector coupling plant. Besides reducing the grid charges, also a reduction of the EEG levy was proposed.

However, regarding an EEG levy reduction, it is mentioned that a trade-off situation would be created, where it is difficult to estimate if incentive creation by EEG levy reduction for flexible energy converters balances the loss of EEG income. Additionally, although the European court (EuGH) decided that the EEG levy does not have to be granted by the European commission, it might be that this will change in the future, because in 2017, the European commission granted the levy. If this would be the case, laws cannot be adapted freely.

Electricity Tax reduction: It is emphasized that it is already possible to reduce the taxes for some kinds of sector coupling technologies. A recent change for batteries was that a tax has only to be paid if a battery is discharged. There is no tax for loading the battery. However, IKEM states that there is no unified law available for the taxation of sector coupling technologies and some technologies, e.g., PtG plants, have more benefits in terms of tax reductions compared to other technologies. It is suggested to couple a tax reduction to the grid situation. If there is a high load in the grid, a high tax has to be paid.

Another suggestion is to change the type of the electricity tax: Currently, a certain tax has to be paid for every kWh of consumed electric energy. This is independent of the price the network operator had to pay for the electricity, so there is no connection to the price. Other taxes, like VAT, are coupled to the price. This could stabilize electricity exchanges, as the demand rises if the prices are low. This suggestion would make it necessary to change European law. Currently, this law prescribes the taxation of electricity with a coupling to the amount of consumed electric power.

Although the summary above is valid only for Germany, it is important to note that partner contributions mentioned very similar problems. This is not surprising, if some obstacles are introduced by European law.

10.4.2 THE NEW ROLE OF CONSUMERS & NEW BUSINESS MODELS

Besides the identification of (at least in part) similar barriers in different countries, the contributed projects shared another similarity: They proposed new business cases centred around consumers which can more actively take part in the trading of energy. This trend is not new, as different studies (e.g. (Agora Energiewende, 2017; International Renewable Energy Agency, 2019; Umweltbundesamt, 2019)) already reported different new approaches for business models built around prosumers, but the contributed projects confirm what the mentioned studies summarized or predicted for future projects.

As an example, The IRENA study (International Renewable Energy Agency, 2019) defined four categories of new business approaches. Indeed, it is possible to map the contributed projects to these categories, as shown in Table 11.

Table 11: Mapping of contributed projects to trend categories from IRENA study

Aggregators	Peer-2-Peer	Communities	Market Design
Ecogrid	Energylab Nordhavn	Energylab Nordhavn	Ecogrid
Flexi-Sync		Winds of Change	FED

We can see that most projects can be sorted into the aggregation (integration of households into a collection of decentral aligned power plants – either by using an aggregator approach or other models, like the one introduced in the Innonex project) and community categories.

Regarding aggregator approaches, we saw that these provide different advantages:

- The option to integrate small household devices into the market landscape
- The option to automate market participation by reaction to price signals
- The option to use household devices as an ancillary service provider for the grid

These advantages will probably lead to more aggregator integrations in the future. New market concepts which make it possible to trade all forms of energy will add even more flexibility and lead to a closer interaction of the households with the markets.

Also the European Union supports a stronger engagement of consumers in the energy markets: With two EU directives ((European Union, 2019, 2018) two types of energy communities were introduced to the European regulatory framework: The renewable energy community and the citizen energy community.

The definition of these community types shall help to increase the share of community owned energy infrastructure. In contrast to the current energy system, where typical larger companies benefit from energy production and trading, energy communities involve a large number of people who actively take part in the energy system.

However, the concept of energy communities is not a new one. In several EU countries, there already exist many different projects involving citizens that come together to form an energy community. Several studies exist which highlight the benefits of energy communities in general. Some of them are:

- They help to increase acceptance of renewable energy and decrease resistance against the deployment of new plants. This is because the community can take part in decisions and benefit directly from the profit made by the producers.
- New jobs are created in the local area as the plants are owned by the community.
- They give incentives for the investments in energy production units in the community

According to (Caramizaru and Uihlein, 2020), the newly introduced types of energy communities have the following aspects in common:

- Governance: Participation has to be open for everybody
- Ownership and Control: The participation of citizens is emphasized in both directives
- Purpose: The primary purpose is to create social and environmental benefits

However, the two concepts also differ in some points. A more detailed description is given in the following, while Table 12 summarizes the most important differences.

Renewable Energy Community: In article 22 of the revised renewable energy directive (European Union, 2018), it is mentioned that each EU member state has to make sure that every household customer can participate in a local energy community. These communities must be entitled to produce and consume renewable energy. It is also allowed to share the produced energy between the participants. Although each household shall have the possibility to participate in a renewable community, the participation is prohibited for large companies.

It should be emphasized that the directive is not only addressing electricity, but all forms of energy in this article. Therefore member states are also encouraged to identify existing regulatory barriers for the establishment of these communities. A further hint that the coupling between heat and electricity sectors plays an increasing role is also given in article 23, point 8. Every four years, district heating operators shall evaluate the potential of grid services together with the operators of the electricity grid.

Citizen Energy Community: According to (Caramizaru and Uihlein, 2020), citizen energy communities act within the electricity sector. They also do not focus on renewable energy, nor are they bound to a localized geographical area.

If a person does not want to be part of the community, alternative energy supplies must be provided. This also means that the current structure of the energy distribution system must not change. The communities are an extension to the currently existing system. However, a citizen energy community may act as a network operator if it applies the same regulatory framework as all other network operators.

The contents of the directives have to be transformed into national laws for each member state. In Germany, a national framework shall exist until June 2021.

The revised directives may provide a clarification of the already existing communities in the different EU countries. However, (eurelectric powering people, 2019) states that the new directives already missed the opportunity to define a transparent regulatory framework, because some uncertainties remain, as no direct link between both types of communities is created and it is also not clear how the existing communities have to be modified in order to fit into the frame given by the directives.

The source (eurelectric powering people, 2019) also enumerates several examples of energy communities that already exist. The concept of the German Stadtwerke is mentioned, which may generate electric energy, distribute it to the consumers and often also take care of the distribution of heat energy. Another example are the energy cooperatives (Energiegenossenschaften). Members of these already have the possibility to become a co-owner of local power plants. The profit is shared among the members and electricity can be bought at a fair price. Also, an example of a company in Belgium – called EcoPower – is mentioned, where members can participate in investment decisions.

Table 12: Differences between Renewable and Citizen Energy Communities

Renewable Energy Community	Citizen Energy Community
No large companies allowed	Everyone can participate
Renewable energy can be shared among participants	Community is based on electricity
All forms of energy are addressed	Not restricted to a local scope
Intended for a local area	

The paper also states that there are some important challenges to cope with. The transformation of the EU directives corner stones into national law requires the development of new business models and many different actors must be respected by the framework. Because the communities are integrated into the traditional energy system, incentives have to be created to establish or take part in an energy community.

The European countries show different levels of energy community integration and corresponding incentives: While Denmark for example drives citizen participation with incentives (20% share must be offered by wind power developers to residents near the windfarm), other countries, have no concepts for community energy yet.

10.5 RECOMMENDATIONS

Many different projects were discussed within the IEA DHC Annex TS3, focussing on regulations and new roles and actors in energy trading as well as business models involving consumers and their individual choices including energy communities. Regulations and business aspect for an optimal Hybrid Energy Network are only partly addressed. Also, these projects were done by only a few European countries: Denmark, Sweden, Austria, and Germany. Thus, general recommendations for European policy strategies cannot be given with having a look only at these countries, nor can general trends regarding business strategies be identified. After having a look at the distribution of electricity and gas prices for different countries, one can imagine that there are some major differences in energy policies between e.g. the Netherlands and Germany.

Nevertheless, if a trend can be identified for new business strategies, then it is the transformation of the energy market structure. There are many suggestions for creating integrated energy markets, where energy can be traded independent of its form. Demonstrators for these integrated markets were set up in Denmark and Sweden with promising results. Dependent on the type of market, a nationwide integration would need investments in technology, e. g. for smart meter devices, as well as changes in the regulatory framework.

On the other hand, the traditional distribution of electricity consumers on the one side, and large production facilities on the other side changes: By installing electricity production plants like PV plants on rooftops or offering flexibility to network operators as heat pump system owners, who were former passive consumers, take an active role and have the intrinsic motivation to take part more closely in energy trading.

This trend is ongoing since several years, as in some European countries, the idea of energy cooperations is very popular. This fact was also noted by the European Union and two forms of energy communities, which emphasize the active role of energy consumers, were introduced by means of two directives which have to be implemented into national law by each member state.

Energy communities might help to reduce regulatory obstacles for the integration of innovative sector coupling concepts.

It is also interesting to note that studies regarding business models and trends have already been done in the past, for example by IRENA. At least in comparison with the partner contributions collected in this subtask, the results identified by these studies were accurate: The IRENA study also emphasized the new role of consumers as well as new market concepts.

Besides the mentioned economic drivers for increasing the share of renewable technologies, it has to be mentioned that the climate change itself is the most important driver for the installation of new emission free devices, and hence forms the basis for new business opportunities, corresponding to the underlying technology.

11 CASE STUDIES

Authors: Anton Ianakiev (NTU), Anna Cadenbach (Fraunhofer IEE), Nicolas Marx (AIT), Kevin Naik (NTU), Ralf-Roman Schmidt (AIT)

This section summarizes different case studies of Hybrid Energy Networks where the IEA DHC Annex TS3 participants were involved; also, relevant case studies from literature have been included. They have been sorted in following categories:

- Technology integration
- Advanced operation and portfolio management
- Flexibility and demand side management
- Cold DHC networks
- Waste heat from electrolysers

More details can on each individual case study be found in appendix H of this guidebook.

11.1 TECHNOLOGY INTEGRATION

LIVØ – Island DH system (Denmark) – realized ("Livø – A micro-scale smart energy system," 2019)**:** Livø is a Danish Island where during the summer period many tourists visit the island. Since 2015 the old district heating grid has been replaced by a new system with lower temperatures; and an electric boiler, heat storage and two air-to-water heat pumps have been installed, together with a 25-kW wind turbine and 33 kW PV panels. The PtH plants are used to better integrate these variable renewable energy sources. Likewise, a liquid-flow battery is installed to balance the output of these variable units.

Brædstrup district heating (Denmark) – realized ("Brædstrup Fjernvarme," n.d.)**:** Brædstrup District Heating is a consumer-owned heat supply company with many different and flexible production units for district heating supply, that can utilise market conditions and keep low production costs: A CHP production capacity is made available on the spot market and a tank thermal energy storage maximise the revenue of electricity sales. The electric heat pump is introduced for boosting the temperature of the discharged water from the borehole storage (that is charged by a solar collector field). It is operated according to the electricity prices at the spot market. An electric boiler can respond quickly to price signals from the electricity market.

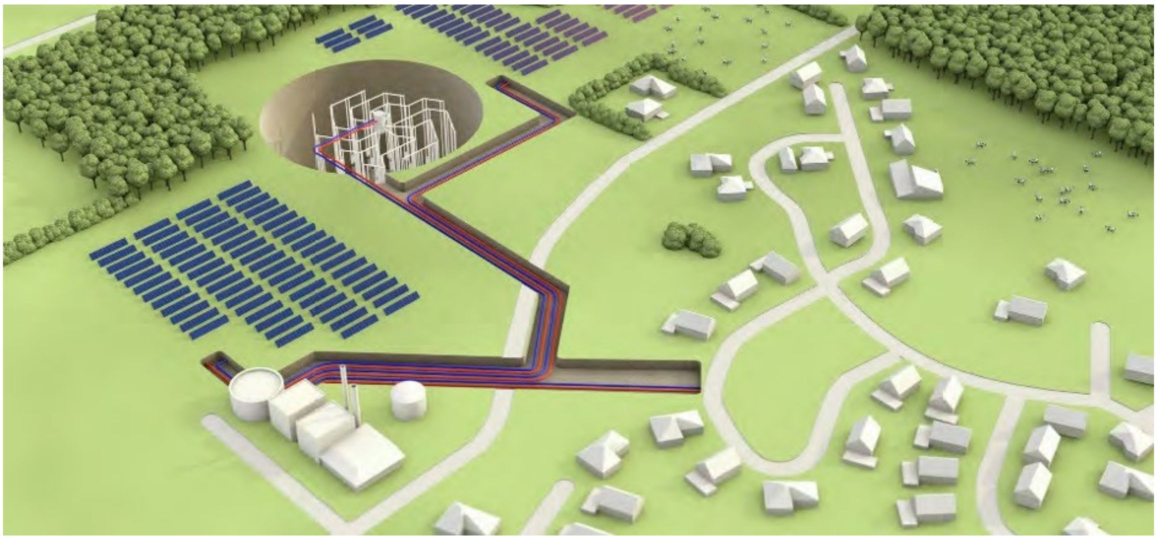


Figure 26: Brædstrup energy configuration

Spittelau heat pump in Vienna (Austria) - planned demonstration project (Kelz, 2022a)**:** The project aims to use the condensation heat from the flue gas cleaning process in the Spittelau waste incineration plant. The waste heat, which is currently released into the environment, will be fed into the district heating network by means of a large high temperature large heat pump system. As a result, the thermal capacity of the incineration plant will be increased from 60 MW to approximately 76 MW. The planned output temperature of the large heat pumps will be approximately 90 °C due to the conditions in the primary DH network, resulting in a COP of 4.7.

Waste heat utilization of a spa in Vienna (Austria) – realized (Wien Energie, 2022)**.** In May 2022 two heat pumps, complemented by an electric boiler were installed at the Vienna spa to utilize waste heat of the thermal water after internal usage to supply surrounding households with district heat. The wastewater is gathered after internal use in two large storages before it is fed to the heat primary side of the heat pumps. The heat pumps will use the approximately 30 °C wastewater to generate 85 °C for district heating. A control algorithm was implemented aiming at an efficient integration of the new generation unit in the existing district heating system. As a follow up project, the optimization of the whole secondary network is planned (Cernohuby-Wallner, 2023).

Vienna wastewater heat pump (Austria) – NOT realized (Kelz, 2022b)**:** The aim of this project was the utilization of waste heat from wastewater to feed into the DH network. Unfortunately, the analyses showed, that the system could not be operated profitably. Profitability of the project was not given due to a) high specific investment costs and b) low full load operating hours due to low efficiency of the HP and high electricity network costs. The following aspects should be considered for future projects a) avoid over-dimensioning of the HP by defining operating points with HP suppliers; b) HPs should be tendered separately from the plant engineering and construction.

11.2 ADVANCED OPERATION AND PORTFOLIO MANAGEMENT

FED fossil free energy district Gothenburg (Sweden) – realized (Lagerfors, 2019; Sommansson, 2021): FED aims to develop, demonstrate and replicate a novel district level energy system at the Chalmers Johanneberg campus, embracing and enhancing the use of technologies such as PVs, heat-pumps and wind. FED optimises different buildings usage profiles; one building's energy needs are balanced with the surplus of another. Intermediate storage consists of heating/cooling storage in the building's structure, accumulation tanks or geothermal heat pumps, and batteries for electricity. To make the cooperation and energy exchange between several stakeholders happen, a local energy market creating business value for each stakeholder will be developed (see also section 10.3.5).

