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1 Introduction

The present report constitutes Deliverable D1.1 *"Catalogue for technologies that enable grid interactions"*, developed within WP1 of MUSE GRIDS. The main aim of the report is to provide a comprehensive catalogue of the technologies needed for decarbonisation on a local/urban level. The report mainly includes technologies that enable grid interactions and establish synergies between infrastructures, such as power-to-heat, electric vehicles, cogeneration, and various types of energy storages. The report also addresses some of the main renewable energy exploitation technologies.

The report is intended for city planners with the responsibility for assisting the transition towards renewable energy systems where smart, integrated energy systems are pivotal. While the report cannot replace an academic smart energy systems' planning programme, it does provide technology data and highlights some of the main issues in regard to technologies and other components of such systems.

The report includes descriptions of the technologies' state-of-the-art, both technical and economic data, based on literature reviews and other gathered data. It also integrates descriptions of the Smart Grids (electricity, heating, gas), and guidelines for the design of such multi-energy grids. The focus is related to energy planning level including for each technologies CAPEX and OPEX, acceptance issues in terms of social and regulatory aspects, scale of the technologies, and technology readiness level (TRL).

The report is based on a combined effort by MUSE GRIDS project partners with AAU as main contributor and leading partner and exploiting the specialised knowledge of the project partners within their respective fields to provide an in-depth and up-to-date catalogue of the relevant technologies.

The report is based on literature reviews, company information and other gathered data and does not include technology development as such.

2 Synergies among energy networks in Smart Energy Systems

Energy systems have moved from being supplied predominantly by storable fuels to being supplied progressively by fluctuating renewable energy sources of a use-it-or-lose-it nature. Fossil fuels like coal, oil and natural gas are both primarily energy sources and a storage in a combination, whereas wind power and solar collectors requires a demand that matches temporally. Unless local conditions favour renewable energy sources with inherent storage capability such as dammed hydro and bioenergy, conversion to renewable energy supply often entails a switch away from supply side stability. This calls for flexibility in the energy system to accommodate fluctuations in supply and demand; a flexibility that can arise from demand side management, storage, sector integration, and any still available dispatchable production units. Renewable energy technologies can also be down-regulated, but upward regulation requires them to be run sub-optimally.

The following figure shows the main principles of Smart Energy Systems; it is however not an exhaustive illustration of all aspects and technologies.

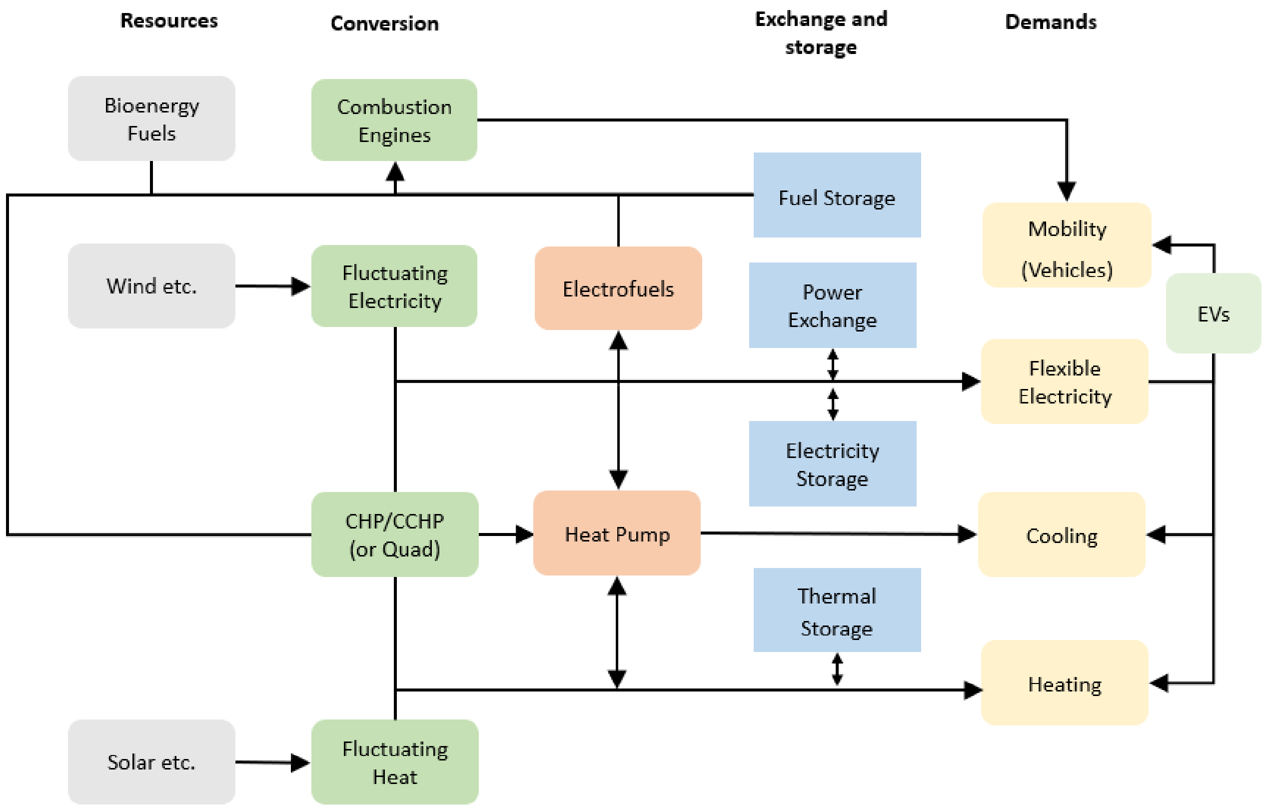

Figure 1: Smart energy system schematic.

