International Renewable Energy Agency

RENEWABLE POWER-TO-HEAT

INNOVATION LANDSCAPE BRIEF

IRENA
International Renewable Energy Agency

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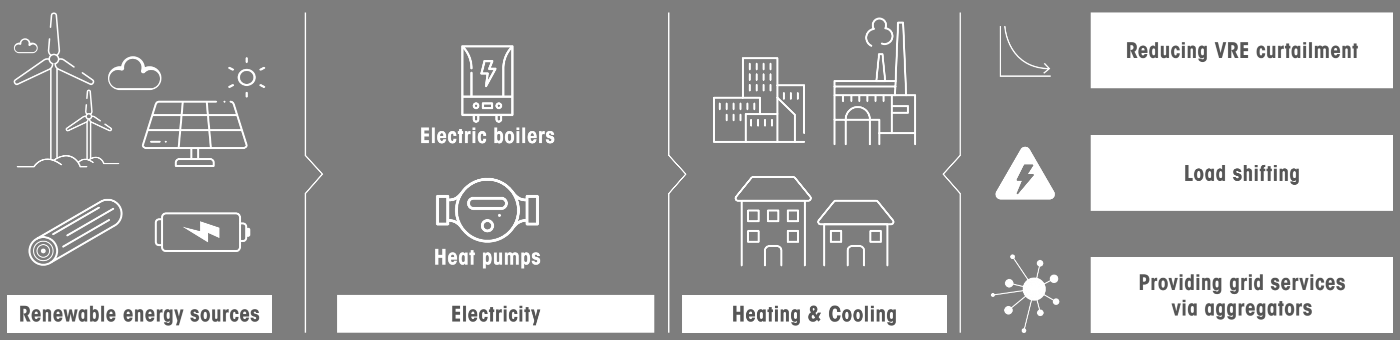
1 BENEFITS

Converting solar and wind power to heat can help transform the power sector, increasing its flexibility:



2 KEY ENABLING FACTORS

- Regulatory support
- Incentives for renewable energy use in buildings and industry
- Market design that allows revenue stacking

3 SNAPSHOT

- ➜ Canada, China, Japan, the US and Europe (primarily Denmark, Germany, Sweden, Switzerland and the UK), all use power-to-heat
- ➜ The European Union met about 19% of it heading demand in 2018 with renewable sources
- ➜ Heat produced by heat pumps costs EUR 0.06–0.12/kWh
- ➜ The EcoGrid EU project in Denmark showed a significant peak load reduction when a heating system is managed smartly

WHAT IS POWER-TO-HEAT?

Heat pumps or boilers serve to convert electric power into efficient heating or cooling. Thermal storage systems enable flexible coupling of power and heat sectors.

RENEWABLE POWER-TO-HEAT

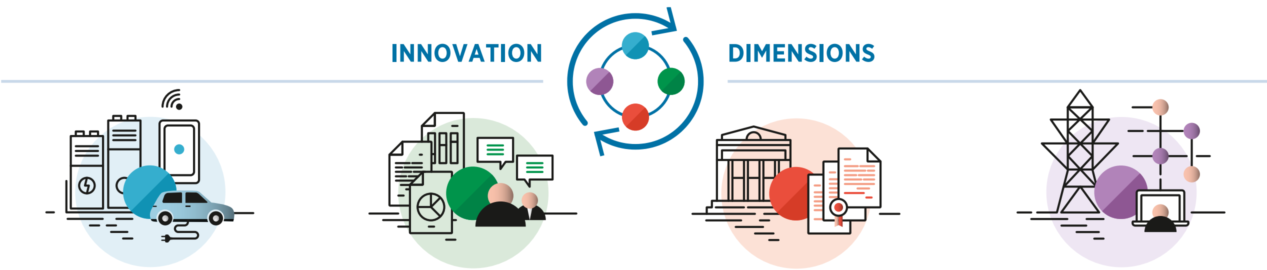
Electrifying the heating sector using renewables **reduces fossil fuel consumption.** Combined with **smart load management,** it increases flexibility in the power system.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
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11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

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16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of renewable power-to-heat and its role in increasing the share of renewable energy in the building and industrial heating sectors. This brief focuses on the use of renewable power-to-heat applications as an energy storage medium for VRE sources such as solar and wind as well as for providing grid-balancing services.

The brief is structured as follows:

I. DESCRIPTION

Heating and cooling applications are among the largest consumers of energy. Industrial heating applications account for nearly 20% of global energy consumption, while space heating and cooling, and water heating in buildings, account for about 15% of global energy consumption (Bellevrat & West, 2018; Dulac, 2017; IEA, 2017a). More precise data for Europe indicates a total energy demand for heating and cooling of more than 6 000 terawatt-hours (TWh), or 51% of the total energy demand (Heat Roadmap Europe, 2017).

Although some countries use renewables and waste to generate process heat for industries, and solar thermal and geothermal systems to generate space heating and cooling, the majority of heating needs are still met by fossil fuels. In the United States, over 60% of annual heating and cooling requirements are met by fossil fuel-based sources, such as natural gas, propane and fuel oil. In Europe, around 75% of annual heating and cooling requirements are met by fossil fuels, while only 19% is generated from renewable energy (EIA, 2018; European Commission, 2019a).

Some heating and virtually all cooling is electric. Heat can be generated from renewable energy sources in two ways: (a) by direct conversion of renewable energy sources to heat (*e.g.* solar thermal applications) and (b) by using electricity generated from renewable energy sources to produce heat via heat pump technology or electric boilers. This brief focuses on the latter (i.e. using electricity from renewable energy to generate heat, also referred to as "renewable power-to-heat") and how these electricity loads can be "smartly" used to increase the flexibility of power systems and facilitate greater shares of VRE.