2050 Homes in Nottingham (United Kingdom) – realized (REMOURBAN, 2020)**:** a Net Zero Energy Building deep retrofitting intervention has been carried out in 39 family houses and bungalows to both reduce their energy demand and to implement a renewable energy fed heating system. The new energy/heating system comprises a PV plant, two ground sourced heat pumps, a thermal energy storage and an electric energy storage. A smart monitoring equipment was also introduced for effective control of the energy flow and recording the results of the analysis. The case study showed that main challenges are of financial nature.

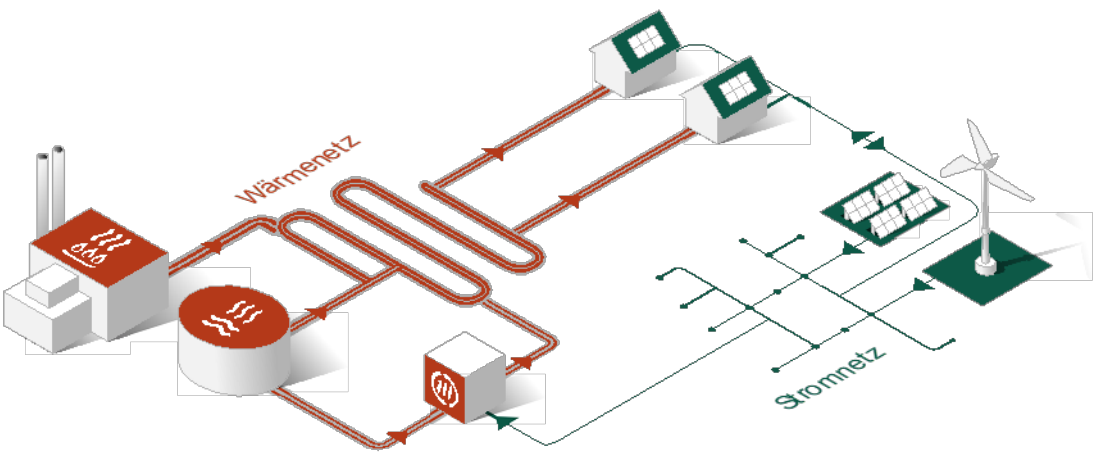


Figure 27: the InnoNEX approach

InnoNEX – innovative DH System (Germany) – planned demonstration project (Kneiske, 2020)**:** The main objective of the two-year "InnoNEX" project is to develop and validate concepts for the utilization of low-calorific, regenerative heat sources in district heating systems. By using central heat pumps, local low-temperature heat sources are raised to a higher temperature level and used to supply the demand of space heating and domestic hot water preparation. Regarding the volatile behaviour of regenerative energy generation, a central thermal storage is installed to buffer fluctuating heating loads and to optimize the electrical load behaviour between the heat pump and the power grid.

Integration of the wastewater treatment plant (WWTP) into the DH network Gleisdorf (Austria) – partly realized (Gruber-Glatzl et al., 2020)**:** The DH grid of Gleisdorf, is transitioning towards a 4th generation DH network, including a heat pump using effluent water as heat source as a flexible element. With a "virtual heating plant" (VHP) approach the current system is optimized. The VHP approach is an intelligent high level control system, leading to a) increasing overall efficiency and flexibility, b) allowing best possible utilization of renewable and locally available energy sources, c) fully exploit the synergies of urban infrastructures like WWTP and DH networks and d) creating a future-proof and resilient system allowing to further improve and integrate innovative measures in future.

100% renewable cross-sectoral energy supply for a smart district in Innsbruck (Austria) – realized (IKB, 2018)**:** The utility provider of Innsbruck demonstrates how a Smart District could be realized and supplied with both heat and electricity from renewables. Several coupling technologies allow efficient usage of surplus electricity for heating. The buildings were covered with PV panels. The sewer pipes are the heat sources for two heat pumps. Additional electricity and heat can be provided by a gas CHP at a biogas tariff. Sporadic excess electricity can further be converted to heat using a power to heat module. Additional batteries allow for further flexibility. The system is distributed among two main buildings, each equipped with heat storages. An innovative Energy Management System operating on the Model Predictive Control principle ensures high rates of self-supply.

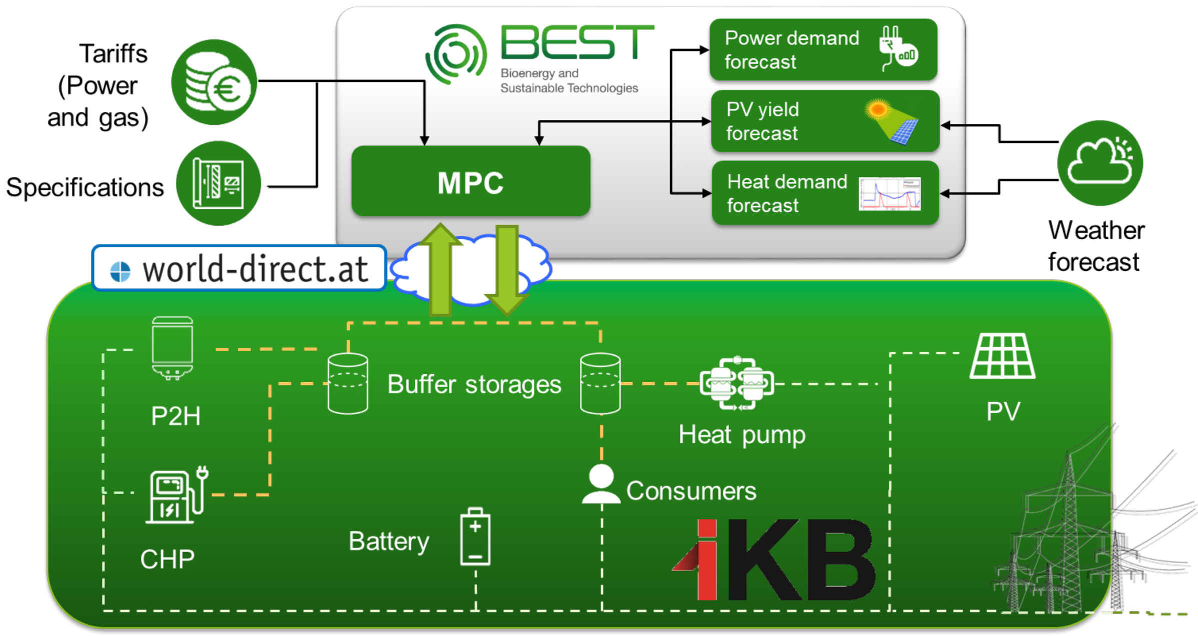


Figure 28 Model of the energy system for the smart district

Hybrid DH Demo Neusiedl am See (Austria) – partly realized (Lehner and Puchegger, 2022)**:** In the region Burgenland, the wind supply often exceeds the demand, additionally, a growing number of the wind parks must be operated on the free market, due to the loss of feed in tariffs. Therefore, the town of Neusiedl is investigating how surplus wind power can be used to generate heat and thereby provide flexibility. Via a direct line from the Neusiedl wind farm, electricity is transported directly to the Neusiedl Energy Hub, where electricity, natural gas and dh networks converge. The installation of a flue gas condensation HP, an air source HP, an extension of the existing buffer storage as well as a battery storage are planned. This will also relieve the biomass heating plant, which was previously responsible for district heating.

The Learning Grid - Institut des Métiers et Techniques (France) – Realized (imt grenoble, n.d.)**:** The Learning Grid implements a pedagogical multi-energy and sector-coupled microgrid at the scale of a campus. The campus is equipped with a heat pump that uses electricity provided partly by PV panels, a micro-CHP plant, water tanks allow flexibility in heat production, and two building-sized Li-ion batteries as well as 6 electric charging stations. Multiple connections of the campus to the DH, gas and electricity network allow to arbitrate between the different provisions requested from those networks. An ongoing research project aims at developing advanced piloting strategies to further enhance operation of the site and determine the best possible trajectory for future site evolution.

Ferney Genève Innovation district energy network in Ferney Voltaire (France) – Realized (panglosslabs, n.d.)**:** The network is based on a principle of balancing heat exchange between buildings. The low-temperature network recovers the so-called fatal energy from cooling and cooling devices of economic activities (e.g., waste heat from CERN's Large Hydron Collider) to heat homes. In addition, this network is based on an inter-seasonal geothermal storage designed to store the most abundant energy of the summer period to return it in winter. This thermal network is intended to be coupled with a PV self-consumption loop to increase the share of renewable energy produced locally. This hybrid system will bring flexibility to the interconnected networks. A digital twin of the thermal smart grid is developed, allowing the simulation of new components and strategies of operation to evaluate their technical and economic interest

Optimized Generation of the East Milan DH System (Italy) – Realized (Capretti and Matteo, 2021)**:** The East Milan DH System has a very complex mix of fossil-fuelled and power-fuelled asset (CHP units with heat pumps, electric boilers, external heat sources and storages), providing a great degree of flexibility (and complexity) in the energy dispatching strategy. The scheduling and management of such system requires the evaluation of multiple economic, technical, and regulatory variables, with potentially significative impacts in the economic operating margin, considering uncertain heat demand and variable prices on the power market. To manage and optimise operations, an advanced solution for analytics and optimization has been provided, maximizing the EBIDTA (economic operating margin).

11.3 FLEXIBILITY AND DEMAND SIDE MANAGEMENT

The following summaries are an extraction of (*Flexi-Sync Project Report*, 2022), where additional case studies can be found.

Maria Laach (Austria) – demonstration project: The utilization of the building thermal inertia by remotely making alternative settings of the substation controllers was tested. Five buildings, representing 50% of the total energy demand in the network, were prepared for live testing. With the optimisation the peak load could be reduced by about 6% compared to regular operation. Key learnings were that preparation of historical operational data takes time and the optimisation planning needs regular plant personnel. The end-users involved did not notice when the buildings were controlled. On the other hand, the cost for flexibility integration, licencing, and operation is possibly too high for small rural grids. Hence, finding a low-cost solution, e.g., automating the optimisation process to reduce operational costs is necessary.

Eskilstuna DHC System (Sweden) – demonstration project: The Swedish municipal energy company Eskilstuna Energi och Miljö teamed up with the municipal housing company KFast to test the thermal inertia of two apartment buildings, as well as a combination of individual heat pumps and district heating. The partners managed to control the buildings to react when it was the most profitable. The building thermal inertia shifted heat demand to hours with lower heat production costs. The building heat pump enabled a shift between a heat pump and district heating, given the lowest cost from a system perspective for each point in time. No indoor climate changes in the buildings were registered, and KFast did not have any complaints from the tenants during the testing period.

Figure 29: Eskilstuna generation system

Parc Bit tri-generation and DHC grid in Palma de Mallorca (Spain) – demonstration project: Sampol operates and maintains a tri-generation plant producing electricity and hot and cold water distributed to customers in the science and technology park Parc Bit close to Palma de Mallorca. Several types of flexibility have been explored: storage flexibility, grid flexibility and individual customer flexibility from the thermal inertia of a heated swimming pool. Practical learnings were that simulations are key to unlock flexibility, including production baseline, demand forecast and grid model. It was also noted that some end-users could be integrated as energy storages due to their large flexibility potential. Finally, to study flexibility using network inertia requires accurate data and there are many factors which might influence the results.

11.4 COLD DHC NETWORKS

Bamberg cold DH system (Germany) – feasibility study (Schmidt et al., 2021)**:** In this feasibility study energy supply concepts of the conversion area "Lagarde" were investigated. The aim was to develop a cold district heating system which supplies low temperature heat from near-surface geothermal collectors to decentralized heat pumps, located in the connected buildings, based on a thermal-hydraulic simulation.

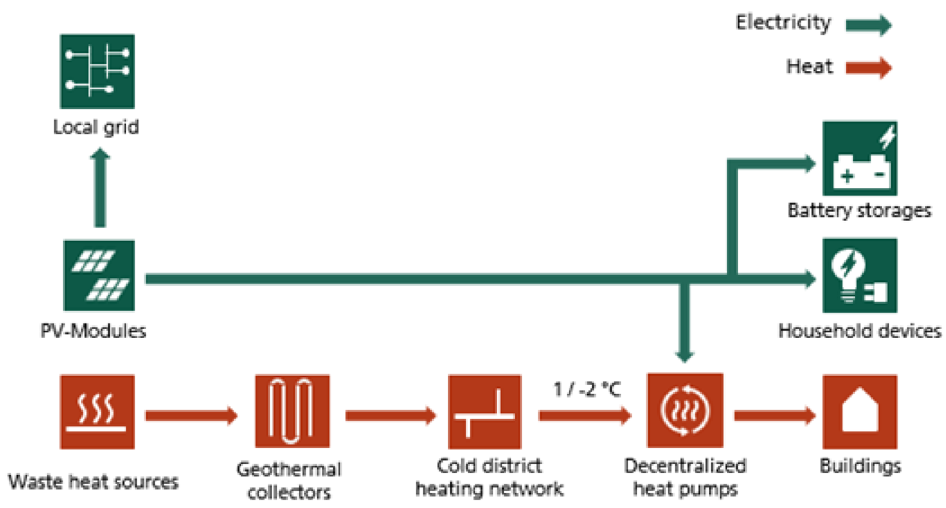


Figure 30: Scheme of the feasibility study for the Lagarde campus

Ospitaletto cold district heating in Brescia (Italy) – Realized (Calixto et al., 2021)**:** The Ospitaletto district heating (DH) network is supplied with sustainable heat (waste heat and aquifer wells) at a temperature between 15 and 25 °C. The network uses partly non-insulated pipes due to the large availability of waste heat (obtained at zero costs from the foundry, which gets the benefit of reduced cooling costs) and to the low supply temperature, which reduces heat losses.

11.5 WASTE HEAT FROM ELECTROLYSERS

This case studies are based on a literature review and no detailed description is available in appendix H. However, they are included for completing the overall picture of Hybrid Energy Networks and their (indirect) connection to gas networks.

MPREIS Hydrogen (Austria): The supermarket chain MPREIS is generating green hydrogen in Völs, Tyrol. The 3.2 MW plant is currently the largest single-stack electrolyser in Europe. Alkaline pressure electrolysis is the chosen technology for the generation. The generated hydrogen is used in their bakeries and as fuel for their own truck fleet. The waste heat is reused in their production processes. 70% of the input electricity is converted to hydrogen while about two thirds of the heat losses are reused ("MPREIS Wasserstoff," n.d.).

Pilot project „Power to Gas" Ibbenbüren (Germany): In the city of Ibbenbüren, a plant for hydrogen production by PEM electrolysis with a rated power of 150 kW is being tested since 2015. The aim of the test is to proof the functionality of an electrolyser in interaction with the fluctuating electricity production from renewables under real-life conditions. This plant is the first one in Germany with a multiple waste heat utilization at a temperature of around 56 °C. The overall efficiency of the system is at 86% (Stabenau and GmbH, n.d.) ("RWE-Demonstrationsanlage Ibbenbüren," n.d.).