There is much focus on smart grids, where focus is on electricity side measures, however smart energy systems are based on a more holistic approach where flexibility and storage throughout the system is considered [1] [2]. Quoting [3]

The smart energy system is built around three grid infrastructures:
Smart Electricity Grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.
Smart Thermal Grids (District Heating and Cooling) to connect the electricity and heating sectors. This enables thermal storage to be utilised for creating additional flexibility and heat losses in the energy system to be recycled.
Smart Gas Grids to connect the electricity, heating, and transport sectors. This enables gas storage to be utilised for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.

This sector integration enables the use of storage in less costly places of the energy system[4]. For instance, if electricity storage can be avoided and replaced by heat storage, this can have similar system benefits at a much lower cost. Sector integration also enables the exploitation of synergies such as heating houses with the waste heat inevitably produced when electricity is converted into electrofuels for the transportation sector.

There are not any barriers designed to hinder the development of smart integrated energy systems, however some factors may have this as a side effect. Ownership structures can impact the development of smart energy systems either through lack of competition or by companies with sunk costs in certain technologies. For instance, there will be little motivation to replace a natural gas grid by a district heating grid even if the district heating system can tap into waste heat sources that are otherwise left unexploited. Framework conditions may also act as a barrier against e.g. district heating systems. In Japan, for instance, district heating is not considered a public utility – thus there is no right of access to lay pipes across streets.

Through DEMATEL (Decision making trial and evaluation laboratory)[5] analyses of a smart energy transition in Accra, Ghana found barriers pertaining to several issues, including financing, insufficient legal framework and lack of information[6], though these barriers also related to renewable energy sources in general.

A larger meta study (literature review) identify several barriers across several fields, finding inadequate regulation and policies, technical and market restrictions, perceptions on risk and uncertainty, lack of information, trust, awareness and more[7]. However, again, these factors relate not necessarily to smart energy systems in particular but renewable energy sources in general.

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[1] From electricity smart grids to smart energy systems – A market operation based approach and understanding - https://doi.org/10.1016/j.energy.2012.04.003
[2] Smart Energy Systems for coherent 100% renewable energy and transport solutions - https://doi.org/10.1016/j.apenergy.2015.01.075
[3] Smart energy and smart energy systems - https://doi.org/10.1016/j.energy.2017.05.123
[4] Energy Storage and Smart Energy Systems - https://doi.org/10.5278/ijsepm.2016.11.2
[5] DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications - https://doi.org/10.1155/2018/3696457
[6] Analyzing barriers of Smart Energy City in Accra with two-step fuzzy DEMATEL - https://doi.org/10.1016/j.cities.2019.01.043
[7] Examining the barriers and motivators affecting European decision-makers in the development of smart and green energy technologies - https://doi.org/10.1016/j.jclepro.2018.06.308

3 Analytical framework for MUSE GRIDS technology assessment

The catalogue is structured with the needs of decision-makers and planners in mind, thus has a focus on descriptions of the technologies' state-of-the-art in terms of both technical and economic data. In addition, characteristics regarding acceptance and readiness are included.

The following template is used for the technologies – with potential deviations when certain fields are not appropriate for particular technologies:

- Leading partner(s) in the technology description
- Technical parameters
    - Description of function including a brief review of competing technologies in the same category
    - Sector integration properties – including dispatchability/flexibility and regulation speed
    - Sizes; general range and range for the data included in the technology catalogue
    - Efficiencies and losses from input to output
- Economic parameters
    - Investment cost
    - Operation and maintenance costs (fixed and variable)
    - Lifetime
- Implementation
    - Social acceptance among citizens - (e.g. role of the social acceptance in the design of grids (electricity, heating, cooling etc.) or for planning technology deployment)
    - Social acceptance among planners and politicians
    - Appropriateness by scale (city-scale vs nation)
    - Market readiness and current deployment

4 Technology overview

The report provides information on a selection of the main technologies needed for decarbonisation on a local/urban level with a focus on those that enable grid interactions and establish synergies between infrastructures.