Renewable power-to-heat refers to technologies that use renewable electricity to generate useful heat [1] for buildings or industrial processes (i.e. via heat pumps or electric boilers). Electric boilers use electricity to heat water, which is then circulated through pipes or disseminated with fan coils to provide space heating, or stored in hot water tanks for later use. Heat pumps use electricity to transfer heat from the surrounding heat sources (air, water, ground) to buildings. Heat pumps can fulfil both heating and cooling requirements by using heat in the ambient air, water or ground as the primary source of energy and a small quantum of auxiliary energy to drive the process. In 2016 there were 20 million heat pumps in the building sector and 0.2 million in the industry sector.

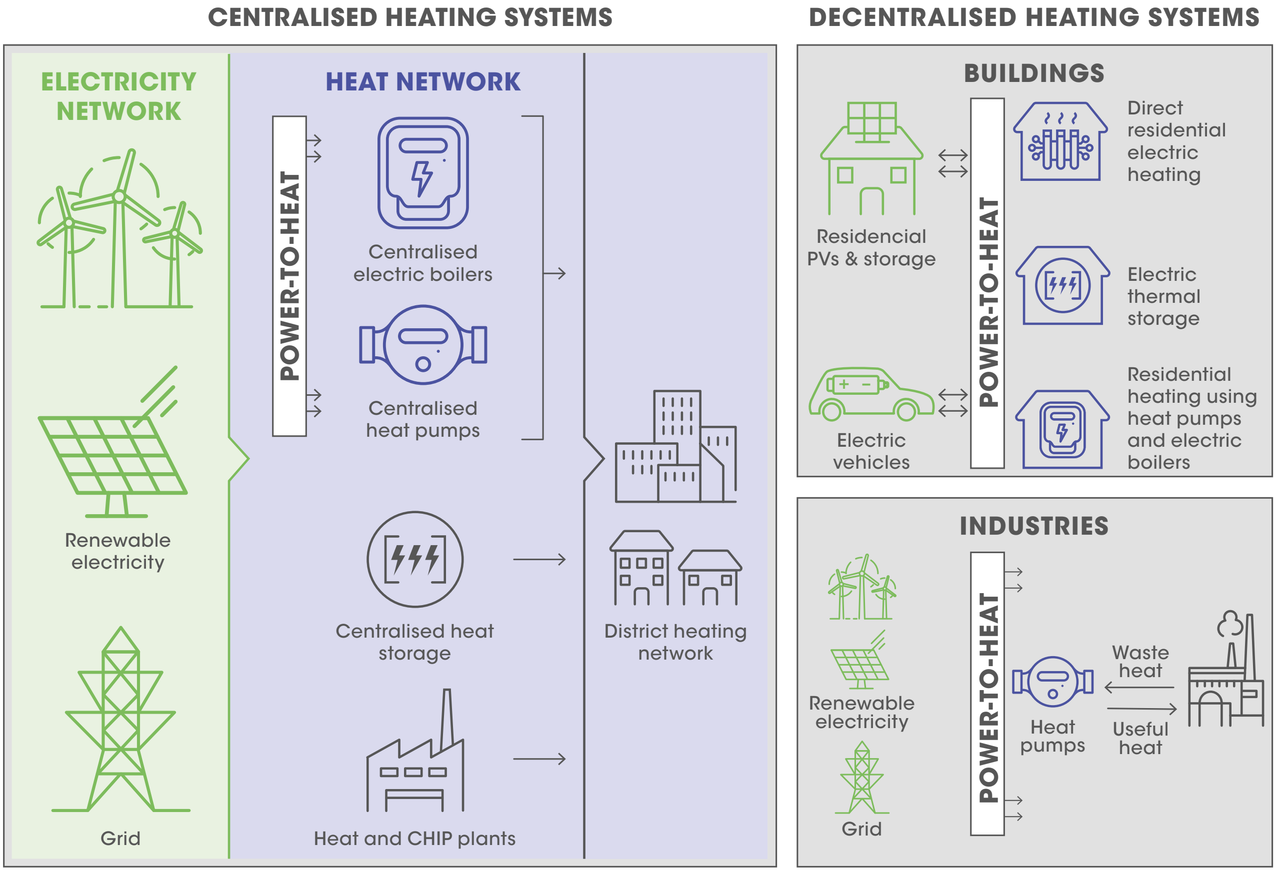
According to IRENA analysis, heat pumps will play a critical role in the building sector and will increase to over 250 million units by 2050, supplying 27% of the heat demand. In the industry sector, 80 million heat pumps will also be installed to meet similar low-temperature heat needs by 2050 (IRENA, 2019b).

1 "Useful heat" is defined as heat delivered to satisfy an economically justifiable demand for heating or cooling (Department of Energy & Climate Change, 2012).

Typically, about 66–80% of the energy required by a heat pump is drawn from ambient sources; the remaining 20–33% comes directly from electricity (Nowak, 2018). The electricity requirement for heat pumps is low because it operates on the principle of "heat transfer" (i.e. moving and upgrading heat from the external environment to a specific area instead of generating heat directly from electricity) (IRENA, IEA-ETSAP, 2013). The coefficient of performance of a heat pump can be 3 to 5, meaning that the addition of 1 kilowatt (kW) of electric energy is needed to release 3–5 kW of heat. This is essentially an efficiency of 300–500%; in comparison, electric resistance boilers have 100% efficiency and fossil fuel boilers have 75–95% efficiency.