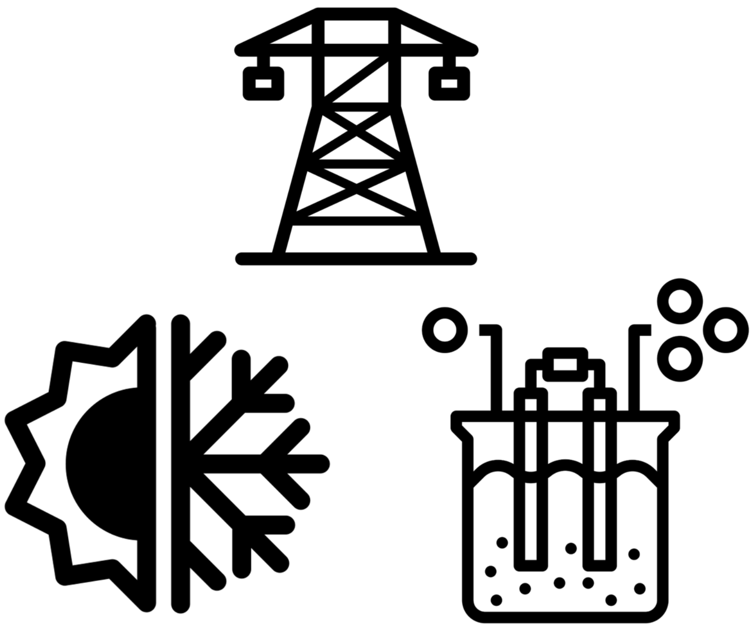
WindGas Falkenhagen (Germany): Uniper has built a demonstration plant for the generation of green hydrogen by alkaline electrolysis fed by wind power. The 2 MW plant is in operation since May 2018. The hydrogen is supplied to a high-pressure natural gas grid. The heat from the process is used in an adjoining veneer factory ("WindGas Falkenhagen," n.d.).

Green Hydrogen Esslingen (Germany): For a newly developed city quarter with a size of 120,000 m², a climate-neural energy concept was developed that includes the production and use of green hydrogen. The 1 MW electrolyser, capable of producing 400 kg of hydrogen per day, is powered by excess electricity from the rooftop PV installations and a nearby wind turbine. The hydrogen is used for different applications: feed-in into the local gas grid, mobility applications and for the generation of electricity in times of low renewable production. The waste heat of the electrolyser is utilized for heating the quarter, raising the overall efficiency of the system to around 90% (Green Hydrogen Esslingen GmbH, 2022).

H-Flex project Nieuwegein (Netherlands): Within the H-Flex project, a 2.5 MW PEM electrolyser is planned in the City of Nieuwegein to supply 250 t of hydrogen per year for a hydrogen refueling station. The system generates waste heat at a temperature of 62 °C that can be used in an adjacent laundry. A detailed techno-economic analysis of the use case revealed that 1,720 MWh of heat can be delivered to the customer at 54 °C, resulting in annual costs savings of 65,000 € and CO_2 savings of 480 t due to reduced natural gas consumption. With the heat utilization, the overall efficiency of the system increases to 91% (Els van der Roest et al., 2022).

PART E – OPTIMIZATION AND EVALUATION

In this part of the guidebook, different tools and methodologies for modelling, simulating, and evaluating Hybrid Energy Networks are discussed (section 12), and a resource exergy analysis of Hybrid Energy Networks is performed (section 13). Finally, the strength, weakness, opportunities, and threats of Hybrid Energy Networks are discussed (section 14).



12 MODELING, SIMULATION, AND OPTIMIZATION

Authors[27]: Edmund Widl (AIT), Daniel Muschick (BEST), Andrej Jentsch (Richtvert/AGFW), Anna Cadenbach (Fraunhofer IEE), Young Jae Yu (Fraunhofer IEE), Dennis Cronbach (Fraunhofer IEE), Peter Sorknaes (Aalborg University), Jaume Fito (CEA), Maurizio Repetto, (Politecnico di Torino), Julien Ramousse (USMB), Anton Ianakiev (NTU).

A transition towards Hybrid Energy Networks is a necessary requirement to implement sector coupling on a large scale. However, this transition poses practical challenges, because the traditional domain-specific approaches struggle to cover all aspects of Hybrid Energy Networks. Methods and tools for conceptualization, system planning and design as well as system operation support exist for all involved domains, but their adaption or extension beyond the domain they were originally intended for is still a matter of research and development.

This section presents innovative concepts for assessing the technical, economic, and ecological aspects of Hybrid Energy Networks in a holistic way. These tools and methods focus not only on the integration of coupling points, but on the effects of coupling energy networks on the system level. This Section presents innovative tools for modelling, simulating, and optimizing Hybrid Energy Networks. To put a strong focus on applicability for potential users, care was taken to select only tools that are publicly available (commercially, open-source or otherwise) and whose use for assessing Hybrid Energy Networks is documented.

12.1 BACKGROUND

Traditional tools for modelling, simulating and optimizing energy networks typically target just one specific engineering domain, e.g., heat networks (Talebi et al., 2016) or power grids (Bam and Jewell, 2005; Foley et al., 2010; Pochacker et al., 2013). At best, only coupling points to other domains can be modelled, but not Hybrid Energy Networks in their full complexity. The reason is that these tools are either the result of long-term academic research efforts of specific fields of engineering or have been developed by industry with a specific aim and audience in mind. With the advent of smart grids, this focus has been broadened to include communication networks (Muller et al., 2018; Duy Le et al., 2019), but not Hybrid Energy Networks.

Research on multi-energy systems has focused primarily on matching supply and demand through the optimization of either the planning or the operation of a diverse set of generation, storage and conversion units (Guelpa et al., 2019; Mancarella, 2014). This is also reflected by the tools and methods used for the assessment of multi-energy systems, see for instance

[27] This is a summary of a journal article on the modelling and simulating Hybrid Energy Networks. Please refer to the publication for full details and additional information (Widl et al., 2022).

recent reviews on tools and methods for modelling energy systems on the urban scale (Markovic et al., 2011; Allegrini et al., 2015; van Beuzekom et al., 2015; Ferrari et al., 2019; Scheller and Bruckner, 2019), for standalone and grid-connected hybrid energy systems (Sinha and Chandel, 2015; Weinand et al., 2020), or the energy transition in general (Chang et al., 2021).

The consideration of effects of multi-energy applications on the related network infrastructures started basically with studies on coupled power and gas grids. In this traditional type of Hybrid Energy Network, the subsystems are primarily coupled through gas-fired generators on a large scale. Research focused therefore on long-term expansion planning (He et al., 2018), long-term optimal planning (Farrokhifar et al., 2020), and short-term optimal operation (Raheli et al., 2021) of coupled power and gas networks. However, it turns out that most publications on this subject introduces methods (i.e., typically a mathematical optimization model combined with an optimization method), but no readily available tools for users.

Work on Hybrid Energy Networks that couple power and heat, in comparison, is a rather new topic (Sorknæs et al., 2015; Lund, 2018). Especially the simulation-based technical assessment of this type of Hybrid Energy Networks –where the focus lies on issues related to the operation and closed-loop control of the networks themselves – has remained a challenge. The development of tools and methods for overcoming this challenge is basically still ongoing (Leitner et al., 2019; Puerto et al., 2019; Lohmeier et al., 2020; Richert and Jensen, 2020; Song et al., 2021; Wirtz et al., 2021).

12.2 SURVEY PROCESS AND SELECTION CRITERIA

Section 12.3 presents innovative tools for modelling, simulating, and optimizing Hybrid Energy Networks. These tools have been identified based on an online survey and a subsequent literature survey. The online survey was targeted at tool developers (from both academia and industry) and was promoted through the international network of the IEA DHC Annex TS3, with the aim of reaching as many potential contributors with a relevant background in energy modelling as possible. The subsequent literature review was primarily based on the review articles on tools and methods for multi-energy systems presented in Section 12.1.

This survey process was successful in covering the outputs from different communities (district heating and cooling, Smart Grids, buildings, etc.) working towards the subjects of multi-energy systems and Hybrid Energy Networks from different angles. The results were correspondingly broad and diverse, which required additional selection criteria for focusing specifically on readily available tools and methods intended for the analysis of Hybrid Energy Networks.

Only tools that verifiably meet all the following selection criteria have been included:

- **Focus on multi-energy networks**: At least two types of energy networks must be considered. Each energy network must be considered at least on the level of energy balances (implicit network model). This includes a focus on the grid infrastructure, so that the results are directly relevant for the planning and operation of hybrid energy grids (e.g., quality of service or congestion).

- **Documentation**: An application in the context of Hybrid Energy Networks must be publicly documented (manual, journal article, etc.).

- **Availability**: An implementation of the tool must be publicly available, either commercially or otherwise (open source, freeware, etc.).

The selection criteria aim at distinguishing tools for multi-energy systems from tools with the narrower focus on Hybrid Energy Networks. They also restrict multi-purpose tools that could be theoretically used for analysing a Hybrid Energy Network to those where a specific demonstration of this use-case was found. This follows the spirit of this work, which explicitly puts the attention on tools for the assessment of Hybrid Energy Networks. The selection criteria also assure that the tools presented in this report are accessible for users and easily applicable to their problems. This is important in view of the discussion in Section 12.4 , which aims at providing a guideline for early adopters for understanding which tools and methods best fit the requirements of their specific applications.

12.3 SELECTED TOOLS

Table 13 lists all selected tools in alphabetical order and presents their purpose in terms of modelling, simulation, and optimization according to the developers. In the following, a brief introduction to each tool is provided, outlining their different approaches for modelling, simulating, and optimizing Hybrid Energy Networks.

Table 13: Selected Tools for Hybrid Energy Networks

Tool name	Modelling Tool	Simulation Tool	Optimization tool
COMANDO	✓		✓
Co-simulation		✓	
EHDO	✓		✓
EnergyPLAN	✓	✓	
energyPRO	✓	✓	✓
ESSIM	✓	✓	
GasPowerModels.jl	✓		✓
Integrate	✓		✓
Modelica	✓	✓	
Pandaplan	✓	✓	
PLEXOS	✓		✓
PyPSA-Eur-Sec	✓		✓
rivus	✓		✓
SAInt	✓	✓	

The open-source framework **COMANDO** (Langiu, 2022) provides component-oriented modelling and optimization for the nonlinear design and operation of energy systems. COMANDO is developed at the Institute of Energy and Climate Research at Forschungszentrum Jülich (Germany). The behaviour of individual components is represented with detailed models, considering dynamic and nonlinear effects with the help of physics-based, data-driven or hybrid modelling approaches. These component models are used for building energy system models, based on which optimization problems related to the design and/or operation of the energy system can be formulated. In addition, COMANDO includes capacitive models[28] for peripheral storage units (electrical, heat, cold). COMANDO allows to

[28] Capacitive models describe all kinds of energy storage systems (batteries, hot water tanks, etc.) by means of their maximum energy storage capacity and state of charge, analogous to a capacitance in an electrical circuit.

consider multiple operating scenarios via stochastic programming formulations, allowing to find system designs that are suitable for operation under uncertainty. To solve these optimization problems, COMANDO translates its models to representations that are suitable for external solvers (Gurobi, BARON, SCIP, etc.). Alternatively, it can be integrated into other algebraic modelling languages (Pyomo, GAMS). The implementation in Python makes it possible to extend COMANDO by including additional Python modules. Examples of applying COMANDO to heat and power networks are given in (Langiu et al., 2021) and (Glucker et al., 2022), respectively.

Co-simulation of network simulators: Modelling an entire system of systems in one universal language, with one tool, may lead to simplifications that neglect important properties and dynamic dependencies (Palensky et al., 2014). In contrast, domain-specific tools provide validated libraries, optimal solvers, and a language that perfectly fits the problem domain. Therefore, combining specialized simulators for different types of energy networks in a so-called co-simulation is a viable approach for assessing Hybrid Energy Networks. In general, co-simulation refers to a generic approach where simulators are coupled at runtime for jointly simulating a system. The simulators exchange data at specific synchronization points, in between they calculate the state of their respective subsystems independently. Dedicated co-simulation environments exist which help with the coupling of simulators and their synchronization. The modelling of the individual subsystems is done separately with the help of the corresponding network simulators. The features of the resulting overall model depends on the features implemented by the selected simulators. A detailed example of using a co-simulation approach for the assessment of coupled power and heat networks is given in (Leitner et al., 2019), which uses the co-simulation framework FUMOLA (Widl, 2017) for interfacing the Modelica library DisHeatLib (AIT-CES, 2022) and Pandapower (Thurner et al., 2018). Similar examples are provided in (Richert and Jensen, 2020) which uses the co-simulation framework mosaic ("Smart Grid co-simulation," 2019) and in (Puerto et al., 2019) which uses the co-simulation framework ZerOBNL(Energy Efficiency research group and CREM, n.d.).

EHDO (Wirtz et al., 2020) is an open-source webtool for the optimal design of complex multi-energy systems. It is developed by the Institute for Energy Efficient Buildings and Indoor Climate at RWTH Aachen University (Germany) for academic teaching. EHDO is conceived as a support tool for the early planning phase of future smart energy systems, optimizing the choice and the sizing of energy conversion units. A user-friendly graphical user interface enables the creation of energy hubs of different sizes (from building complexes to large districts) from a variety of component models (PV, wind turbines, fuel cells, electrolysers, biomass, and waste-to-energy technologies, etc.). In addition, it provides capacitive models of peripheral storage units (electricity, gas, hydrogen, heat, cold). EHDO uses mixed-integer linear programming (MILP) to define a set of mathematical constraints for each component model and asserts energy balances, conversion efficiency ratios, maximal load limitations, and storage constraints at hourly time steps. It relies on an external solver (Gurobi) for solving optimization problems. The implementation in Python makes it possible to extend EHDO by including additional Python modules. An example for using EHDO for Hybrid Energy Networks is given in (Wirtz et al., 2021), where the developers present the full range of supported systems and carriers, and provide two illustrative case studies.

EnergyPLAN (Department of Development and Planning, n.d.) is a freeware simulation tool for holistic energy system analyses including all energy sectors. EnergyPLAN is programmed in Delphi Pascal and is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University (Denmark). EnergyPLAN is based on a series of endogenous priorities within, e.g., power and heat production and predefined procedures for simulating the operation of units that are freely dispatchable. In addition, it provides capacitive models for peripheral storage units (electricity, gas, hydrogen, heat, hydro). The inputs to EnergyPLAN are energy demands, energy conversion units and resources, costs, and choices related to simulation methods incl. operational constraints in relation to electricity grid stability. EnergyPLAN chronologically simulates the operation of an energy systems for a leap year on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors and the interconnections between these. EnergyPLAN provides a graphical user interface (GUI) but can also be used from the command line or via dedicated toolboxes from MATLAB (Cabrera et al., 2020) and Python (Prina et al., 2018). An example for using EnergyPLAN for Hybrid Energy Networks is given in (Lund, 2018), which analyses the benefits of a combined, cross-sectoral use of all types of grids (power, heat and gas) for renewable heating strategies.

energyPRO (Jernes, n.d.) is a tool for combined techno-economic analysis and optimization of energy flows with a focus on combined energy supply of e.g. electricity and thermal energy (process heat, hot water, and cooling). energyPRO is a commercial tool that is developed and maintained by EMD International A/S (Denmark). The focus of energyPRO is on the operation of energy conversion technologies and energy storage technologies (electrical, fuel, heat, cold, pumped hydro). However, capacity constraints in energy grids can be included in the modelling, as they relate to the operation of energy conversion and storage technologies. energyPRO optimizes the operation of the modelled components based on the technical and economic parameters defined in the model, which can include local energy demands, fuel costs, tariffs, electricity markets, part-load efficiencies, etc. This optimization is either performed via an internal analytical method or via a MILP approach (using CBC or Gurobi as solver). energyPRO provides a GUI but can also be used in batch mode from the command line. An example for using energyPRO for Hybrid Energy Networks is given in (Sorknæs et al., 2015), which analyses how small-scale district heating plants can improve their economic feasibility by providing balancing services to the electricity system.