In addition to technologies enabling grid interactions, the report includes a selection of single-grid or single-sector technologies that are foreseen to play a main role in future high-RES energy systems. This includes e.g. wind power, photovoltaics and solar collectors. The following technologies are described with one section per technology:

- Renewable energy exploitation technologies
  - Grid-connected wind power
  - Photovoltaic panels
  - Solar thermal collectors
  - Hybrid PV/Solar thermal
- Energy conversion technologies
  - Cogeneration of heat, cooling and power
  - Heat pumps
  - Direct electric heating
  - Electrofuels
  - Gas boilers
  - Biomass boilers
- Power control and conversion technologies
  - Chargers for electric vehicles (integration between converter and grid)
  - Vehicle-to-grid/home power converters (integration between converter and grid)
  - Control systems
  - Communication in Smart Energy Systems (SES)
  - Wider area network system
  - Asset aggregation and virtual power plant (VPP) technology
  - Home energy management System
- Storage
  - Communal heat/cold storage
  - Communal electricity storage
  - Gas storage
  - Smart Electric Thermal Storage (SETS)

- Grids
    - Electricity
    - Gas
    - Heating/cooling

5 RE Exploitation technologies – Grid-connected wind power

Leading partner(s) in the technology description: AAU

Technical description

Wind turbines exploit the movement of air through typically a three-blade rotor connected to a generator either directly or through a gear box. The rotor, generator and possible gearbox are placed on and in a nacelle placed at the top of a tower which is pointed against the wind using a yaw mechanism.

An alternative constellation is the vertical axis Darrious wind turbine, however this is not as efficient and are thus not deployed significantly.

Sector integration properties

Wind power does not per se have sector integration properties however the technology is a staple element in integrated or smart energy systems scenarios. Some concepts such as “wind powered heating systems” exists where e.g. electricity from a wind turbine is provided for heat generation, however unless seen from the perspective of a stand-alone energy system or an actual integrated unit, the wind power system and the heating system may as well be perceived as separate systems connected through an electric grid. Systems with a so-called “private wire” may also be perceived as an integrated system where the “private wire” (as opposed to public grid) typically entails the absence of taxes and levies on the electricity consumption – but also of potential subsidies on the power production.

Older wind turbines were typically fitted with asynchronous generators connected directly to the grid – which had the implication that they could not supply ancillary services in the form of voltage or frequency control. This limited the share of wind power to the grid in any given moment as ancillary-service providing units needed to account for a significant minimum share; e.g. around 30%. Modern wind turbines can act more intelligently, controlling for instance reactive power (and thus voltage). They can provide downward regulation (and thus downward frequency control) and if operated sub-optimally with e.g. wing blades pitched imperfectly, they can also provide upward regulation (and thus upward frequency regulation).

The technology cannot be freely dispatched but is limited by the fluctuating resource. There is a downward regulation possibility – but upward regulation requires an available resource in the moment in question as well as operation that is not optimal. Assuming the wind is blowing, wind power can be regulated very quickly within seconds or minutes.

Sizes

Wind turbines come in different sizes and designed for different applications; land-based, off-shore and small-scale for individual houses.

Modern utility scale wind turbines are typically in the MW range. According to the Danish wind turbine register[8], wind turbines erected in Denmark in 2018 had an average size of 4591 kW ranging from an average of 2474 kW for land-based wind turbines to an average of 8093 kW for off-shore wind turbines. The figure below shows the size distribution in Denmark at the end of 2018 with the wide bars showing the number of turbines in each size range and the narrow bars showing the cumulated capacity in the size range.

[8] *Master data register for wind turbines at end of December 2018* - https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/overview-energy-sector

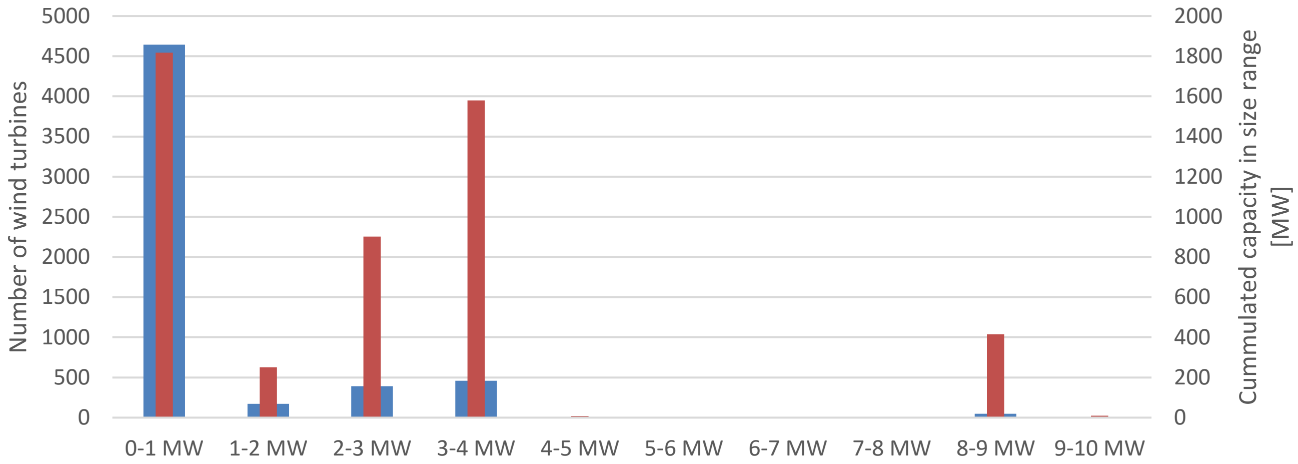

Figure 2: Cumulative capacity of wind turbines installed in Denmark.