Electrification of the heating sector is feasible in the short term as most of the required infrastructure is already in place and the electrical grid already reaches most demand points: buildings, houses, commercial sites and industrial factories. Electricity from renewable sources can be delivered with the existing infrastructure to (a) the final heat customers or (b) centralised heating production stations. However, in the event of a large-scale increase in electricity demand due to the production of heat from electricity, the transmission and distribution network would probably need additional investments to increase its capacity. Power-to-heat systems can be centralised or decentralised systems, as illustrated in Figure 1.

Figure 1: Types of heating systems that use electricity



CHP = combined heat and power; PV = photovoltaic.
Based on: Bloess et al. (2018).

Centralised heating systems

Centralised heating systems that use electricity include large-scale electric boilers and heat pumps that are supplied with electricity directly from the main grid. In this case, the electricity supplied depends on the electricity matrix of the respective system and might also include fossil fuel generation. However, producing heat via heat pumps can still offer significant carbon reductions compared with direct fossil fuel combustion. In centralised heating systems, electricity is used to power large-scale electric boilers and heat pumps, whose heating and cooling output is then transmitted to several buildings through a network of pipes. Such systems are also known as "district heating or cooling networks". Besides the electricity network, district heating systems can use other sources for heat, such as combined heat and power plants.

Buildings can be equipped with thermal storage systems to enable demand-side response by using the stored heat and, in turn, reducing demand on the power grid during periods of peak electricity demand. In both centralised and decentralised heating systems, storage systems for heat or electricity play an important role. The main features required of storage for the power-to-heat system are (1) high capacity (i.e. bulk storage), (2) the capability for one or more charge-discharge cycles per day and (3) a medium-to-long response time (typically 10–30 minutes).

Decentralised heating systems

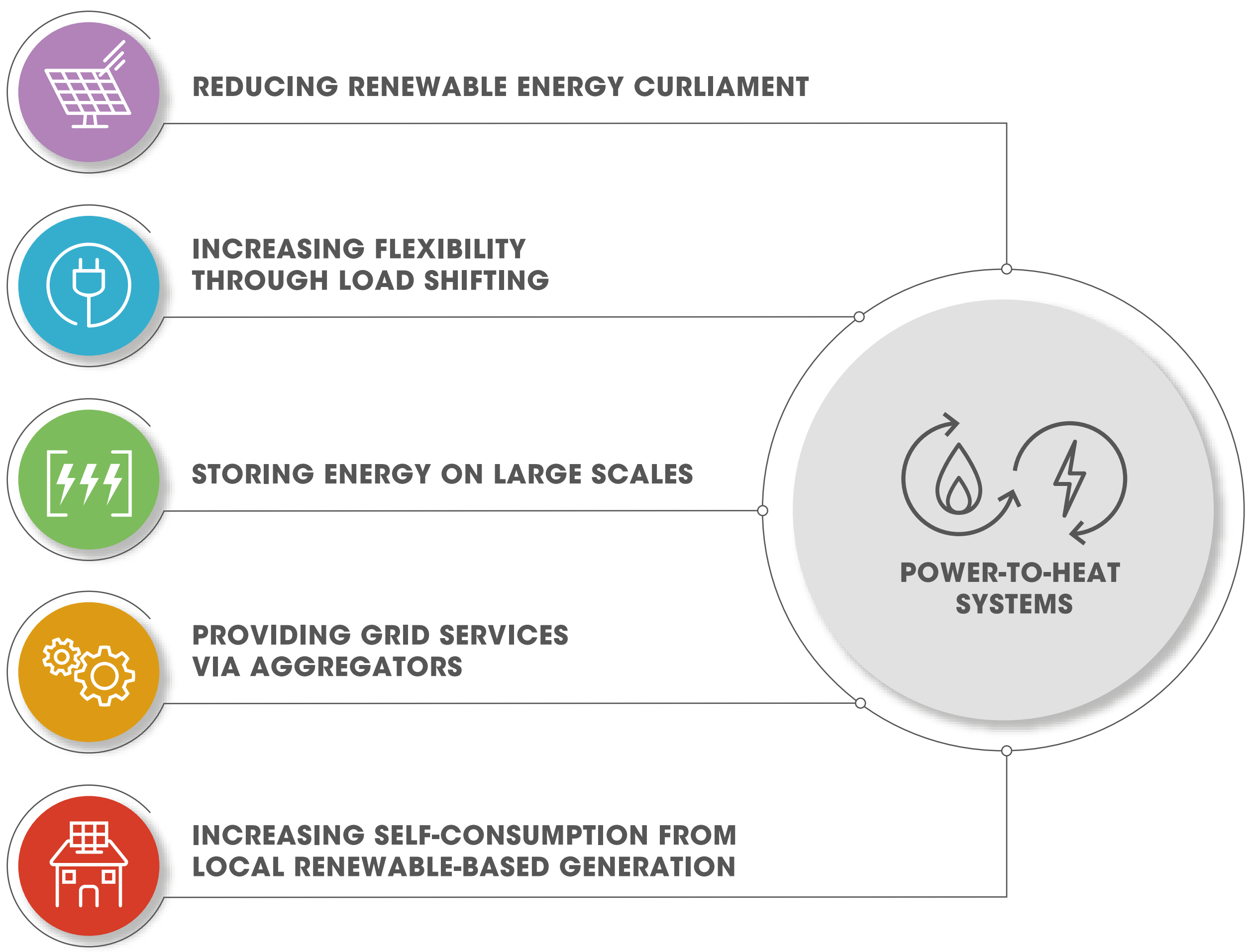
Decentralised heating systems that use electricity include small-scale heat pumps or electric boilers used to generate heat or cooling. These decentralised heat pumps and electric boilers can be powered by the electricity grid directly or by a local generator or energy source, such as rooftop solar photovoltaic installations, behind-the-meter batteries, electric vehicle batteries or other electricity storage systems. Unlike the centralised system, decentralised systems do not require a heat network infrastructure, as they are placed directly at the consumption point. This placement reduces maintenance costs and eliminates distribution losses.