The **Energy System Simulator (ESSIM)** (Subramanian et al., 2021a) is an open-source tool for calculating energy flows in interconnected Hybrid Energy Networks developed by TNO (The Netherlands). ESSIM calculates energy flows between network components – referred to as assets – and between different types of networks over a period of time with hourly intervals. Assets representing peripheral storage devices (electricity, gas, hydrogen, heat) are included as capacitive models. For each time interval, the scheduling of controllable, "flexible" assets and the energy balance for all involved networks is determined based on marginal costs. ESSIM is implemented using the modelling language Energy System Description Language (ESDL). A GUI is provided for defining assets and their geographical locations, see Figure 31. ESSIM computes and visualizes key performance indicators and gives insights into how well the assets in a network are dimensioned, e.g., if there is overloading in any given transport asset (pipe, cables, etc.). ESSIM provides a REST API that allows users to interact with it and enables the combination with more detailed power flow models (e.g., Pandapower). An example for using ESSIM for Hybrid Energy Networks is available online (Subramanian et al., 2021b), which demonstrates how excess electricity production from local energy sources is converted to hydrogen and used in a hydrogen gas network.

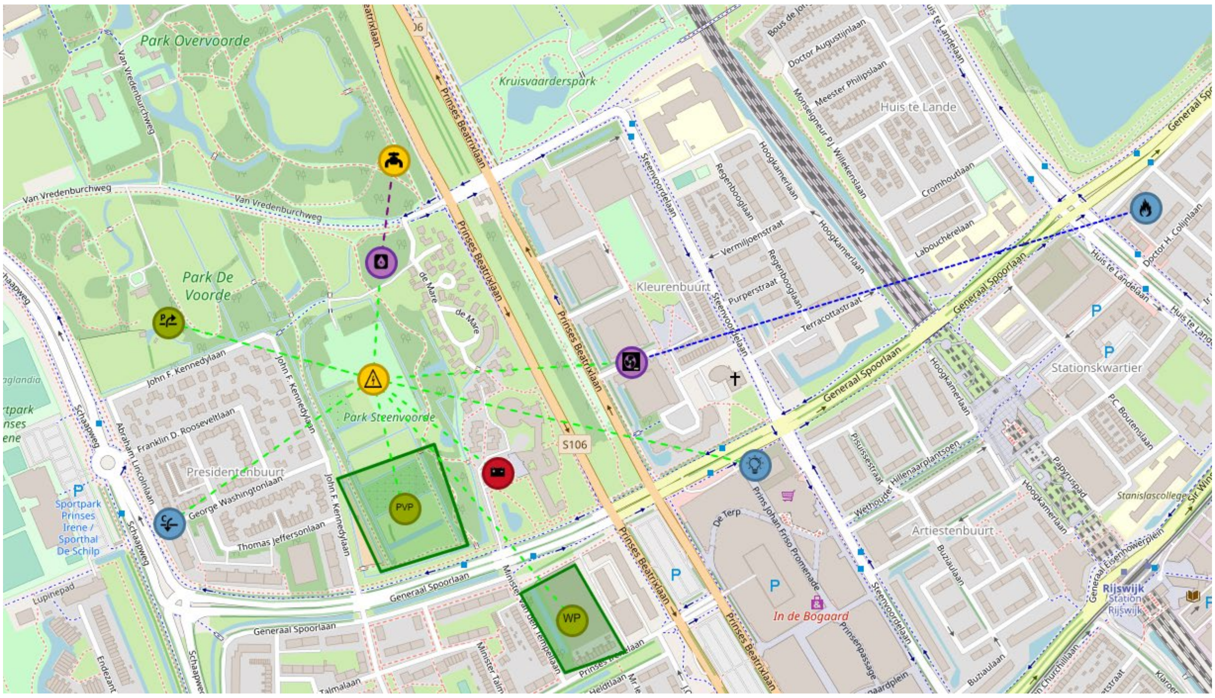


Figure 31: Screenshot of ESSIM's map editor showing a model comprising an electricity network coupled to a hydrogen network (source: https://essim-documentation.readthedocs.io).

GasPowerModels.jl ("GasPowerModels," n.d.) is a package for the joint optimization of power transmission networks and natural gas networks. Its development is a joint effort of the Los Alamos National Laboratory, the University of Michigan and the Pennsylvania State University.

The package combines elements and steady state models from two preceding packages, i.e., GasModels.jl for gas flows and PowerModels.jl for power flows. The model used by GasPowerModels.jl decouples network formulations (e.g., mixed-integer convex) from problem specifications (e.g., network expansion planning). Thanks to this decoupling, it is possible to define a variety of optimization formulations and compare them on common problem specifications. The resulting models are in general mixed-integer nonlinear programs. GasPowerModels.jl is implemented in JuMP which makes it possible to extend it by including additional Julia or Python modules. JuMP depends on external solvers for solving optimization problems and supports several open-source (SCIP, Ipopt, etc.) and commercial solvers (Gurobi, CPLEX, etc.) for a variety of problem classes. The application of GasPowerModels.jl to Hybrid Energy Networks is documented and illustrated in (Bent et al., 2018), analyzing the natural gas and electric power systems in the Northeastern United States, and (Sanchez et al., 2016), which combines the IEEE 14-bus test system with the Belgian natural gas network.

Integrate (Askeland, n.d.) is a tool for investment planning of multi-carrier energy grids (Bakken and von Streng Velken, 2008). Formerly called eTransport, it is being developed by SINTEF Energy Research (Norway). Integrate considers projections in energy demands as well as mature and emergent technologies for energy supply, conversion and distribution of different energy carriers. It provides capacity models for different types of peripheral storage units (hot water tanks, hydrogen storage, etc.) and also considers carbon dioxide capture and storage (CCS), to comply with end-use measures and CO_2 emission restrictions. Integrate performs an operational optimization by formulating a MILP problem, solved with the COIN-OR solver. It minimizes investment, operation and emissions costs while meeting predefined demands of electricity, space heating, tap water heating and gas over a given time horizon, including alternative supply infrastructures (Bakken and von Streng Velken, 2008). The tool comes with a graphical user interface for modeling energy systems. At the time of writing, Integrate provides no API but a connection with the Spine (Spine, 2017) toolbox is planned. The application of Integrate to Hybrid Energy Networks is documented in (Kauko et al., 2022), which analyses the potential of seasonal thermal storage for local energy systems.

Modelica (Modelica Association et al., 2000) is an object-oriented language for modelling cyber-physical systems, developed by the Modelica Association. A system modelled in Modelica may combine electrical, mechanical, thermal, or hydraulic components. It is also possible to add controllers to simulate different control strategies. A comprehensive standard library is available open-source, additional relevant libraries are available either free of charge (e.g.,TransiEnt (Becker, n.d.) for Hybrid Energy Networks, OpenIPSL (de Castro et al., 2023) for power systems, or the DisHeatLib (AIT-CES, 2022) for heat networks) or commercially (e.g., the multi-domain Modelon Library Suite (Modelon, n.d.)). Modelica relies on differential, algebraic, and discrete equations for modelling, enabling the analysis of both static and dynamic system behaviour. Modelica itself is a text-based modelling language but there are several Modelica-based modelling and simulation environments available (both open-source and proprietary). They typically provide graphical user interfaces for modelling (see Figure 32), advanced numerical solvers for simulation, and various interfaces to other simulation environments, e.g. via the Functional Mock-up Interface (Blochwitz et al., 2011) standard. An example for using Modelica for Hybrid Energy Networks is given in (Song et al., 2021), where the effects of cascading failures are analysed for a coupled heat and power network. Another example is given in (Anne Senkel et al., 2021), where networks for gas, heat and power are coupled through a combined-cycle power plant with heat extraction and an electrolyser.

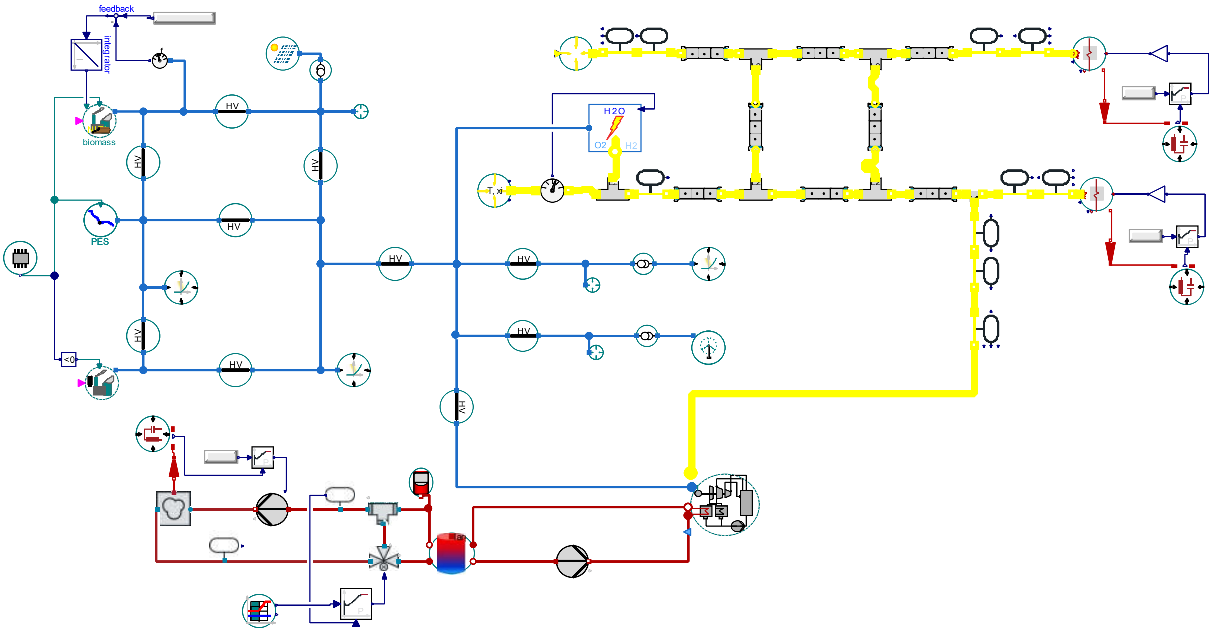


Figure 32: Example for the graphical representation of a Hybrid Energy Network in Modelica, showing a TransiEnt model coupling networks for power (blue), heat (red) and gas (yellow).

Pandaplan (Fraunhofer IEE, 2020) consists of the two open-source tools Pandapower (Thurner et al., 2018) and Pandapipes (Lohmeier et al., 2020). It is developed at the Fraunhofer Institute for Energy Economics and Energy System Technology (Kassel, Germany). Both Pandapipes and Pandapower are based on the programming language Python. While Pandapower can be used to model and simulate power grids, Pandapipes can be utilized to evaluate the pressure, flow velocity and temperature distribution in gas and district heating grids. Pandapower and Pandapipes use the same data structure to describe networks and can thus be combined easily to simulate coupled infrastructures. Coupling points, like heat pumps or power-to-gas plants may be modelled using controller components, which can also be used to implement a specific operational strategy. In addition, Pandapower provides capacitive models for electrical storages. Components are described by algebraic and/or differential equations, and the resulting system of equations is solved with the Newton-Raphson method. While it is possible to simulate time-dependent systems, it is not possible to study the dynamic system behaviour, as inertial effects are neglected. The implementation in Python makes it possible to extend the simulation by including additional Python modules. The application of Pandaplan to Hybrid Energy Networks is illustrated in (Lohmeier et al., 2020), which studies the flexibility potential of power-to-gas in a coupled power and gas grid.

The PLEXOS Integrated Energy Model (Energy Exemplar, n.d.) is an energy modelling and forecasting platform. PLEXOS is a commercial tool that is developed and maintained by Energy Exemplar Pty Ltd (Australia). Previously developed as an electricity market simulator, its functionality has been extended to integrate electric power, gas, and hydro. PLEXOS supports primarily assessments such as price forecasting, portfolio optimization (unit commitment and economic dispatch problems) or long-term capacity expansion planning. However, it also supports network modelling at different levels of detail (regional, zonal, nodal) which allows to capture technical aspects relevant for Hybrid Energy Networks such as congestion and network losses. In addition, it provides capacitive models for batteries, pumped hydro storage and gas storage. Modelling is generally carried out using deterministic linear programming techniques that aim to minimize a single objective function subject to the expected dispatch costs, considering several constraints including availability and operational characteristics of generating plants, fuel costs, operator and transmission constraints, and others. PLEXOS is primarily used through a graphical user interface but also has an API that can be used from any .NET environment. PLEXOS allows to use different commercial optimization engines (e.g, CPLEX, Gurobi). The application of PLEXOS to Hybrid Energy Networks is illustrated in (Devlin et al., 2017), which shows a multi-vector energy analysis for interconnected power and gas systems in Britain and Ireland.

PyPSA-Eur-Sec (PyPSA-Eur-Sec, 2019) is an open model of the sector-coupled European energy system. At the time of writing, the tool is maintained by the Department of Digital Transformation in Energy Systems at the Technical University of Berlin (Germany), developed in collaboration with the KIT Karlsruhe Institute of Technology (Germany) and Aarhus University (Denmark). PyPSA-Eur-Sec is designed as a module of the PyPSA toolbox (Brown et al., 2018), enabling the modelling of the transmission networks of the ENTSO-E area. It can model electricity, hydrogen, and gas grids, with numerous sources (e.g., renewables, biomass, or fossil fuels) and generation technologies (e.g., heat pumps, fuel cells or CHP). In addition, it provides capacity models for energy storage at different time scales, including batteries, pumped hydro storage, hydrogen storage and hot water storage. Moreover, PyPSA-Eur-Sec considers transformations in industry, aviation and shipping, and the use of CCS. PyPSA-Eur-Sec uses a myopic approach with 5-year time steps from 2020 to 2050, minimizing for every time step the total system cost (incl. CO_2 constraints). For every time step, the overall model is optimized with the help of an external solver (Gurobi, CPLEX, etc.), assuming a long-term market equilibrium with perfect competition and perfect foresight. The implementation in Python makes it possible to extend the simulation by including additional Python modules. An example for using PyPSA-Eur-Sec for Hybrid Energy Networks is given in (Victoria et al., 2022), which identifies economy-optimal energy transition paths at the European level under different carbon budgets.

rivus is an optimization model for capacity planning for multi-commodity energy infrastructure networks, developed at the Technical University of Munich (Germany). Its name – Latin for stream or canal – stems from its origin as a companion model for urbs (Dorfner, 2016), an optimization model for urban energy systems. rivus implements a single-objective MILP model that finds the minimum cost energy infrastructure network to satisfy a given energy distribution for multiple commodities (e.g., electricity, heating, cooling). Time is represented by a (small) set of weighted time steps that represent peak or typical loads. Spatial data can be provided in form of shapefiles, while technical parameters can be edited in a spreadsheet. rivus relies on Pyomo for modelling equations and as the interface to optimization solvers (CPLEX, Gurobi, CBC, etc.). The implementation in Python makes it possible to extend the simulation by including additional Python modules. An example of using rivus for the assessment of Hybrid Energy Networks is reported in (Alhamwi et al., 2022), where different network topologies for coupled power, heat and gas networks are analysed for a city district.