While sizes in general are increasing, there is also a large stock of smaller turbines – also of a more recent date. For instance, the smallest size range in the chart includes 1148 small wind turbines of 10 kW erected from 2013 to 2018.

Efficiency and loss

Wind turbines have an efficiency that varies with the wind speed. Typically, for modern wind turbines it is around 45%[9]. While the input of course is free, harvesting the inputs is not, thus the rotor's uptake of energy is a focus for refinement.

Other characteristics are equally important; wind conditions, the topology of the landscape, the roughness of the surroundings and the hub-height. Wind speed increases with hub-height, generally following a power function in the form $v = v_{Ref} * (\frac{h}{h_{Ref}})^{\alpha}$, where v_{Ref} is the wind speed at the reference height h_{Ref}. The exponent in the function varies with the roughness of the landscape. The roughness is a determinant, basically describing objects in the landscape. Thus, over water, for instance, the wind speed increases faster than over a forest or over an urban area. Topology describes the wider landscape features like hills, mountains, and valleys that can act as a local barrier or help funnelling wind.

Economic parameters

Wind turbines have size-dependency both in terms of performance and costs that calls for larger units. Also, off-shore turbines are more expensive than corresponding on-shore wind turbines. This is not duly compensated through better wind conditions. The table below shows a comparison of costs of the three typical applications.

All data are for 2015[10]	**3.5 MW land-based turbine**	**8 MW off-shore turbine**	**Small <25kW turbine**
Investment cost	1.05 M€/MW	2.86 M€/MW	4.0 M€/MW
O&M – Fixed	25,600 €/year/MW	25,600 €/year/MW	100,000 €/year/MW

[9] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

[10] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

O&M – Variable	2.8 €/MWh	2.8 €/MWh	2.8 €/MWh
Lifetime	25 years	25 years	25 years

The investment cost for land-based wind turbines can approximately be split up into 71% equipment, 24% installation and 5% grid connection costs, while the investment cost for off-shore wind turbines can approximately be split up into 39% equipment, 47% installation and 14% grid connection costs. Both are of course very sensitive to local conditions. For small-scale wind turbines, 90% of the investment cost lies in equipment.

Note that the fixed O&M includes insurance, which for the smallest category (<25 kW) comprises around half the annual cost.

Social acceptance among citizens
Wind power is known for mixed receptions among citizens. Issues of e.g. flickering, shadows, warning lights, noise are well known and described in the literature and are amplified by the circumstance that wind turbines through the nature of the wind must stand in open areas as high above ground as possible. The impact and disturbance of wind turbines on the existing landscape and its preservation is also very important and potentially a critical barrier to social acceptance among citizens[11]. This combined with available space is one of the movers for going off-shore – and is a motivating behind limiting the size of turbines erected on land.

Acceptance of citizens can generally be improved through shared ownership and profits.

One Scottish analysis[12] compared public attitudes to wind farms with either community-based or investor-based ownership, finding a higher acceptance for the former. Even so, also with investor projects, the general stance was positive. On the other hand, results from 18 case studies from England, Wales and Denmark[13] *"indicate that projects with high levels of participatory planning are more likely to be publicly accepted and successful".*

Social acceptance among planners and politicians
Planning frameworks for wind turbines vary with local context. Where countries with a long history of wind turbines like Denmark has well-established procedures for handling wind power projects, other countries do not. Thus, where Denmark for instance has specific distance requirements to different landscape features, Canadian experiences have been more diverse with larger municipality responsibility and looser requirements.[14]

Acceptance among planners and politicians can be considered in parallel with acceptance among citizens, though uncertain planning regulations and assumed citizen opposition may impede development.

Appropriateness by scale
Wind power already plays a role at different scales from small-scale home-systems to GW size off-shore wind farms. Typically, optimal siting requires a number of wind turbines in a cluster to reduce visual impacts; a cluster of four in a certain geometric pattern is generally preferred to four individual turbines placed apart.

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[11] Planning of renewables schemes: Deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation https://doi.org/10.1016/j.enpol.2006.12.002
[12] Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland https://doi.org/10.1016/j.landusepol.2008.12.010
[13] Wind energy planning in England, Wales and Denmark: Factors influencing project success - https://doi.org/10.1016/j.enpol.2006.10.008
[14] Determining appropriate wind turbine setback distances: Perspectives from municipal planners in the Canadian provinces of Nova Scotia, Ontario, and Quebec - https://doi.org/10.1016/j.enpol.2011.11.046

Market readiness and current deployment

Wind power is deployed worldwide with a deployment at the end of 2017 of 539 GW. In 2017, 13 countries had a wind-share of more than 10% of their electricity demand[15]. The technology is thus well-established and depending on specific local conditions, can provide electricity at a cost comparable to fossil alternatives in the best cases.