Industries typically use decentralised heating systems in which the waste heat generated is recovered and upgraded using electricity-based systems installed on site. For instance, a heat pump can use the waste heat from the refrigeration system to provide heat for drying processes. Heat pumps are typically used for processes that operate in the low-temperature range (<160 °C) (DryFiciency, 2018).

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Electrification of heating can help decarbonise the sector when the extra load is supplied with renewable electricity and smartly managed. Power-to-heat systems can help integrate greater shares of VRE by using heat pumps and electric boilers as a source of demand-side flexibility in power systems. These electric loads can be used to reduce curtailment of surplus renewable generation, to load shift to coincide with renewable energy generation, and to provide grid services (see Figure 2).

Figure 2: Power-to-heat systems support VRE integration



Reducing renewable energy curtailment

Increasing electricity generation from renewable energy resources such as solar and wind can lead to curtailments when supply surpasses demand and the system is not flexible enough. Power-to-heat systems can use the excess electricity supplied from these sources to address heating needs and thereby avoid curtailment of renewable energy generation.

For instance, the Inner Mongolia Autonomous Region in China had about 22.3 gigawatts (GW) of installed wind power at the end of 2014. However, regional transmission constraints resulted in high curtailment levels (9% wind curtailment in 2014); during 2012, over 30% of wind energy was curtailed (Zhang, 2016).

To avoid curtailment, the Chinese National Energy Administration is installing electric boilers with a capacity of 50 megawatts (MW) that can be used to generate heat using excess renewable energy for the district heating system, which has conventionally depended on inefficient coal boilers. The project is targeted for completion in 2020 and aims to generate about 2.8% of yearly district heat generation (IRENA, 2017).

Increasing flexibility through load shifting

In decentralised heating systems, heat pumps can provide demand-side flexibility, resulting in peak shaving or valley filling, by switching their electricity consumption from high-demand time intervals to low-demand time intervals. In Germany, an average heat pump can provide up to 10.7 kilowatt-hours (kWh) of load-shifting potential per pump and load-shifting cycle (Delta Energy & Environment, 2018). Importantly, however, load-shifting potential is negligible in summer compared with in winter and the shoulder seasons (Delta Energy & Environment, 2018). Furthermore, when heat pumps are installed without storage, using them for load shifting should be done smartly, so as not to compromise consumer's comfort.

The ability to reduce peak load by adding flexibility to residential heating demand was demonstrated as part of the EcoGrid EU project. The EcoGrid EU consortium includes leading energy companies from Nordic countries and global technology companies, working together on a project demonstrating a smart grid system by integrating 28 000 customers on Bornholm Island, Denmark. The project includes evaluating the use of flexible electricity consumption by remotely controlling 1 000 heat pumps and electric radiators across the island. The project was launched in 2016 and was concluded in June 2019 (Jensen, 2018). The main findings of the project are:

- Time-of-use tariffs and real-time price signals are useful in activating flexible consumption.
- There is a significant potential for peak load reduction: The activation of flexible consumption with a 5-minute real-time signal reduced the total peak load of the EcoGrid EU participants by approximately 670 kW, or 1.2% of the peak load on Bornholm Island.
- Households with equipment that controlled their heating system so that it responded automatically to price signals accounted for 87% of the peak load reduction (EcoGrid EU, 2015).

Storing energy on large scales

Thermal storage can store energy for days or even months to help address seasonal variability in supply and demand. This is of particular benefit to energy systems in regions that have a significant difference in heating and cooling demands between seasons. The key benefit of using thermal storage in district heating and cooling schemes is the opportunity to decouple heat and cold generation from consumption. Surplus heat produced with renewables in the summer can be stored in thermal storage, which then can be used to meet winter heating demand, thereby reducing the need for non-renewable sources of heat during peak times. Thermal storage also can be used to store natural cold in winter, which can then supply space cooling during the summer (IRENA, forthcoming). Key technologies for seasonal storage are aquifers or other forms of underground thermal energy storage.

Drakes Landing is a technical demonstration project that uses solar thermal energy and seasonal underground thermal energy storage for a district heating scheme supplying a residential community of 52 houses in Alberta, Canada. It was born out of the desire to improve the efficacy of seasonal storage for district heating. A total of 1.5 MW of solar thermal capacity installed on the garages of each house capture solar energy during the summer, before storing it underground using borehole thermal storage.

In winter months, during periods of high heating demand, heat is extracted from the stores and distributed to each home. The project enabled the provision of almost 100% of space heating from local solar thermal generation. Through effective energy storage, the project demonstrated that the problem of seasonal mismatch between the supply of renewable energy and the demand for heat could be resolved. As a result, each household's greenhouse gas emissions were reduced by more than 5.5 times each year (IRENA, forthcoming).

Providing grid services via aggregators

Traditional storage heaters were designed to consume electricity during night (off-peak) hours to generate heat, and the heat was stored for use during hours of peak electricity demand. Considering the growth in the share of VRE sources such as solar and wind in the electricity system, there can be periods of excess supply during the day that will in turn translate to lower electricity costs.

New "smart" storage heating solutions are designed to take advantage of variations in electricity prices throughout the day. These smart storage heaters can be remotely controlled by aggregators to both optimise heating costs for consumers and provide grid-balancing services to the national grid. In the United Kingdom, energy provider OVO Energy, together with energy solutions provider VCharge, has developed a solution to aggregate smart heating systems used in nearly 1.5 million homes in the country, representing a combined peak capacity of 12 GW (OVO Energy, 2017).