SAInt (encoord, n.d.) is a simulation tool for assessing security of supply in interconnected gas and electrical transmission networks. SAInt is a commercial tool that is developed and maintained by encoord GmbH (Germany). It comprises a transient hydraulic model for the gas system to reflect the changes in pressure and the quantity of gas stored in pipelines, enabling for instance the assessment of imbalances between gas supply and gas demand and the resulting fluctuations in linepack. For the electrical power system an augmented AC optimal power flow model is used, which includes dispatchable loads and considers ramp rates and the start-up times of generation units. The bidirectional interconnection between both systems is considered through equations describing the fuel gas offtake for power generation in gas fired power plants, and the electric power supply to liquefied natural gas terminals (LNG) terminals and electric driven compressors in gas compressor stations. The resulting system of equations is solved iteratively by a sequential linearization method which updates the boundary conditions expressed by the coupling equations at each iteration step. SAInt can assess the gas storage capacity in pipeline systems and also provides models for gas storage in peripheral facilities (LNG terminals, underground caverns, etc.). SAInt is mainly programmed with Visual Basic and uses IronPython as a scripting language for interacting with the user. It provides a graphical user interface (see Figure 33) and an API that can be used from any .NETenvironment for accessing solvers and classes representing the different assets in gas and power systems.

The application of SAInt to Hybrid Energy Networks is illustrated in (Pambour et al., 2017), which shows how disruptions in a coupled gas and power system can affect the operation of both systems and how counter measures to mitigate their impact can be assessed.

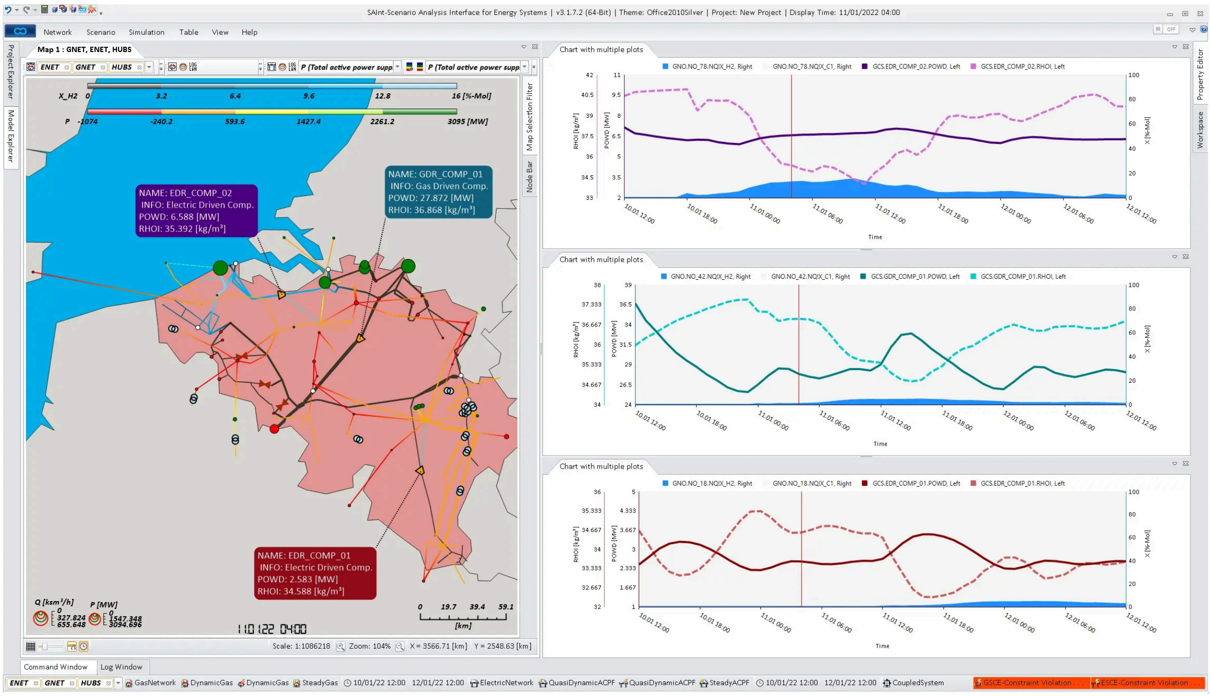


Figure 33: Screenshot of SAInt's user interface showing the model and simulation results for a coupled electricity and gas network (source: https://www.encoord.com).

12.4 CLASSIFICATION OF TOOLS

The tools described in Section 12.3 are not simply extensions of established domain-specific or multi-energy tools, but rather provide new features specifically for analysing Hybrid Energy Networks, e.g., the assessment of the combined state of the networks or the mutual impact of the networks on each other. They cover a wide range of modelling and simulation approaches, and thus enable different insights regarding Hybrid Energy Networks. As such, they help to provide as results the real technical, economic, and environmental advantages of the hybrid paradigm.

However, not every tool is suitable for every task. To provide a concrete recommendation of which tools to use for which applications, four areas of application specific to Hybrid Energy Networks have been defined: characterization/state determination, optimization of planned grids, operational optimization (technical), and operational optimization (economical). See Table 14 for details. Each area of application is characterized by an objective, i.e., the rationale and intended purpose of using a specific tool.

Table 14: Applications areas for selected tools for Hybrid Energy Networks

Application Area	Description	Examples
Characterization/ state determination	evaluation of the state of a Hybrid Energy Network without interpreting or changing its properties	calculation of gas/heat storage potential of pipelines; load flow analysis for calculating the voltages, currents, pressures or temperatures at the network nodes
Optimization of planned grids	useful for the planning of Hybrid Energy Networks, where the overall network design is optimized	improvement of grid topology for optimizing the efficiency of coupling points; positioning of plants and devices for reducing network losses
Operational optimization (technical)	improvement of the Hybrid Energy Network system performance with a main focus on technical aspects	model-predictive control for storages to improve local self-consumption; control algorithm for power-to-gas plants to maintain a given gas composition in the grid
Operational optimization (economical)	improvement of the Hybrid Energy Network system performance with a main focus on economic aspects	model-predictive control for cost-optimal unit commitment of plants; algorithm deciding how to use PV excess power (grid feed-in or self-consumption) based on market price predictions

An expert review was performed to assess the selected tools in terms of their usefulness for these areas of application. Table 15 shows the corresponding results. These results can also be summarized by classifying the tools in the following application categories:

- **technical assessments**: Pandaplan, Modelica, co-simulation, COMANDO, SAInt
- **operational optimization** (technical & economical): energyPRO
- **planning on the scale of cities / regions**: EHDO, EnergyPLAN, ESSIM, Integrate, rivus
- **planning on the scale of nations / continents**: GasPowerModels.jl, PLEXOS, PyPSA-Eur-Sec

Table 15: Intended purpose of selected tools for Hybrid Energy Networks

tool	characterization / state determination	optimization of planned networks	operational optimization (technical)	operational optimization (economical)
Pandaplan	✓		✓	
Modelica	✓		✓	
Co-simulation	✓		✓	
COMANDO	✓		✓	
energyPRO			✓	✓
EHDO		✓		
EnergyPLAN		✓		
ESSIM	✓	✓		
Integrate		✓		✓
rivus		✓		
GasPowerModels.jl		✓	✓	✓
PyPSA-Eur-Sec		✓		✓
PLEXOS		✓		✓
SAInt	✓	✓	✓	

13 RESOURCE EXERGY ANALYSIS

Main author[29] Andrej Jentsch (AGFW), Contributing authors: Anna Cadenbach (Fraunhofer IEE), Young Jae Yu (Fraunhofer IEE), Julien Ramousse (USMB)

This section presents the results of resource exergy analysis (REA) of Hybrid Energy Networks. REA (Jentsch, 2023) is a proven type of exergy analysis that can replace primary energy analysis with a more comprehensive and consistent methodology, thus helping to avoid suboptimal decisions that lead to an avoidable increase in overall greenhouse gas emissions. See also Appendix I for details.

13.1 INTRODUCTION

To stop climate change it is necessary to minimize short- and long-lived greenhouse gas emissions[30] (GHGE) as much as possible. But energy systems that are free of direct GHGE can still cause an overall increase GHGE if the energy economy is still using GHGE-emitting sources. The reason for this effect is avoidable consumption. Avoidable consumption in otherwise GHGE-free energy systems decreases the amount of GHGE-free energy supply available for the rest of the energy system.

If energy supply systems that cover additional demands (i.e., marginal power plants) generate significant amounts of GHGE, fewer GHGE-free energy supply systems increase overall GHGE. Whether this system-wide increase is higher or lower than the direct reduction caused by an energy system varies, but only a consistent consideration of overall system consumption can ensure that low-impact solutions can be selected.

[29] Please refer to (Jentsch, 2023) for full details and additional information The underlying calculations for the results have been performed with the energy system assessment and comparison tool “exergypass.com”.
[30] The 100-year horizon for evaluating CO_2 equivalents is a convention that underrepresents the effect of short-lived GHG gases such as methane. If significant amounts of natural gas are used it is recommended to also consider a 20-year horizon for the calculation of CO_2 equivalents. On this time scale natural gas combustion contributes similarly to climate change as coal combustion. The mid-term GHG gas mitigation is very important in order to avoid triggering tipping points in the climate system (Traber and Fell, 2019).

Definition of exergy: Exergy associated with a flow of mass or energy is the maximum work obtainable by using an ideal thermodynamic process to bring the flow into equilibrium with a clearly defined reference environment. The thermodynamic properties of the reference environment such as temperature, pressure and chemical composition should reflect properties of the ambient environment that do not change noticeably when exchanging energy or mass with the considered flow. The reference environment properties are thus assumed constant. (Rant, 1956; Jentsch, 2010)

Resource exergy analysis (REA) can help to minimize avoidable consumption and thus reduce system wide GHGE.

The exergy analysis performed in IEA DHC Annex TS3 illustrates how REA can replace primary energy analysis with a more comprehensive and consistent methodology thus helping to avoid suboptimal decisions that lead to an avoidable increase in overall GHGE.

REA builds on the concept of exergy and uses comprehensive system boundaries that allow to include all losses along the supply chain.

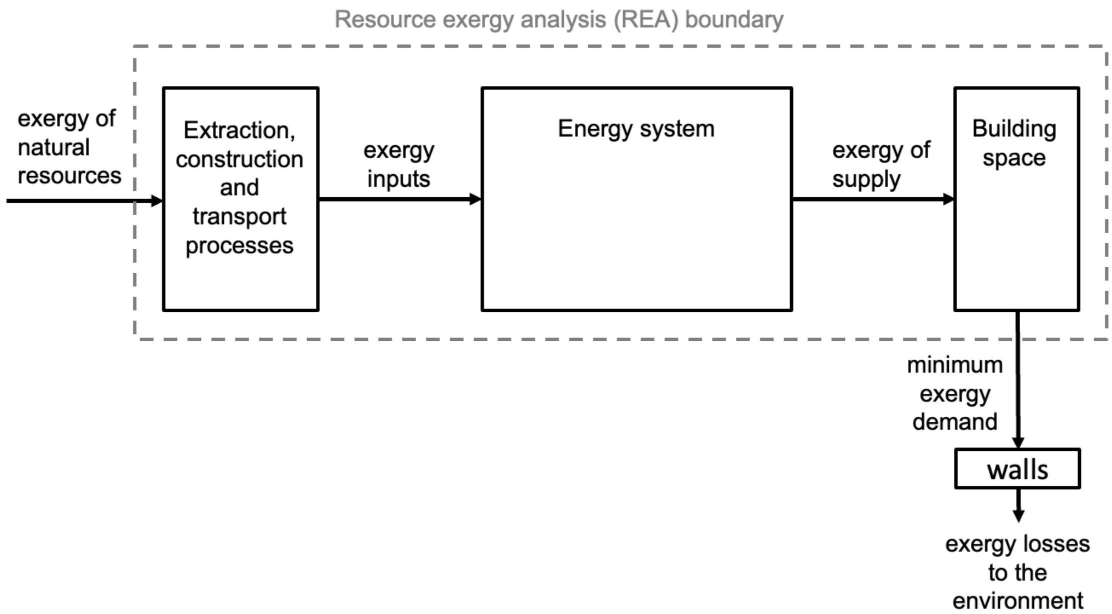


Figure 34: Balance boundaries to assess resource exergy consumption and resource exergy efficiency of thermal supply systems using resource exergy analysis

The following list shows key assumptions used in a simplified REA methodology that only considers energy resource flows and neglects the exergy associated with non-energy mass flows:

1. Only flows of directly storable primary energy are considered as input flows. In cases where the primary energy is not storable without transformation (solar radiation or kinetic energy of wind and running water) the first storable secondary energy is the resource for the comparison.

2. For the calculation of resource exergy efficiency, the minimum required amount of exergy with which the task could theoretically be accomplished is considered as the demand.

3. The comparability of the considered alternatives is ensured by keeping the supply task, such as thermal comfort and needs for mechanical and electrical work fixed. This makes it easier to pinpoint the causes for the identified improvements in energy supply systems.

To support decision making REA should be complemented with an analysis of GHGE and life cycle costs. Therefore, the fundamental calculations in the presented analysis have been done comparing energy systems using REA and GHGE analysis. Costs were not considered as they are not a physical criterion and vary greatly among countries, communities and with time. A cost assessment can always be added once energy systems with desirable environmental characteristics have been identified.

13.2 CALCULATION BASICS

For IEA DHC Annex TS3, six different heat supply scenarios are examined based on a new housing settlement in Neuburg on the Danube (Yu et al., 2020). The six scenarios (S) that were compared are

- S1: decentralized gas boilers,
- S2: low temperature district heating using 50% heat from a natural gas block combined heat and power (CHP) plant and 50% heat from a central natural gas boiler,
- S3: decentralized air-source heat pumps,
- S4: a very low temperature district heating network with a large central heat pump and decentralized electrical boilers,
- S5: a cold district heating network using heat from the ground as a source for decentralized water-water heat pumps and
- S6: a deep geothermal low temperature district heating network.

Scenario 1 and Scenario 6 are intended to provide reference scenarios for the evaluation of the considered hybrid energy systems. S1 allows a comparison with the current status quo. S6 shows one of the most resource saving and green thermal district heating sources.