[15] Renewable 2018 Global Status report - http://www.ren21.net/gsr-2018/

6 RE Exploitation technologies – Photovoltaics

Leading partner(s) in the technology description: ASTEA

Technical description

Photovoltaic (PV) technology takes advantage of the photovoltaic effect, a physical phenomenon occurring in certain semiconductor materials when exposed to solar radiation, generating an electrical current. By combining a matrix of cells made of semiconductor materials in panels, the production of relevant quantities of electricity can be achieved. Electricity production from PV panels is direct current at low voltage, thus, to complete the system a DC-AC inverter and a transformer is needed.

Sector integration properties

PV technology has no capability for sector integration by itself but still has a pivotal role in modern smart energy system scenarios, which supposedly is going to be more and more reliant on electricity as a vector.

Production from a PV system varies as a result of the daily and yearly solar radiance levels, and currently most PV systems will always supply all produced power to the grid. With large installed capacities in the future this could potentially lead to unwanted production peaks and thus voltage spikes. Modern PV inverters however enable grid operators to remotely control systems and provide grid-stabilisation in the form of reactive power and variable voltage, thus enabling PV to be regulated within seconds. The technology cannot be freely dispatched but is limited by the fluctuating resource. There is a downward regulation possibility – but upward regulation requires an available resource in the moment in question as well as operation that is not optimal.

Sizes

The size of a PV systems can be expressed as its total surface in square meters but is most commonly identified by its nominal power capacity in kW_p. This is the production of the system under standardized test conditions.

Given that a PV system can be fundamentally thought as a set of panels (which individual size is of 200-350 W_p) the size of such systems can span from very small to very large, in the order of MW_p. Thus, adapting to a wide variety of scenarios, from rooftop systems for individual residential users to large plants.

Efficiency and loss

Only a small fraction of the radiation hitting the panels can be converted to electricity. Adding to the intrinsic losses of the physical phenomena described, additional losses further reduce the electricity output. These are related to difference from the actual working conditions from the standardized test ones (panel temperature, light spectrum etc.) and the losses intrinsic to the additional electric equipment.

Overall the electric efficiency of a system is in the range 16-19%, independently of the size of the system. While dealing with PV systems it is important to take into account the degradation of performance with time, which is due mostly to chemical phenomena within the cell. Such wear of performance can be considered a loss in conversion efficiency for the whole system of around 0.25-0.5%[16].

Economic parameters

[16] Energinet, Danish Energy Agency. Technology data for energy plants for electricity and district heating generation. 2016-2019

PV system costs have been continuously dropping for the past several years and can be distinguished depending on the size of the system. Such costs are to be considered for the whole system: panels, inverter, transformer etc.

	Small/Residential	Medium/Commercial	Large/Utility Scale
System size [kW_p]	1-8	50 – 500	1000+
Investment cost [€/kW_p]	1000	800	700
O&M cost [€/kW_p/year]	12	10	8
Lifetime [years]	30	30	30

Social acceptance among citizens

Social acceptance of PV panels is mixed among citizens. As public opinion is increasingly recognizing the need to assess the challenges brought by climate change, the acceptance of renewable energy sources is raising. But, depending on location and placement, PV panels do have a significant visual impact, which can be a problem in densely populated areas or country sides. For instance, it has been shown that the financial aspect is only one of the aspects that influences the choice regarding PV system adoption. Other important elements for the community are aesthetic concerns, the perception of technical, operational and bureaucratic barriers. There is also the so-called neighbourhood effect that operates in two ways: first, viewing the panels stimulates interest, and second, the social interactions lead to better information and produce imitation effects[17].

Social acceptance among planners and politicians

PV technology is widely accepted among policymakers, which in order to support its growth enforced different energy policies and support programs, with considerable differences among countries. In the last years there has been a growing trend in deployed PV capacity in Europe that reached 108 GW at the end of 2017[18], but this has been mostly due to the huge expansion in PV technologies market. The support schemes could not actually keep up with such expansion, often needing to be reviewed and leading to a decreased confidence by investors. Among the incentives already in place for PV systems development lie capital subsidies, VAT reduction, taxes credits, quota obligation, net-metering, feed'in tariffs (FiTs)[19]. But as mentioned often their implementation and dissemination to the community is unsatisfactory[20]. Therefore, not only the policies should facilitate the adoption of renewable energy sources, but also the other aspects mentioned above as well as the strong environmental attitude, which includes a green social image that has become a very common mentality in many countries.

Appropriateness by scale

PV systems can be deployed on any rated power scale and adapted to different settings: from single residential units to warehouses rooftops and fields. The scale of the system poses also different level of challenge to how to deal with the unpredictable production pattern. While this might not be a problem for small domestic systems the introduction of large shares of PV systems within existing grids can be pose serious issues to the already existing infrastructures[21].