As an alternative to storage heaters, the thermal inertia of buildings, especially well-insulated buildings, can be used as the storage, while electric heating devices such as heat pumps and boilers can be remotely controlled by an aggregator to optimise electricity consumption. In Switzerland, Tiko solutions has connected over 10 000 electric heat pumps and hot water boilers; they are continuously monitored, and their electricity consumption is controlled (without disturbing the customer's comfort) to provide flexibility services to the national grid (Geidl et al., 2017).

In the case of district heating systems, such networks would help foster co-operation between various stakeholders, such as waste management agencies (for biogas), the power sector and water utilities, for efficient management of the district heating system (IRENA, 2017).

Increasing self-consumption from renewable local generation

Consumers with solar rooftop systems can use the locally generated electricity to power heat pumps. This would help increase self-consumption of the energy generated from distributed solar installations and, in turn, generate savings by reducing electricity purchased from the grid (Battaglia et all, 2017). This is particularly useful in regions where net energy metering or net billing is not implemented and hence there is no mechanism of valuating energy injected back into the grid. Further, during hours of peak solar generation, the distribution system operator may not be able to absorb all generation from distributed sources. In such cases, heat pumps help maximise self-consumption by converting the locally generated electricity to heat or space cooling.

Potential impact on power sector transformation

Cases from different countries highlight the impact of renewable power-to-heat technology:

- **Load shifting:** EcoGrid EU was a demonstration project on Bornholm Island, Denmark, evaluating the use of flexible electricity consumption by remotely controlling 1 000 heat pumps and electric radiators. The results showed that a real-time price signal can be used to activate flexible consumption. Load shifting by activating demand response with a 5-minute real-time signal **reduced the peak load of customers by approximately 670 kW**. This was equivalent to **1.2% of the overall peak load** on Bornholm (55 MW). More than half of the peak load reduction came from customers with fully automated control of their heating system (52%), while one-third of the reduction was achieved by those with semi-automated control of heat pumps or electric heating (35%). The industrial and commercial customers accounted for 9% of the reduction, and the manual control group for 4% (EcoGrid EU, 2015).

- **Load shifting:** EctoGrid (Sweden) has developed a technology to connect the thermal flows of multiple buildings. The buildings use heat pumps and cooling machines to supply or withdraw heat energy from the grid. A cloud-based management system is used to balance the energy demands of all buildings connected to the grid. This results in a **78% reduction in energy required for heating systems** and **reduces customers' energy bills by nearly 20%** (EctoGrid, n.d.; Solar Plaza, 2018).

- **Reusing waste heat:** In the United States, Kraft Foods, a food and beverage producer, uses heat pumps to capture waste heat and upgrade it to useful heat. At its plant in Iowa, the company uses heat pumps to upgrade 2.1 MW of waste heat from its refrigeration system for heating water. This system has resulted in **savings of over 14 million gallons of water and over USD 260 000** in annual savings (Emerson, 2012).

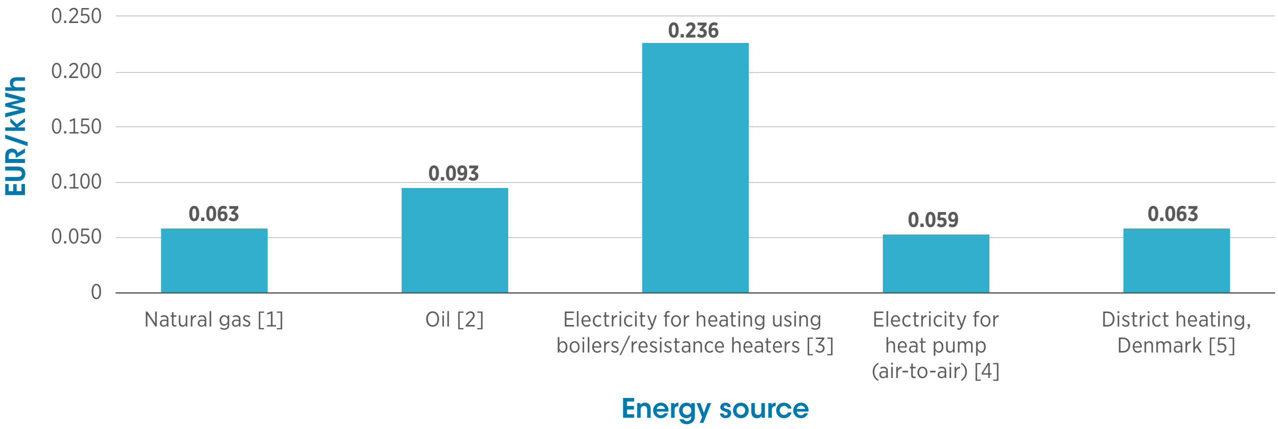
- **Increasing self-consumption from local renewable-based generation:** SolarChill is a partnership between technical organisations (such as the Danish Technical Institute) and development organisations (including the World Health Organization, UNICEF[2] and the United Nations Environment Programme) that is working towards installing solar energy-powered refrigerators for medical uses in regions with insufficient electricity. The refrigerator uses a solar photovoltaic panel to operate the compressor. The refrigerator unit is well insulated so that the temperature is maintained for five days, even with poor sunlight. Currently, around 15 000 to 20 000 SolarChill refrigerators have been installed in countries across Africa, Asia, Latin America and the Caribbean for storing and transporting vaccines (SolarChill, n.d.).