On the demand side, the new housing settlement presented in this work consists of 31 single family houses and one multi- family house (see Figure 35), which are planned according to the German Energy Saving Ordinance. The calculated annual heat demand for space heating amounts to 324 MWh/a and for domestic hot water supply to 110 MWh/a (Holway, 2020). The electricity used in all scenarios is assumed to come from PV panels that are newly built on the roofs of the district's buildings. Thus, all results for hybrid energy systems can be considered best-case scenarios.

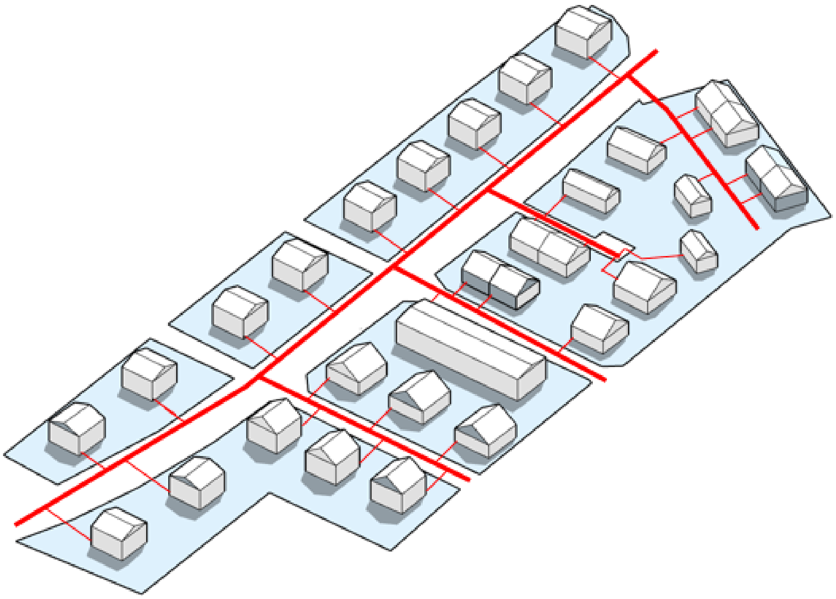


Figure 35: perspective drawing of the new housing settlement (Yu et al., 2020)

The REA applied to this scenario has been simplified to consider only effects of the operation of the heat supply system scenarios for the considered district and the cumulated energy consumption (CEC) for PV electricity, geothermal heat, and natural gas. The analysis does not consider the resource exergy of the material resources used or the resource exergy of the energy required to build the local energy systems and recycle them later.

13.3 RESULTS

The results of the performed analysis show that Hybrid Energy Networks can be among the most resource saving and low carbon heat supply solutions possible.

To achieve this outcome, it is important to ensure that the electric demand generated by these systems is covered by dedicated GHGE-free power supply. Using any other power source, even if labelled as GHGE-free, might not suffice as it can lead to an overall increase in GHGE. This is the case when additional fossil fuels are burned due to the electricity consumption of heat pumps.

In comparison to natural gas boilers hybrid energy systems can save more than 70% of resource exergy and over 90% of GHGE. All considered hybrid energy systems produce similar savings, so that the decision on what type of hybrid energy system is best for a given community largely depends on the heat demand density, the potential for heat networks or air-water heat exchangers and the availability of suitable heat sources apart from life-cycle cost considerations.

While Hybrid Energy Networks can be among the top solutions for decreasing resource exergy consumption (REC) and GHGE, they are not the only technology suitable for resource saving and climate friendly heat supply. Scenario 6 (District heating with deep geothermal heat) shows that district heating using suitable thermal sources can match or even outperform even best-case Hybrid Energy Networks. However, since thermal sources that can directly provide heat at the temperature levels required by the building stock and the potential for decentralized heat pumps can be locally limited, Hybrid Energy Networks with dedicated GHGE-free powers supply are one of the key technologies to supply low carbon heat to areas with high heat demand density.

Figure 36 shows the savings achievable in comparison to a decentralized natural gas boiler in terms of resource exergy consumption and GHGE (GWP100).

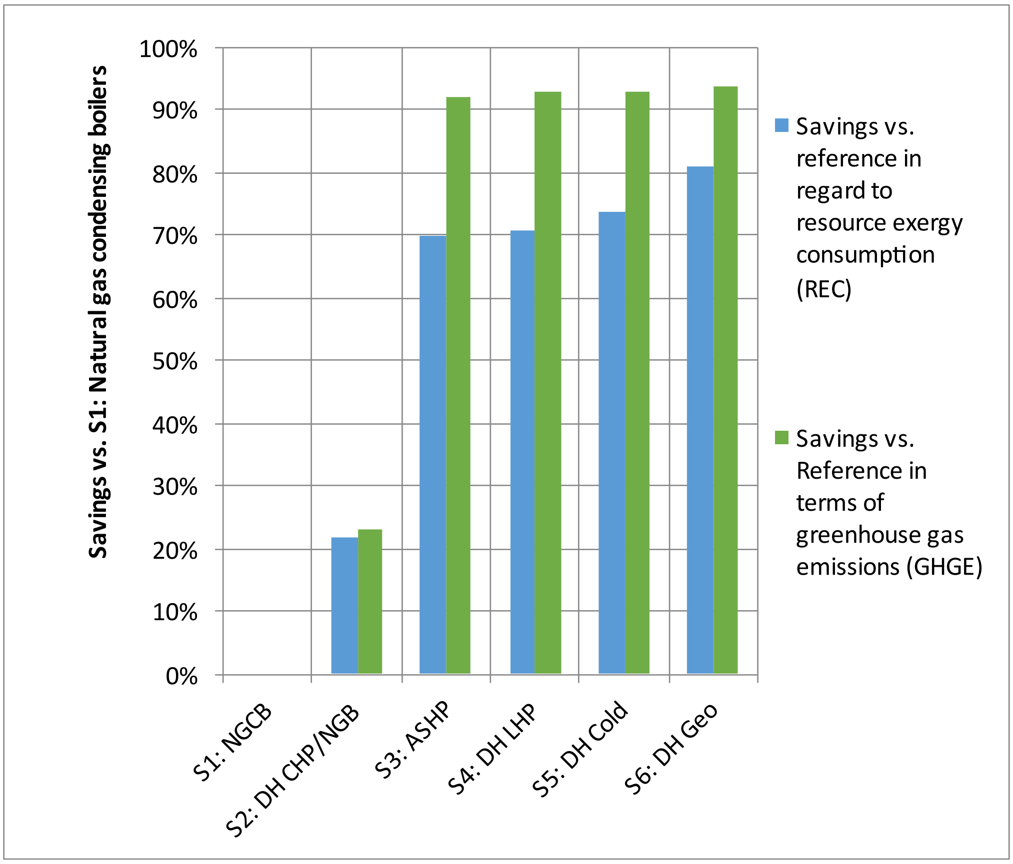


Figure 36: Savings versus a decentralized gas boiler achieved with the considered scenarios

Figure 36 shows that conventional district heating systems using 50% heat from CHP can already reduce REC and GHGE by over 20%. Since all this improvement stems from the CHP alone, this also shows that increasing the share of CHP in district heating can be a smart intermediate step to reduce emissions if fossil fuels are to be used.

Furthermore, it becomes obvious that all non-fossil systems (S3 – S6) considered, show significant improvements over the natural gas condensing boiler. Using dedicated PV power, the hybrid energy systems (HES) in S3 – S5 allow to achieve similar REC savings from 69% to 74% and GHGE savings from 92% to 93%.

While these slight differences could be explained if looking at the details of the analysis, any explanation would be very specific to the assumptions made. A small change in COP or in temperatures could void the minor improvements of one system over the other, so that in general all considered HES using dedicated PV power can be considered equally attractive in terms of REC and GHGE savings.

The assumptions made for the presented analysis show that heat losses and additional pump power needed for district heating systems can be compensated by higher COPs of the heat pumps used. This allows dense urban areas to benefit to a similar degree from heat pump technology as more rural or suburban structures, where air-water heat exchangers required for air-source heat pumps are usually more acceptable.

13.3.1 COMPARISON TO PRIMARY ENERGY ANALYSIS

In the following, the results of three types of primary energy analysis are shown and compared with the results of REA and GHGE analysis. The aim of the following comparison is to demonstrate how the choice of analysis methodology influences the results of energy system assessment and the following conclusions.

To assess the overall primary energy consumption (PEC) including the energy used for extraction, construction, and transport three different indicators are used.

1. Cumulated primary energy consumption (CPEC) uses the specific Cumulated Energy Consumption to represent pre-chain losses. It is the most scientifically accurate factor of the three energy indicators considered and can be found in free public databases. It also can be used as an element in a simplified REA if cumulated exergy consumption values are not available (Jentsch, 2023)
2. Total primary energy consumption (TPEC) is based on industry norms (DIN, 2010) that provide a simplified approach to assess pre-chain losses. It includes renewable and non-renewable energies alike but does not consider primary energy required for construction of the pre-chain infrastructure.
3. Fossil primary energy consumption (FPEC) only considers fossil primary energy. Renewable primary energy is not considered. Like TPEC it is based on industry

norms (DIN, 2010) and the most commonly used assessment criterion apart from CO_2 emissions in German law making at the time of writing.

Figure 37 shows the savings that can be achieved in respect to the five selected indicators.

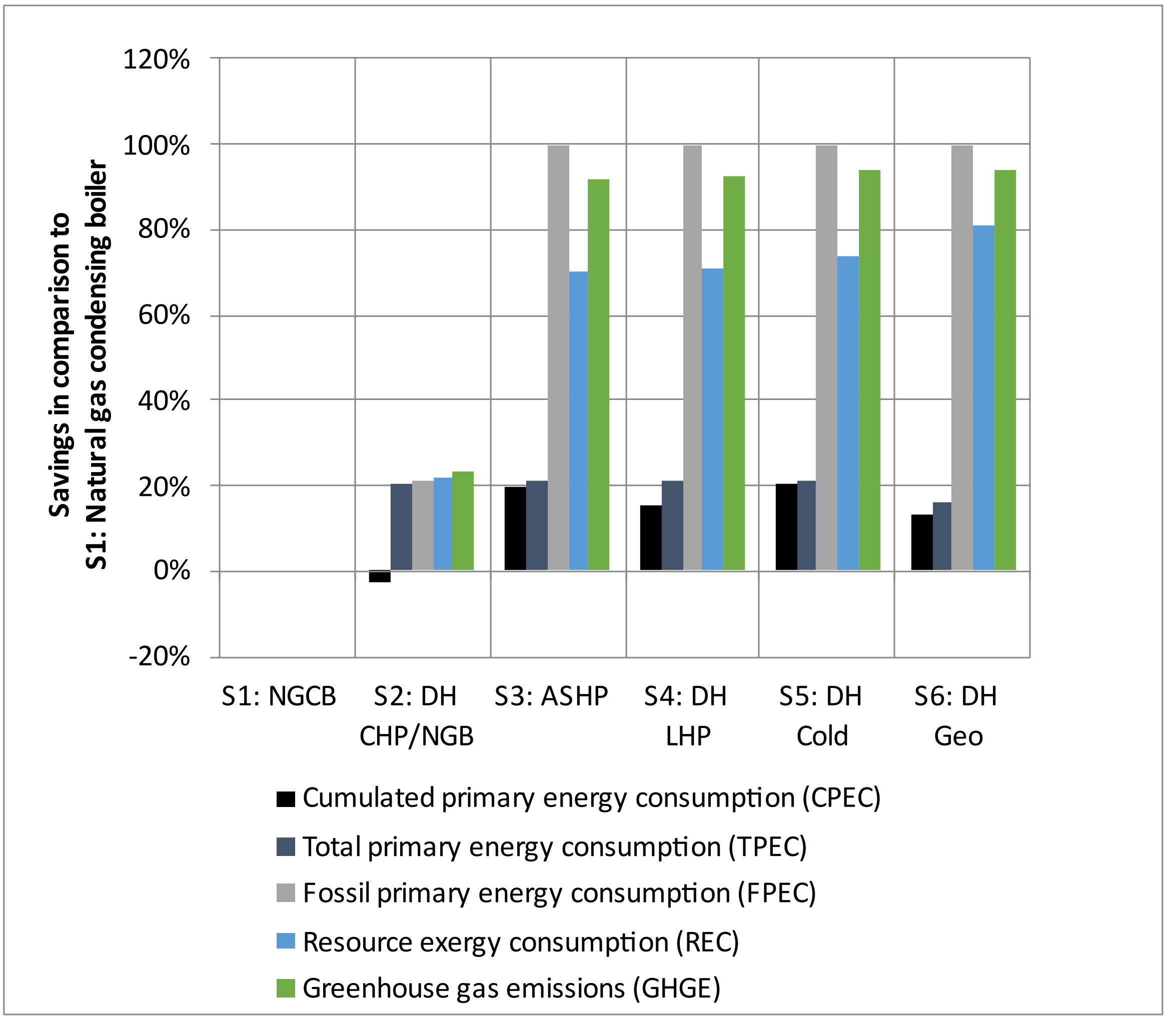


Figure 37: Comparison of ecological key performance indicators in terms of savings in comparison to S1: Natural Gas Condensing Boiler

Using CPEC, S2: DH CHP/NGB – a system with a significant amount of CHP can be deemed less efficient than a natural gas boiler. This illustrates why the consideration of energy quality is so important and underlines the lack of suitability of this indicator for energy system comparison. Also, the savings for renewable energy systems are systematically underestimated thus making them less attractive than if using REA.

While TPEC allows to assess the savings of the considered system in S2 close to the REC, it fails to do so for all other systems. The reason for this effect is an inconsistent use of the energy balance in its underlying assumptions. While exergy aspects are considered for heat from CHP by using primary energy factors below 1 they are not considered for thermal sources and demands.

Using TPEC and CPEC for renewable energy assessment can thus easily damage climate change mitigation efforts as both indicators fail to provide insights into the loss-reduction benefits of low-GHGE systems.

The savings achievable by FPEC using renewable power are always 100% in comparison to S1: NGCB since the fossil primary energy factors of most renewable sources are set to zero. Thus, FPEC systematically ignores losses in non-fossil energy systems. For S3, S4 and S5 REC indicates that the savings are 30% - 26% lower for HES than indicated by FPEC. This means that FPEC overestimates the consumption reduction achievable by renewable energy systems while at the same time not allowing to differentiate between different renewable energy sources.

As explained in (Jentsch, 2023), minimizing avoidable consumption in all energy systems is key to avoid an indirect and potentially very significant increase in GHGE in the overall energy system. This is valid not only for fossil fuels but also for the use of low-GHG energy sources in an overall system that still uses fossil fuels.

Consequently, the use of FPEC for the analysis of non-fossil energy systems leads to a systematic underestimation of the overall system effect and thus likely leads to an avoidable increase of climate change. REC provides a viable alternative indicator that is independent from GHGE and allows to identify the most resource saving solutions, which help to minimize global GHGE.

In summary the investigated scenarios show clearly that the three types of primary energy analysis presented are significantly flawed when it comes to assessing the overall consumption of energy systems. To obtain a more realistic assessment of the impact on overall system resources REA should be used instead or at least additionally to primary energy analysis.

Further proof for the need to replace CPEC analysis with a more comprehensive methodology such as REA can be found in (North and Jentsch, 2021b).