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[18] Jäger-Waldau, A., PV Status Report 2018, EUR 29463 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97465-6, doi:10.2760/826496, JRC113626

[19] A. Campoccia, L. Dusonchet, E. Telaretti, G. Zizzo, An analysis of feed'in tariffs for solar PV in six representative countries of the European Union, Solar Energy, Volume 107, 2014, Pages 530-542, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2014.05.047

[20] Strazzera E., Statzu V., Fostering photovoltaic technologies in Mediterranean cities: Consumers' demand and social acceptance, Renewable Energy, Volume 102, Part B, 2017, Pages 361-371, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.10.056

[21] California ISO. (2012). What the duck curve tells us about managing a green grid. https://doi.org/CommPR/HS/10.2013

Market readiness and current deployment

PV systems are already a mature technology, with an always growing capacity being deployed worldwide in a wide variety of settings. Nevertheless, research and development efforts are still ongoing with costs which are expected to tumble in the upcoming decades along with panel conversion efficiencies which are increasing[1]. Costs per kW_p of the whole system are predicted to drop to between 600 and 280 €/kW_p[22] by 2050, compared to a current system cost of around 800 €/kW_p.

In 2017, the cumulative installed capacity of solar reached 398 GW, generating more than 460 TWh[23].

[22] F. ISE, Current and Future Cost of Photovoltaics, Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems, Technical Report, 2015.

[23] Solar Energy - International Energy Agency 2018 - https://www.iea.org/topics/renewables/solar/

7 RE Exploitation technologies – Solar collectors

Leading partner(s) in the technology description: AAU

Technical description

Solar collectors – or solar thermal collectors – rely on sunlight to heat a heating fluid which usually through a heat exchanger is used for space or domestic hot water heating. Typical applications include flat panel solar collectors where an absorber combined with a coil is placed behind an anti-reflex-treated glass and placed in a well-insulated enclosure of e.g. aluminium (see e.g.[24]). Other applications include evacuated tube solar collectors where a low-pressure glass pipe contains an absorber attached to an inner tube through which the heating fluid is running and solar troughs where a tube is placed in the focal point of a parabolic mirror trough.

Sector integration properties

Solar collectors do not per se have sector integration properties however the technology is a typical element in integrated or smart energy systems scenarios. With a yearly production profile in phase opposition to the demand, it does however require actual energy systems analyses to see how much solar heating there is an opening for and how this is impacted by thermal storage. The opening is also restricted by other energy system heat sources including industrial waste heat, heat from cogeneration of heat and power (including waste incineration plants), and heat from the production of hydrogen or other electrofuels.

It is possible to regulate the flow of heating fluid in the collectors, allowing the output temperature to be adjusted according to current solar insolation levels. Because solar collectors have no interaction with the electricity grid, they provide no potential for grid regulation or balancing. The technology cannot be freely dispatched but is limited by the fluctuating resource. In tracking systems, downward regulation is possible – and upward likewise though subject to insolation and suboptimal operation.

Sizes

Installations ranging from single-house to district heating systems occupying entire fields. Typical house installations are in the single-digit square meter range while the largest district heating connected solar is the 110 MW and 156,694 m^2 large plant in Silkeborg, Denmark.

Efficiency and loss

Solar collectors have various losses to the surroundings in the form of reflection of incoming light, radiation as a consequence of the temperature of the collector, convection and thermal conductivity through mounting. Apart from reflection, losses are temperature dependent, thus the higher temperature requirements, the higher the losses. This makes the solar collector more favourable for low-temperature applications. In an analysis of low-temperature district heating, improved efficiency at a forward temperature of 55°C / return 25°C compared to standard 80°C/40°C values resulted in 30% lower production costs as output increases from the same panel[25].

Economic parameters

Flat panel collectors have size-dependency that favours larger units. The table below shows a comparison of costs of the two typical flat panel applications. The single-house systems result in approximately 666€/m^2 while the district heating system costs approximately 193 €/m^2 collector

[24] http://arcon-sunmark.com/products/collector-ht-heat-boost

[25] *The status of 4th generation district heating: Research and results* - https://doi.org/10.1016/j.energy.2018.08.206

All data are for 2015[26]	**4.2 kW flat panel house installation (6 m²)**	**10000 m² district heating system**
Investment cost	4000 €/unit	429 €/MWh_{output}/year
O&M – Fixed	69 €/unit/Year	0.09 €/MWh_{output}/year
O&M – Variable	0	0.19 €/MWh_{output}
Lifetime	20	30

References to capacity or production with different sizes in the table refer to Danish conditions with approximately 1000 kWh/m²/year.

For district heating systems, costs are distributed with 85% for equipment and 15% for installation. Investment for the house installations is 65% equipment and 35% installation. Note that costs depend on circumstances. The included costs are for existing buildings. Installing solar collectors on new buildings is cheaper than indicated in the table.

Social acceptance among citizens

Compared to wind turbines, solar collectors generally face less challenges related to social acceptance due to it being a less protruding technology as a result of the low profile, absence of moving parts, and the possibility of location smaller systems on roof-area with limited competing area-wise interests. However, for large-scale systems issues of reflections and land use conflicts are prevalent, especially for large-scale systems where the area occupation per MW is very high.