2 United Nations Children's Fund.

III. KEY FACTORS TO ENABLE DEPLOYMENT

Incentives to decarbonise the heating sector lead to deployment of heat pumps at a steady pace. On average, the operating costs of using electricity to generate heat are comparable to those of using fossil fuel-based sources. High-performance heat pumps can generate more than 4–5 kWh of useful heat for every 1 kWh of electricity consumed (EHPA, 2018a). Efficient heat pumps and lower cost electricity from renewable energy will further reduce the cost of operating a renewable power-to-heat system. Figure 3 shows the estimated generation cost per kWh of heat using various fuel types (in the European Union) and the average price of per kWh of heat sourced through the district heating network in Denmark. The district heating price in Denmark has been chosen as an example. The network in Denmark is widespread, with over 460 plants and units generating heat for the district network, which caters to nearly two-thirds of the households. The plants and units use a mix of renewable energy-based sources and fossil fuels, such as coal, natural gas, biogas, solar thermal, biomass and municipal waste (Danish Energy Agency, n.d.; Jessen, 2016).

Figure 3: Levelised cost of hydrogen (LCOH) produced via alkaline electrolyser in Denmark



Notes:

[1] Average natural gas prices for household consumers in the Euro area with consumption between 20 GJ and 200 GJ, inclusive of all taxes and levies in 2018. Source: (Eurostat, 2018a)

[2] Calculated using average oil price of EUR 0.795 per lit of heating oil, 80% boiler efficiency and energy conversion factor = 10.72 kWh/lit. Source: (European Commission, 2018) (RenSmart, 2018)

[3] Average electricity price for household customers in the Euro area, including all taxes and levies for consumption band 1 000 kWh–2 500 kWh in 2018, Source: (Eurostat, 2018b)

[4] Price per kWh of heat pump is obtained as price of electricity/3.83, assuming, a typical air source heat pump has a co-efficient of performance (COP) of 3.83. In other words, the heat pump consumes 1 kWh of electricity to generate 3.83 kWh of useful heat. Source: (Bo Shen, 2017)

[5] Average of prices in March 2018 provided by the district heating companies' price reviews for the Danish Electricity Authority. Assumed currency conversion: 1 Danish Krone = 0.13 EUR Source: (Forsyningstilsynet, 2018)

Additional heat storage notably helps to lower the cost of heat from heat pumps. The price of EUR 0.06/kWh (USD 0.066/KWh)* of heat, using the heat pump, was reached with the average electricity cost of EUR 0.24/kWh (USD 0.27/kWh)*. Efficient storage of heat would allow use of low-cost electricity during low-peak times (*e.g.* during the night), which would result in a price of EUR 0.02/kWh (USD 0.02/kWh)* of heat. This would require both heat storage and time-of-use electricity tariffs being in place. Enabling heat storage and time-of-use electricity pricing will support a bigger shift towards higher usage of renewables.

Using the simultaneous heating and cooling function of a heat pump will reduce operation costs even further, as both heating and cooling can be provided with one unit of electricity. For cooling, the energy efficiency factor is about 3–4, meaning that a typical heat pump can remove about 3–4 units of heat for each kWh consumed. When heating and cooling functions are used simultaneously, the energy efficiency can reach 7–9. However, simultaneous use of the heating and cooling functions of heat pumps is limited. First, not all heat pump technologies are designed for this, and when they are, the technology cost is higher. This application is mostly used in commercial buildings. Economies of scale in a growing heat pump market will contribute to lowering the capital expenditure.

Policies and regulatory support

A significant push to the deployment of power-to-heat technologies would be given by limiting the use of fossil fuel boilers and introducing requirements for new buildings to include renewable energy sources for supplying heat. In Germany, the Renewable Energy Heating Act bans the use of oil burners for heating new buildings and requires all new buildings to use energy generated from renewable energy sources for space and water heating. The national goal is to boost Germany's percentage of renewable heat to 14% by 2020 (HPT, 2019). Similarly, in 2017 Norway's Ministry of Climate and Environment passed a law banning the use of oils and paraffin from 2020 in heating applications.

The government of the Netherlands has started the complete transition away from gas in end-user residential buildings. Part of this initiative is a change in taxation levels, reducing the burden of using electricity, increasing the levy on fossil energy and eliminating a "right to be connected to the gas grids" for new buildings (Potter, 2018). Furthermore, ending subsidies on fossil fuels will help faster adoption of renewable energy for several applications, including heating.

Secondly, incentivising energy efficiency would boost the uptake of power-to-heat applications. The introduction of net zero energy building concepts could have a significant impact. Although the definition of net zero energy buildings varies by region, the overall objective is to improve buildings' energy efficiency and lower consumption. The European Union's directive on the energy performance of buildings requires all new buildings in the European Union to be net zero energy buildings by 2021 (European Union, 2010; European Commision, 2019b). Innovative business models can emerge from such policy. For instance, Energiesprong develops solutions for refurbishing houses into net zero energy homes that can generate their own energy for heating, cooling and powering appliances. The cost of refurbishment is recovered through savings on energy bills and reduced maintenance and repair costs (Energiesprong, n.d.). Energiesprong has provided solutions to homes across Canada (Ontario and British Columbia), France, Germany, Italy, the Netherlands, the United Kingdom and the United States (New York).

Policies that enable the interconnection of heating and electricity markets should be implemented. For instance, in the Inner Mongolia Autonomous Region in China, excess power generation that is otherwise curtailed is sold directly to the heating system operator, and in Lemgo, Germany, electric boilers are allowed to participate in the ancillary services market (IRENA, 2017).

Finally, targets for more renewable energy-based heating and cooling are required. In China, the 12th five-year plan set targets for enhancing its district heating networks.