13.4 CONCLUSION

For IEA DHC Annex TS3 six energy systems that cover the heat demand (space heating and domestic hot water) of a residential district are compared. The comparison is performed by using resource exergy analysis (REA) (Jentsch, 2023) and complemented with an assessment of greenhouse gas emissions (GHGE). The two comparison criteria used are: resource exergy consumption (REC) and greenhouse gas emissions (GHGE).

GHGE savings show the direct reduction of GHGE by using the considered system.

REC indicates how much a considered system supports the goal of reaching climate targets in time. Less REC means less need to build GHGE-free energy systems and thus allows to achieve a fully GHGE-free energy system faster.

The analysis has been performed assuming dedicated PV power to cover all electrical demands of the considered energy systems. Thanks to the global indicators and the universally applicable assumption about power coming from PV, the results obtained can be generalized to any country, independently of their respective electricity mix.

The results highlight the high influence of the resource exploited. As expected, the use of fossil fuels such as natural gas results in high GHGE, particularly in the case of individual gas condensing boilers and large shares of heat from boilers in district heating networks.

The considered hybrid energy systems (air-source heat pumps) and Hybrid Energy Networks (large heat pumps in a very low temperature district heating network and decentralized water-water heat pumps in a cold district energy network) achieve similar savings in comparison to heat supply from a decentralized natural gas condensing boiler.

The similar performance is caused by the fact that additional energy demands of heat networks, e.g., heat losses and pumping power needed, are counterbalanced by higher energy efficiency of the considered supply technologies (water-water heat pumps instead of air-source heat pumps).

Consequently, all types of hybrid energy systems show a large potential to support the effective decarbonization of heat, if the supply temperatures are kept as low as possible, dedicated GHGE-free power is used and the performance factors of the used heat pumps are optimized.

Furthermore, it is shown that GHGE-free thermal sources (e.g., deep geothermal heat) can reach similar improvements over a natural gas condensing boiler as the best cases of hybrid energy systems even if providing heat at higher temperatures (70/40 °C instead of 45/25 °C).

Finally, the performed analysis demonstrates the importance to shift from primary energy analysis to resource exergy analysis to obtain a realistic picture of system wastefulness and avoid judgment errors when making energy system choices.

In summary, the REA of hybrid energy systems shows that hybrid energy systems, Hybrid Energy Networks and low temperature district heating from thermal sources can all help to significantly reduce GHGE (>90%) and REC (>70%) in comparison to heat supply by decentralized natural gas condensing boilers.

However, to ensure that the full potential of hybrid energy systems is harnessed, it is key to ensure that any power consumed by them is provided by dedicated GHGE-free sources.

14 ANALYZIS OF THE STRENGTHS, WEAKNESSES, OPPORTUNITIES, AND THREATS

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Hybrid Energy Networks can be seen from different angles and the coupling of the different energy networks doesn't necessarily have only advantages. To qualitatively analyse the strengths, weaknesses, opportunities, and threats (SWOT) of Hybrid Energy Networks, a three-stage process has been conducted based on a literature search, qualitative input from experts during a dedicated workshop and a comprehensive feedback and discussion phase with stakeholders. As a result, several SWOT factors has been identified. Finally, an online survey has been conducted collecting over 60 responses from all over the world, rating and commenting the different SWOT factors.

14.1 INTRODUCTION

A SWOT analysis is a strategic method to identify internal factors (strengths and weaknesses) and external factors (opportunities and threats) favourable and unfavourable to achieve a specific objective or to assess any kind of business case. SWOT assessments in combination with empirical surveys are frequently used to summarize and classify heterogeneous views of experts. They are especially valuable for topics with insufficient knowledge, lack of historical data, or lack of consensus found within the studied field. In this context, the following aspects are analysed:

- Strengths: characteristics of Hybrid Energy Networks that give an advantage over individual networks.
- Weaknesses: characteristics of Hybrid Energy Networks that give a disadvantage relative to individual networks.
- Opportunities: elements in the environment that Hybrid Energy Networks could exploit to their advantage.
- Threats: elements in the environment that could cause trouble for Hybrid Energy Networks.

The SWOT analysis aims at supporting the general understanding of the properties and characteristics of a Hybrid Energy Network, considering different viewpoints, e.g., the overall energy system, electricity and DHC network, etc., and thus trying to be an intermediate and facilitator between the different stakeholders.

14.2 METHODOLOGY

The SWOT analysis was performed in a three-stage process to structure and guide expert involvement is being conducted.

- **First**, a preliminary list of SWOT factors was collected employing a literature search, including qualitative input from experts during a dedicated workshop meeting.
- In the **second** stage, a comprehensive discussion phase with experts took place to add, discuss, clarify, and classify SWOT factors. During this process experts were able to comment on existing factors, add additional ones and exchange ideas and concerns to help in clarification and classification of SWOT factors. This stage also involved direct stakeholder interviews.

Results of the first and second phase are published in (Schmidt and Leitner, 2021).

- The **third** stage consisted of a survey to assess the relative importance of SWOT factors. Therefore, an online form has been generated for evaluating every SWOT factor and distributed via various channels in 2021/2022.

In total above 60 responses have been received for the online survey; mainly from Europe[31], their occupation was mainly at research and technology organizations (RTOs) including universities; also, consultancies, the public and the energy sector was participating. Figure 14-1 gives an overview of the countries of origin of the participants and the type of institution / branch of the participants.

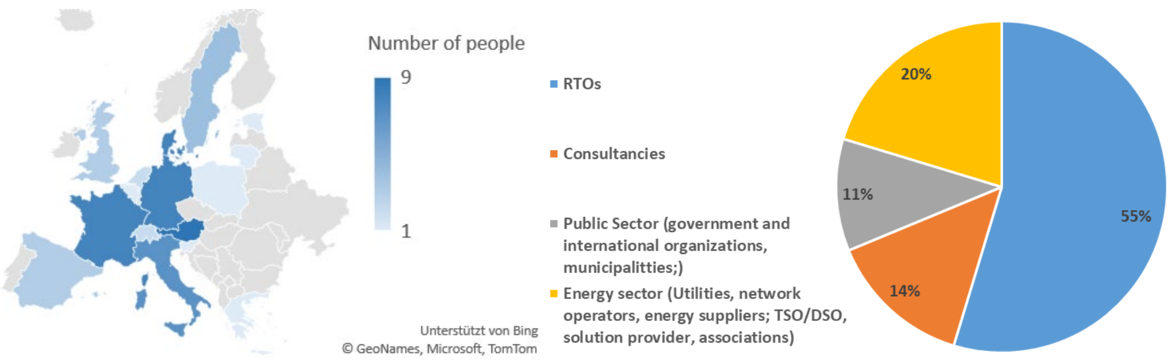


Figure 14-1. overview of the participants of the online survey on SWOT factors of Hybrid Energy Network (left: countries of origin; right: type of institution / branch)

[31] One person each responded for the United States, India, Turkey, and China

14.3 RESULTS

In the following tables the overall results of the survey are summarized. Every factor was rated between 1 (little to no relevance) and 5 (maximum relevance). A colour code has been implemented, where higher ratings are brighter, while lower ratings are darker. In the adjacent right column, the standard deviation of the average rating is displayed.

Table 16: - Overall results of the SWOT analysis sorted by the average rating from the online survey (bright shading refer to high and dark shading to low rating respectively)

		average	+/-
Strengths	Higher system flexibility	4.1	1.0
	Decarbonization of DHC network	4.1	0.9
	Higher degree of freedom for planning/operation	4.0	1.0
	Higher security of supply, resilience	3.9	1.0
	Counteract limitations of the electricity network	3.7	1.0
	Manage various temperature-levels via heat pumps	3.7	1.1
	New business models (ancillary services, markets)	3.6	0.9
	Economic added value (investment in coupling points)	3.2	1.2
	Reduce electricity grid losses	3.1	1.3
Weaknesses	Increasing level of complexity	3.7	1.2
	Price signals do not yet take the grid situation into account	3.6	1.1
	Present electricity tariffs and taxes are barriers	3.6	1.3
	Regulatory restrictions for electricity grid operators	3.4	1.2
	The reconversion of heat to electricity has low efficiency	3.4	1.4
	Only renewable if fossil - free electricity is used	3.3	1.4
	Additional investments into coupling points	3.3	1.2
	Seasonality of the heat demand	3.2	1.2
	Availability and condition of DHC infrastructure	3.1	1.3
	Cybersecurity concerns	3.0	1.4
	Supply competition in DHC (especially in summer)	2.6	1.3
Opportunities	Digitalization supports handling of the complexity	4.1	1.0
	More research, products, demo projects, trainings available	4.0	0.9
	Decarbonization incentives can support sector integration	3.9	1.0
	Increasing PV and Wind => More flexibility required	3.9	1.0
	Tendency for the reduction of DHC temperatures	3.9	1.0
	Improved performance of coupling points/controls	3.8	1.1
	Green financing options	3.8	1.0
	Acknowledgment and support by policy makers	3.7	1.0
Threats	A possible disruption of existing business models	3.8	1.2
	Risk of stranded investments due to uncertainties	3.6	1.0
	Overall higher electricity demand	3.2	1.3

It can be seen in general, that the positive properties (strength and opportunities) are rated more relevant by the experts than the negative properties (weaknesses and threats): up to 4.1 compared to 3.7 and 3.8.

The following sections summarize the different SWOT factors in detail, the average rating, the standard deviation as well as some exemplary comments from the expert survey. For a full inside into the comments, please refer to appendix I.

14.3.1 STRENGTHS

Higher system flexibility	**average 4.1**	**+/- 1.0**
A higher level of system flexibility enables one to • Manage / mitigate temporal imbalances of intermittent electricity production / demand • support the containment and restoration of the system frequency and the maintenance of the voltage levels • reduce internal portfolio imbalances and thereby minimize imbalance costs • levelized electricity market prices		
Exemplary comments from the expert survey: • *Needs to be shown that this is cost-effective, reliably, and quickly available for future energy systems (RTO, UK)* • *in future with very high penetration of distributed energy resources …, this could turn to be critical … (RTO, Spain)* • *… we need to see a system that pays the DH companies fairly for the security of supply that their CHP plants provide to the electricity grid (RTO, Denmark).* • *… hybrid networks could ensure the end-users' energy needs without compromising their comfort (consultancy, France)* • *… enables one to accommodate more fluctuating thermal sources in district energy systems (solution provider, Denmark)*		

Decarbonization of DHC network	**average 4.1**	**+/- 0.9**
A decarbonization and diversification of the DHC networks, if using renewable electricity and thus to increase the stability in operation of the heating (and cooling) plants, the fuel supply security, system resilience and to reduce back-up requirements		
Exemplary comments from the expert survey: • *pure electrification is not the best solution; solar thermal, geothermal, etc. should be part of the diversification strategy aiming at higher efficiency (RTO, Switzerland)*		

Higher degree of freedom for planning/operation	**average 4.0**	**+/- 1.0**
A higher degree of freedom for planning and operation of the energy system, including multiple options for energy transformation and storage, i.e. • Power-to-Heat (PtH) plants can make low temperature heat sources such as ambient heat and waste heat as well as cost-efficient thermal storage capacities available.		

- Power-to-Gas (PtG) processes (i.e. electrolysis) and subsequent processes can generate renewable fuels, suitable for e.g. industry applications. Recovering the waste heat associated with the electrolysis process increases the overall efficiency.
- Combined heat and Power (CHP) plants can make the best use of renewable fuels by generating heat for DHC networks and electricity for grid supply or ancillary services.

Exemplary comments from the expert survey:

- *there might in practice be a counteracting increase in complexity for planners and operators (government organization, Denmark)*
- *This depends on the value that is seen by the other networks, who may be able to obtain the same services from other sources (RTO, UK)*
- *… for P2X, the necessity of utilizing the 'waste heat' from these processes, is key (government organization, Denmark)*

Higher security of supply, resilience	**average 3.9**	**+/- 1.0**

A high level of security of supply and system stability due to multiple and distributed options for covering energy demand between the networks in combination with storages on different time scales

Exemplary comments from the expert survey:

- *… for any given energy vector there is "always" a non-renewable source available or a storage option to ensure supply (consultancy, France)*
- *For the power system, the instantaneous balance between demand and generation has traditionally been a major constraint. Storage … allow providing these functionalities, mitigating these requirements (RTO, Spain)*
- *the networks already have independently these attributes … (consultancy, Poland)*

Counteract limitations of the electricity network	**average 3.7**	**+/- 1.0**

The options to counteract limitations of the electricity network transfer capacity and thus to avoid investments into grid reinforcement by

- local utilization of excess electricity (e.g. by PtH or PtG units) from additional deployment of local intermittent renewable electricity production capacities (e.g. repowering of existing wind farms) exceeding the network transfer capacity
- local supply in case of electricity shortage (e.g. by CHP plants) in the case of significantly increasing number of consumers (e.g. large-scale roll-out of electric vehicles) exceeding the network transfer capacity

Exemplary comments from the expert survey:

- *Cold spells occur in large areas coincidentally. When heat buffers run out, PtH-solutions will place a very high demand on the electricity grid (RTO, Netherlands)*
- *local solutions need to be assessed with a wide system perspective (DHC network operator, Sweden)*
- *Very important for the electricity grid, especially in a system with much more decentralized power production form intermittent sources … (RTO, Denmark)*
- *The combination with the electricity network can greatly reduce the limitations in the DH system, ... e.g. electric boilers are high capacity, small volume, emission free and practically noiseless and hence can be installed at critical locations where it would be impossible to install other heat generation facilities (solution provider, Denmark)*

Manage various temperature-levels via heat pumps	**average 3.7**	**+/- 1.1**
The option to efficiently manage various levels of temperatures, i.e. low temperature heat sources by using (booster) HPs and/ or eBs for (locally) adapting the temperature level.		
Exemplary comments from the expert survey: • *… Low temperature DH is very important, as it increases the efficiency of the heat pumps upgrading the energy (RTO, Denmark)*		

New business models (ancillary services, markets)	**average 3.6**	**+/- 0.9**
Options for innovative and adapted business models and new revenue streams including new services (e.g. ancillary services), increasing the self-sufficiency by maximizing own consumption; optimize the revenues from participation in different energy markets.		
Exemplary comments from the expert survey: • *… Too narrow approaches may lead to sub-optimization and the risk of lock-in effect since infrastructure has a long-term lifetime (DHC network operator, Sweden)* • *… This is a new field for this sector, and it should be analysed before wide implementation of hybrid networks (RTO, Estonia).* • *For large scale heat pumps, it seems that the ability to provide ancillary services is more import for the economy than a [good] COP … (RTO, Denmark)*		

Economic added value (investment in coupling points)	**average 3.2**	**+/- 1.2**
An increased economic added value i.e. by creating jobs due to the investment in coupling points		
Exemplary comments from the expert survey: • *Probably a thorough coupling could even lead to a loss of jobs (RTO, Germany)* • *… people who can install, maintain these services need to be highly skilled in IT and in energy systems, while these job markets are already extremely tight* • *… training of professionals on best practices for hybridization of networks [is required] (consultancy; France)* • *Coupling of the energy sectors can lead to more local energy being used which leads to strengthened local economy as less money would be flowing out from the local economy towards energy/fuel supply countries (solution provider, Denmark).*		