For house installations specifically, a survey from China distributed among urban and rural residents indicated a high level of social acceptance and awareness towards solar collectors [27] - while on the other hand, PV systems were less accepted, and awareness was lower. A study from Australia indicates an important barrier for deployment of solar collectors include uncertainty regarding costs and maintenance – in addition to an up-front invest cost barrier[28].

Social acceptance among planners and politicians

The deployment of solar collectors varies among countries not only as a result of solar irradiation levels, but also due to the local perception and acceptance among planners and politicians, including political ambitions, regulation and legislation.

The high area occupation of district heating systems could cause potential political land-use conflicts and aesthetic disagreement related to landscape disturbance. To mitigate this, the planning and design phase should aim to best incorporate the solar collector field into the existing landscape.

Appropriateness by scale

Solar collectors are available in all scale, ranging from house installations to large-scale district heating systems. Solar district heating systems are increasingly applied internationally, often combined with large storages, providing substantial economy of scale effects and independence from potential energy price increases.

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[26] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

[27] Social acceptance of solar energy technologies in China—End users' perspective - doi.org/10.1016/j.enpol.2011.01.003

[28] Solar water heaters uptake in Australia – Issues and barriers - https://doi.org/10.1016/j.seta.2018.08.006

House-installations might have to compete with solar photovoltaic installations for the same roof area, which could hinder the future deployment of solar collectors.

Market readiness and current deployment

Solar collectors are a well-known, robust, and proven technology as exemplified by its utilisation in more than 100 Danish district heating areas. While the initial capital cost per MW is high, the previously mentioned conditions combined with a long technical lifetime makes solar collectors a low-risk technology.

Solar collectors are deployed world-wide and at the end of 2017 a total of 472 GW thermal capacity for water heating was installed[29].

[29] Renewable 2018 Global Status report - http://www.ren21.net/gsr-2018/

8 RE Exploitation technologies – Hybrid PV/Solar collectors

Leading partner(s) in the technology description: RINA-C

Technical description

Solar thermal can be combined with solar PV as a single hybrid technology, known as Hybrid PV-T ('PV-T'). The concept is based on heat transfer between the back of the PV panel and the fluid, the fluid removing heat from the PV panel thereby improving the efficiency of PV-generated electricity and causing an increase in the temperature of the fluid which can be used for heating purposes. The heating fluid can be either a mix of water and glycol, or air. PV-T systems, which combine the basic principles of PV and solar-thermal collectors, generate both electricity and a useful thermal output simultaneously from the same aperture area, and therefore have advantages of requiring a smaller area compared to separate PV panels and solar thermal collectors.

Hybrid PV-T panels are typically building roof mounted and can also be ground mounted as part of a larger district energy system. Solar electrical efficiencies can increase by between around 4 and 12% when compared to conventional solar PV. The efficiency of silicon solar cells drops by 0.4% per °C temperature rise above 25 °C, and PV-T is generally most effective during periods of high solar irradiation and high outside air temperatures.

The electricity generated by a hybrid PV-T system can be used for local loads or exported to the grid. The heat generated by a PV-T system can be used for the following purposes.

- To provide a pre-heat for a hot water cylinder or thermal store to supply hot water (HW).
- To provide a pre-heat feed into a boiler for hot water and/or space heating.
- To provide a pre-heat or direct feed for an air source heat pump ('ASHP').
- To provide heat to charge a ground loop, borehole(s), earth bank or other inter-seasonal storage for a ground source heat pump ('GSHP').
- To provide a pre-heat or direct feed for HVAC/ warm air heating systems.
- To provide a pre-heat or direct feed for absorption cooling applications.

In the case of all pre-heat options, additional heating plant is required in order to provide for the full heat demand of the end use.

Typical low temperature hot water ('LTHW') flow temperatures from a PV-T system are around 40 - 50°C, which is suitable for low temperature heating applications, for example swimming pools and earth energy storage ('EES'). However, this is lower than required for safe HW storage (for protection against Legionella) and therefore additional energy is required where heat is stored, periodically to heat above the Legionella survival temperature (60°C), and/ or as needed for higher end use temperature requirements.

Careful sizing of the PV-T system and planning of energy use (demand-side management) is important to provide efficient operation. The optimal PV-T system solution will take into account the following:

- The spectral characteristics of the solar PV cell.
- PV cell solar absorption.
- Internal heat transfer from PV cell to heat collection system.
- Installation geometry (orientation and inclination).

- Integration into heating/ cooling and electrical systems.
- Heat/ cooling and electricity demands.
- Temperature requirements of heat demand.

The PV-T products for the domestic market typically include unglazed PV panels with thermal insulation, using a water/ glycol mix as the transfer medium, providing an indirect feed often via a heat exchanger for domestic hot water (DHW) and/ or space heating. Other types of products are also available, including glazed PV cells, those without thermal insulation, collectors with concentrators, and the use of air as the heat transfer medium. The typical arrangement of a PV-T panel is shown in the figure below.