* Converted at the exchange rate EUR 1 = USD 1.1

The targets include setting up geothermal plants and solar heating plants, as well as increasing the share of renewable energy sources like biomass in district heating systems (Danish Energy Agency, DBDH, n.d.). China is on track to include 20 billion square metres of floor area in its district heating network (IEA, 2017b). On a more regional scale, the government of Beijing started the "clean up coal program" in 2014, encouraging the switch from coal boilers to electric heat pumps, which has had immediate effects on overall energy efficiency and the pollution from household heating (Zhao, n.d.).

Incentives for increased use of renewable energy in heating and cooling applications

Incentives should be offered for increasing the use of renewable energy in heating and cooling. Both domestic and industrial consumers will have to make upfront investments to shift towards renewable energy for heating and cooling applications, and schemes that reduce the economic burden on consumers will encourage faster adoption of renewable energy in heating and cooling. However, these schemes should be tailored to the needs of different consumer segments, types of building (residential vs. industrial) and types of heating system (centralised vs. decentralised), as well as to other external factors, such as climate zone.

District heating and cooling systems require different types of incentive. Demonstration projects that will help increase consumer and investor confidence should be encouraged. These projects can be expanded once commercial viability is established and user acceptance is obtained. Securing financing is an important barrier to setting up district heating and cooling systems. The demonstration projects will help establish the commercial viability of the business model and hence reduce uncertainty.

Identifying complementary financing sources and stabilising demand will also help establish district heating systems (IRENA, 2017).

Market design enabling revenue staking

Upon widespread adoption of heat pumps and smart storage electric heaters, these systems can be used to provide ancillary services to the electricity market. But to make efficient use of these resources in adding flexibility to the grid, appropriate market design should enable power-to-heat systems to "stack" revenue for providing flexibility services to the grid, possibly via aggregators. Additionally, efficient metering, verification, settlement and billing mechanisms are required to enable heating devices to provide flexibility within a short response period (Darby, 2017).

Implementing time-of-use tariffs for consumers would create an economic incentive and encourage consumers and aggregates to generate revenue from energy arbitrage, while supporting the grid.

Aggregators

Heat pumps can provide some ancillary services for the grid, but their power capacity is limited; thus, a single heat pump cannot provide these services for the period of time needed by the power system. However, when heat pumps are aggregated, they can complement one another, resulting in a virtual power plant able to provide grid services required by the system. Tiko, in Switzerland, connects over 10 000 electric heat pumps and hot water boilers to provide flexibility services to the national grid (Geidl et al., 2017).

Consortium or network of stakeholders for a holistic vision

Building national-level consortiums that bring together various stakeholders, such as local government, energy providers, utility companies, civil engineers, designers and end consumers, would lead to better understanding of the requirements for effectively electrifying the heating sector. Additionally, existing consortiums with a focus on renewable energy-based technologies in buildings and industry can focus on promoting power-to-heat technologies.

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

The table below highlights some key indicators that illustrate the current status of power-to-heat solutions.

Table 1 Current status of power-to-heat solutions

Status indicator	Key facts
Key regions where power-to-heat systems have been implemented	Canada, China, Japan, the United States and Europe (primarily Denmark, Germany, Sweden, Switzerland and the United Kingdom).
Sectors in which power-to-heat systems have been implemented	**Residential/commercial**: Air source and ground source heat pumps for space and water heating. **Industry:** Heat pumps for capturing waste heat for use in relatively low-temperature applications (≈100 °C). Industries that use heat pumps include paper and pulp, food and beverages, textiles, automotive and chemicals.
Heat pumps installed	**Worldwide:** Global heat pumps sales rose by nearly 10% between 2017 and 2018 – double the 2016–17 growth rate; 80% of household heat pump installations in 2017 were in China, Japan and the United States[1]. **EU21 countries:** 10.5 million units installed in 2017, with a storage capacity of 368 GW and contributing to 116 TWh of renewable energy[2].
Expected growth rate in yearly sales of heat pumps in Europe	7–8%[3]
Use of power-to-heat technology in selected markets	**China:** • Policies to eliminate coal-fired boilers for heating have driven growth for heat pumps in China. Government subsidies encourage consumers to switch to electricity-based heat pumps from coal-fired boilers. Over 1 million air source heat pumps for water heating were sold in 2014[4]. **Canada:** • The government of Canada, as part of its USD 2.1 billion efforts to curb emissions, will be modernising government-owned heating and cooling plants in the National Capital Region[5]. • Two municipalities in British Columbia and one in Ontario have committed to providing 100% of power, heating and transportation requirements through renewable energy sources by 2050[6]. **Denmark:** • The government of Denmark is investing EUR 3 million (USD 3.31 million*) in 13 heat pump projects to be installed at district heating plants across Denmark. • The electric heat pumps would provide heating to 29 000 households and increase the use of VRE sources[7].

Sources: [1] Abergel (2019); [2] EHPA (2018a); [3] EHPA (2018b); [4] Zhao et al.(2017); [5] Public Services and Procurement Canada (2017); [6] Renewable Cities (2017); [7] DBDH (2018).
* Converted at the exchange rate EUR 1 = USD 1.1

Table 2 describes select projects and case studies in which power-to-heat technology has been adopted for different purposes.