Reduce electricity grid losses	**average 3.1**	**+/- 1.3**
A reduction of electricity grid losses by maximizing local consumption of (renewable) electricity sources instead of transporting the electricity to remote demand locations.		
Exemplary comments from the expert survey: • *A local demand should not be created to reduce network losses … (RTO, Germany)* • *The loss in transportation is limited … It is not efficient … to maximize local consumption by using temporal flexibility (NGO, Netherlands)*		

14.3.2 WEAKNESSES

Increasing level of complexity	**average 3.7**	**+/- 1.2**
An increasing level of system integration results in an increasing level of complexity for planning, designing, and operating, due to a higher number of optimization parameters and stakeholders involved. This is including the risk of a high interdependency of the different sub-systems, thus a disturbance in one domain might affect the other negatively.		
Exemplary comments from the expert survey: • *… the lack of sector coupling means that disturbance in one domain cannot be balanced by another domain (association / interest group, Sweden)* • *Complexity is unavoidable in the future … (government organization, Germany)* • *… shortage of people who can manage such complex systems (NGO, Netherlands)* • *… Ideally, a polycentric governance model should be considered, to ensure a balance between stakeholders (consultancy; France)*		

Price signals do not yet take the grid situation into account	**average 3.6**	**+/- 1.1**
price signals provided by the wholesale markets for electricity in Europe do not yet take the grid situation into account, such as localized grid constrains and the location of generation with respect to demand.		
Exemplary comments from the expert survey: • *This is a must. No problem at all with a little metering (RTO, Denmark)* • *I am not sure this is true: in my experience (Italy), when there are issues with the grid, price increase (TSO electricity, Italy)*		

Present electricity tariffs and taxes are barriers	**average 3.6**	**+/- 1.3**
Present electricity tariffs and taxes are barriers to exploiting the potential of Hybrid Energy Networks.		
Exemplary comments from the expert survey: • *with appropriate business models, regulation should adapt to make things happen (TSO for electricity, Italy)* • *tariff/pricing structures can be expected to change 1. more emphasis on kW compared to kWh and 2. impact of EVs (RTO, UK)*		

Regulatory restrictions for electricity grid operators	**average 3.4**	**+/- 1.2**
electricity grid operators currently have regulatory restrictions (mainly due to unbundling) for • the co-optimizing the distribution and generation of energy • investment and ownership into coupling points • accessing the flexibility in the DHC network.		
Exemplary comments from the expert survey: • *In my view, unbundling is a necessary and good thing (RTO, Denmark)* • *needs to be addressed also in other areas of the energy system, less related to hybrid networks only (RTO, France)* • *Solving regulatory issues is critical for the system to be able to be put in practice (RTO, Spain)*		

The reconversion of heat to electricity has low efficiency	**average 3.4**	**+/- 1.4**
Once electricity is transformed into heat, the re-conversion into electricity (Heat-to-Power, HtP) has a very low round trip efficiency and can only be cost-efficient at high temperatures.		
Exemplary comments from the expert survey: • *… heat is the flexibility for the electrical markets… (RTO; Denmark)* • *Only because HtP is possible it is not necessary to use it… (RTO; Germany)* • *Energy should only be transformed once and then used or stored for later consumption (RTO; Germany)* • *This might be applicable in molten salt / concentrated solar systems. But in the context of HEN systems this is just out of place (solution provider, Denmark)*		

Only renewable if fossil - free electricity is used	**average 3.3**	**+/- 1.4**
The CO_2 emissions will only decrease if fossil-free electricity is used in the PtH processes, however, currently, the electricity mix in many countries is still dominated by fossil fuels and the highest heating peak demand in the coldest periods tend to coincide with low availability of electricity supply from solar.		
Exemplary comments from the expert survey: • *… using fossil-based electricity in a highly efficient heat pump can be less emission intensive than using natural gas (RTO, Germany)* • *… politicians and electricity producers really needs to step up to ensure that the build out of wind turbines and PV can keep pace with the demand, currently and particularly in an electrified future (RTO, Denmark)* • *… If heat pumps use GHG-free electricity that is already used in the grid, thereby pushing other demand to use GHG-loaded electricity nothing is won… (Government organization, Germany)* • *The premises of applying HEN should not be that all energy is fossil free, but that the HEN can contribute towards minimizing or getting rid of fossil fuels (solution provider, Denmark)*		

Additional investments into coupling points	**average 3.3**	**+/- 1.2**
The requirement of additional investments into coupling points.		
Exemplary comments from the expert survey: • *The additional investments will be heavily outweighed by the advantages gained by sector coupling (RTO, Denmark).* • *[we should] minimize the coupling points (RTO, Austria).* • *… It will always be more compact to meet a given demand through an energy source that matches that demand's vector, rather than through conversion processes, which are costly and imply energy losses and irreversibilities in most of the cases (consultancy; France).* • *… with renewables there will always be periods of mismatch between the generation and demand, … use the excess energy in another network is not energy loss, independent on the conversion loss… (solution provider, Denmark)*		

Seasonality of the heat demand	**average 3.2**	**+/- 1.2**
the seasonality of the heat (or cold) demand may lead to price surges on the electricity market.		
Exemplary comments from the expert survey: • *Seasonal heat and cold storage is key! (RTO; Austria)* • *… Large scale heat pumps, electrical boilers, and CHP units … are highly flexible and can adapt to the supply (price) of electricity (RTO, Denmark)* • *Diversified multi-vector thermal generation in DHC systems is a good practice and would provide the basis for successful and optimal HEN operation (solution provider, Denmark)*		

Availability and condition of DHC infrastructure	**average 3.1**	**+/- 1.3**
suitable DHC infrastructures for efficient sector coupling might not be available or be in a bad condition.		
Exemplary comments from the expert survey: • *with the right conditions in place, there will be incentives to retrofit and modernise DHC (TSO, electricity, Italy)* • *District heating is present in almost all big cities across Europe … (RTO, Germany)* • *Many countries only have very limited DHC infrastructure (RTO, Denmark)*		

Cybersecurity concerns	**average 3.0**	**+/- 1.4**
A highly integrated and interdependent system could offer multiple gateways for attacks thus resulting in a threat to cybersecurity.		
Exemplary comments from the expert survey: • *… this is the same in all other technologies, which transfer data via the internet (RTO; Austria).* • *Create local networks that can run without the internet… (government organization; Germany)* • *The more widespread the operating/coupling points are and less dominating each individual point of the system is the more resilient the system is to cyber-attacks, or any other disturbance (solution provider, Denmark)*		

Supply competition in DHC (especially in summer)	**average 2.6**	**+/- 1.3**
Additional heat (and cold) supply units in the DHC network result in an increasing supply competition among each other and to other renewables (e.g. solar- and geothermal energy) especially in summer times.		
Exemplary comments from the expert survey: • *there are multiple options to choose from when designing the system. (consultancy / RTO; Denmark)* • *Competition usually reduces prices for the end user (Government organization; Germany)* • *HEN would increase the supply competition which would favour the system operators, due to increase choice of heat sources, and the heat consumer as this would/should lead to lower heating costs (solution provider, Denmark).*		

14.3.3 OPPORTUNITIES

Digitalization supports handling of the complexity	**average 4.1**	**+/- 1.0**
Digitalization together with a higher penetration of sensors and other data collectors could open many opportunities in network design and operation		
Exemplary comments from the expert survey: • *The Danish experiences with decentralized CHP units show that the right price signals are more important than digitalization … (RTO, Denmark)* • *not only data collection, but also (and mostly) decision support systems to transform data into operational value (RTO; Italy)*		

More research, products, demo projects, trainings etc.	**average 4.0**	**+/- 0.9**
An increased focus on sector integration in research and industry as well as an increasing number of trainings and education programs		
Exemplary comments from the expert survey: • *Some of the technologies, especially PtX and CCS/U, are still quite immature (solution provider (software)/ consultancy; Denmark)*		

Decarbonization incentives can support sector integration	**average 3.9**	**+/- 1.0**
Current and future decarbonization incentives and measures can directly or indirectly support the sector integration		
Exemplary comments from the expert survey: • *… France relies heavily on nuclear power and leaves wind energy aside. Decarbonization incentives may not be sufficient (association / interest group; France)* • *the challenge will be to develop certification schemes to compute the greenhouse gas savings really correctly (RTO, Austria)* • *I would reformulate the opportunity as "Current and future decarbonization incentives and measures MUST directly or indirectly support the sector integration" (government organization, Italy)*		

Increasing PV and Wind => More flexibility required	**average 3.9**	**+/- 1.0**
higher shares of (fluctuating) renewable electricity sources such as wind and PV lead to more incentives for flexibility services and thus support the sector integration		
Exemplary comments from the expert survey: • *… I have trouble seeing how stakeholders will prefer a whole different source, a conversion process, and a reworked network instead of classical storage (association / interest group; France)* • *It's increasing the need for … oversizing renewable electricity production against renewable heat and energy saving (international organisation; Greece)* • *Hopefully - if the politicians and regulators managed to develop the necessary market mechanisms (RTO; Denmark*		

Tendency for the reduction of DHC temperatures	**average 3.9**	**+/- 1.0**
A general tendency for the transformation of the DHC networks towards lower temperatures, larger thermal storage capacities as well as decentralized structures support the integration of (decentralized) sector coupling points		
Exemplary comments from the expert survey: • *I see no additional advantage of hybrid networks (DHC network operator; Germany)* • *lower temperature systems also make it easier to apply decentralised equipment as solar thermal and heat pumps (international organisation; Greece)*		

improved performance of coupling points/controls	**average 3.8**	**+/- 1.1**
More research and development can lead to improved performance of coupling points, smart controls and integrated planning and implementation processes		
Exemplary comments from the expert survey: • *more pilot projects will help (RTO; Estonia)* • *More research and development would help even without the coupling between systems (association / interest group; Spain)*		

Green financing options	**average 3.8**	**+/- 1.0**
Green financing options and many investors favouring investments into renewable energy projects as well as accepting higher CAPEX and long-term amortization periods.		
Exemplary comments from the expert survey: • *… no additional advantage of hybrid networks (DHC network operator; Germany)* • *… The competition with P2X is … a conflict if not balanced (government organization, Denmark)* • *Pension funds … generally require large investments for projects to become interesting. Further on, HEN provide long term and very stable payment streams (solution provider, Denmark).*		

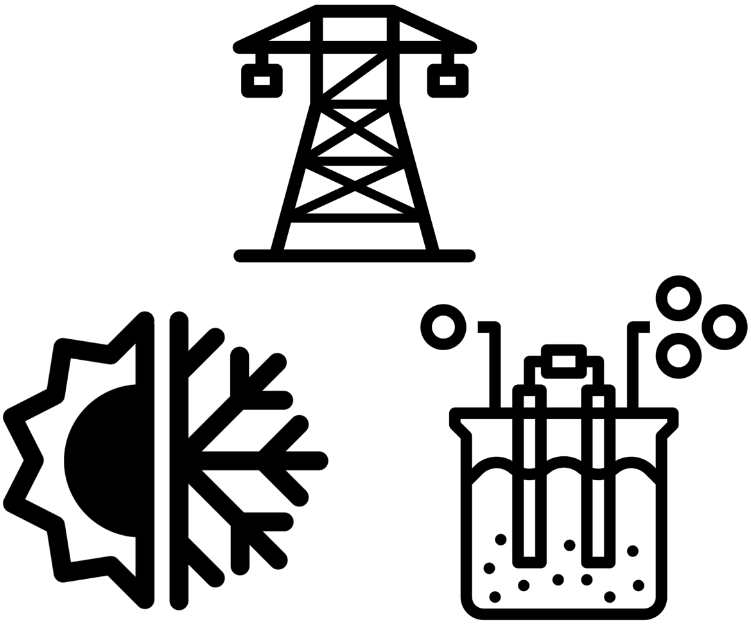
Acknowledgment and support by policy makers	**average 3.7**	**+/- 1.0**
The European Commission is acknowledging the role of an integrated energy system and upcoming regulations for energy communities / self-consumption can support sector integration measures		
Exemplary comments from the expert survey: • *Depending on final wording this could lead to sub-optimization instead (RTO; Denmark)* • *… there seems to be an obsession with buildings that produce their own energy. The point is, that it shouldn't matter, where the (renewable) energy is produced, and collective solutions like DHC are often more cost effective than single building solutions (RTO; Denmark)* • *the EC is acknowledging, what the experts propose, so please continue to introduce knowledge in the EC (RTO; Austria)*		

14.3.4 THREATS

A possible disruption of existing business models	**average 3.8**	**+/- 1.2**
Silo thinking of many actors and stakeholders and a possible disruption of existing business models		
Exemplary comments from the expert survey: • *… The threat are white elephants such as fossil companies or / and fossil exporting countries that are creating obstacles (RTO; Austria)* • *Even more dangerous than silo thinking is the energy diverted and lost looking at false claims and greenwashing (consultancy / RTO; UK)* • *… The point is to make a strong case for HEN to the extent clear and demonstrated benefits are brought into the picture (RTO, Italy)*		

Risk of stranded investments due to uncertainties	**average 3.6**	**+/- 1.0**
Risk of stranded investments in coupling points due to uncertainties of the future development of key enabling factors such as • Political situation, regulatory framework, and market design: e.g., subsidies/ CO2 pricing; allowed ownership of coupling points; the options to participate in the different electricity markets / the availability of suitable network tariffs; • The market development in terms of electricity prices as well as the number of alternative flexibility providers (e.g. electric vehicles) / degree of diffusion of coupling points and resulting competition • medium- and long-term availability of waste heat as a source for HPs from industries or from the service sector that suddenly cease their activity		
Exemplary comments from the expert survey: • *Fossils will be stranded! (RTO; Austria)* • *Thorough planning and a massive build out of RE electricity should be good remedies against this threat (RTO; Denmark)* • *All long-term investments face this threat - and are more difficult to finance as a result (RTO; United Kingdom)* • *… if the heat demand decreases, due to energy renovations or disconnections, than the investments in heat generation equipment can become stranded investment (solution provider, Denmark).*		

Overall higher electricity demand	**average 3.2**	**+/- 1.3**
PtH and PtG units can lead to an overall higher electricity demand		
Exemplary comments from the expert survey: • *… more electricity is used much more efficient - thus the final energy demand significantly reduces! (RTO; Austria)* • *… the threat is in the capacity limit of the electricity infrastructure (consultancy; Netherlands)* • *Yes, another danger of electrifying everything obsessively… other vectors need to be considered! (association / interest group; France)*		



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APPENDIX

All appendices can be found as separate pdf documents on
https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts3

- Appendix A Large Scale Heat Pumps in District Heating Networks
- Appendix B Country Report Austria
- Appendix C Country Report Denmark
- Appendix D Country Report Germany
- Appendix E Country Report Italy
- Appendix F Country Report Sweden
- Appendix G National Scale Assessments for Austria and Denmark
- Appendix H Case Studies – Details
- Appendix I Exergy Pass – Comparative Study for Planning Options
- Appendix J SWOT Analysis - Detailed Results