Table 2 Power-to-heat system projects and case studies

Project/case study	Location	Description	Impact
Vattenfall	Germany	Vattenfall, a Swedish utility company, operates an electric boiler in Hamburg using excess wind generation, avoiding thus wind power curtailment. Also, Vattenfall will be investing in power-to-heat boilers to generate district heat in Berlin. The units will use electricity from renewable energy sources to heat water, which will transmit heat to residences and commercial buildings (Vattenfall, 2017).	In Berlin, the electric boilers replaced one unit in a coal-fired plant and provided a total capacity of 330 MWh, reducing the use of fossil fuels in heating applications.
Heat Smart Orkney	Orkney Islands, Scotland	As a part of the Heat Smart Orkney project funded by the Scottish government, a wind power-to-heat scheme is being implemented. Households will be provided with energy-efficient heating devices that will draw excess power generated from the community-owned wind turbine, which would have otherwise been curtailed. The household heating devices will be connected to the internet and will get switched on when the wind turbine receives a curtailment signal (Colthorpe, 2018).	Excess power from wind energy is converted to heat
Power-to-heat expansion in Denmark	Aarhus, Denmark	The city of Aarhus in Denmark expanded the capacity of an existing combined heat and power plant by adding an 80 MW electric boiler and a 2 MW electric heat pump in 2015 to provide district heating to the neighbourhood. The heat pump's capacity is planned to be expanded up to 14 MW after assessing the performance of the existing heat pump (IRENA, 2017).	The electric boiler and heat pump are designed to use excess wind generation in western Denmark, which is typically greatest in winter months, coincident with increased demand for heat.
District heating network	Qingdao, China	The city of Qingdao is investing USD 3.5 billion to build a district heating network. The district heating systems will use heat pumps that transfer heat from the air, the ground and the waste heat from industries to buildings in the city. Qingdao District Heating & Power Co. is also investing in upgrading the buildings to be compatible with the district heating network.	The city aims to use clean energy sources for all its heating needs, which would reduce coal consumption by over 3 million tonnes annually (C40 Cities, 2017).
Smart Energy Islands	Isles of Scilly, United Kingdom	This project is led by Hitachi Europe, in partnership with Moixa and PassivSystems. About GBP 10.7 million (USD 13.2 million*) has been invested to double the islands' renewable energy capacity and implement smart energy systems to balance supply and demand. As part of the project, smart energy technologies such as air source heat pumps and smart batteries will be installed and connected to smart home energy management solutions (Moixa, 2017).	Given their remote location, the islands have to import fossil fuels through underwater pipes for their energy usage. The project will double the islands' renewable energy usage to 448 kW. The smart energy systems will provide flexibility to the network by contributing to the grid, according to its supply and demand requirements.
GM Smart Energy trial	Manchester, United Kingdom	Greater Manchester Combined Authority is working with Japan's New Energy and Industrial Technology Development Organization to demonstrate the ability of heat pumps to provide flexibility to the grid. This pilot project connected 500 heat pumps via an aggregator to provide ancillary services to the grid (Delta Energy & Environment, 2018).	Heat pumps as flexibility provider for the grid.

*Converted at the exchange rate GBP 1 = USD 1.23

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Heat pumps for decentralised heating systems • Large-scale heat pumps or boilers for cold source or district heating systems • Pipeline infrastructure for district heating systems • Sufficiently insulated buildings for effective thermal storage • Sufficiently dimensioned hot water storage; in the case of industry, sufficient thermal energy storage technology that is technically and economically feasible • Metering equipment, such as smart meters or devices, built into the storage systems (required to provide real-time power consumption and production
	Software: • Optimisation software for heat pump systems that can adjust consumption according to demand • Aggregation software with algorithms calculating the optimal operation of each unit • Real-time communication between the aggregator and the hardware system • Distribution system management software to ensure reliability and safe operations
POLICIES NEEDED	• Appropriately value and capture the unique set of benefits that energy storage systems can provide (*e.g.* valuation through demand-side management studies; capturing of value through wholesale market or demand-side management programme participation) • Establish targets for using renewable energy for heating and cooling systems; these targets could be linked to the contribution of renewable energy to the electrical grid • Provide financial incentives for promoting power-to-heat systems for both residential and commercial buildings; these incentives can be in the form of initial capital subsidy or interest subvention and based on generation, etc. • Incentivise reduction in use of fossil fuels for heating • Support the development and implementation of residential and commercial building energy codes

REGULATORY REQUIREMENTS

Retail market:

- Time-of-use tariffs and net billing schemes to incentivise demand response programmes and therefore maximise the benefits of heat pumps for consumers
- Provisions to allow distributed energy resources, including heat pumps, to provide grid services
- Definition of technical and operational standards
- Update of building codes and the thermal insulation standards for residential and commercial buildings
- Establishment of clear, fair and non-discriminatory valuation and remuneration frameworks
- Establishment of fair and non-discriminatory charges

Distribution and transmission operators:

- Regulations allowing transmission and distribution system operators to procure market-based flexibility services from distributed energy resources, including heat pumps or district heating systems
- Establishment of local markets for distribution system operators to procure services to avoid grid congestion and ensure reliability
- Increased co-ordination between distribution and transmission system operators

Wholesale market:

- Participation of aggregators and distributed energy resources in electricity wholesale markets and ancillary service markets
- Regulations allowing decentralised resources to provide services to central or local grids
- Clear price signals to guide the operations of aggregators and behind-the-meter batteries

STAKEHOLDER ROLES AND RESPONSIBILITIES

Service providers:

- Form consortiums to enable cross-sharing of knowledge and resources among various providers in the utility space; this could result in identifying synergies that could be exploited for a cost-effective implementation of renewable power-to-heat technologies; the consortium could take measures to increase end-user acceptance
- Develop integrated utility delivery systems, in which a utility provider is responsible for the supply of electricity, heating, cooling and water to consumers in a region; these multi-utility systems can exploit synergies in operations and maintenance and thereby reduce costs for consumers

State:

- Increase funding for pilot projects to evaluate measures to reduce capital expenditure for district heating networks

ABBREVIATIONS

GJ	gigajoule
GW	gigawatt
kW	kilowatt
kWh	kilowatt-hour
L	litre
MW	megawatt
TWh	terawatt-hour
VRE	variable renewable energy

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