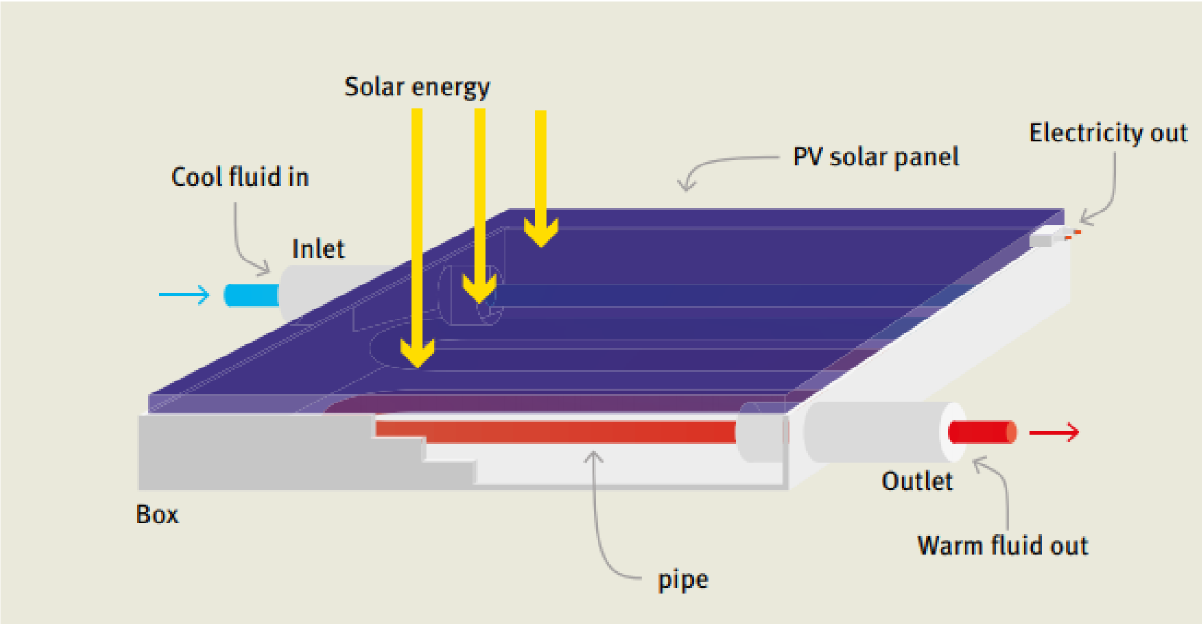

Figure 3: PV-T panel concept illustration[30].

Sector integration properties
PV-T technology is available at a range of scales, from roof mounted systems serving individual domestic properties to larger systems linked to mixed uses as part of a community or district energy scheme. Hybrid PV-T systems are suitable for integration with local energy grids as follows.

- Heat output to thermal storage, supplying LTHW to HW storage.
- Heat output to thermal storage, supplying LTHW to heat networks providing HW only, or space heating and HW.
- Thermal output to low temperature heat storage, supplying GSHPs, including both low temperature source-side networks supplying multiple GSHPs, and GSHPs supplying heat via LTHW heat networks.
- Thermal output to ASHPs supplying heat via LTHW heat networks, communal HVAC or warm air heating systems via warm air distribution systems.

[30] Imperial College - Grantham Institute Briefing paper No 22. May 2017

- Thermal output to absorption cooling generators, supplying cooling via chilled water (CHW) networks.
- Electricity output to local loads, battery storage and thermal storage.

PV-T systems are usually sized based on the thermal requirements of the connected energy load, and typically require a suitable amount of thermal storage to buffer between heat generation and heat demand. In conjunction with GSHPs, large buffer tanks have the capability to store the equivalent of several hours of heat load, offering significant potential for demand shifting.

Where HW demands are limited during spring, summer and autumn, in order to maximise the use of heat generated from a hybrid PV-T system a method of storing thermal energy is required, for use during the heating season when solar irradiation is much lower. Inter-seasonal heat storage involves pumping low grade heat from the PV-T panels into a relatively low-temperature underground store via a ground loop, borehole or similar. In winter the heat is then captured from the underground store by pumping in reverse, or more often via a heat pump. This arrangement ensures that the PV-T panels are never allowed to reach high operational temperatures, ensuring solar PV efficiencies are not adversely affected. The efficiency of use of inter-seasonal stored heat for space heating can be improved where buildings are well insulated, and therefore suitable for low temperature heating systems. Inter-seasonal storage of solar heat is applicable to both individual domestic properties and community scale heating schemes. A significant proportion of the domestic PV-T systems installed in the UK to date have used domestic scale underground inter-seasonal stores to provide winter heating to individual homes. Systems which store heat inter-seasonally as part of community scale installations will include a large number of PV-T panels, with higher electrical and thermal capacities.

The technology is not inherently expensive (especially if a GSHP would be used in any case). EES systems have potential for new build housing estates that are off the gas grid. If the installed cost became cost competitive with an equivalent area of PV and solar thermal, then PV-T could take up a significant proportion of this market.

Good applications for PV-T are considered to be leisure centres, sports facilities, nursing homes and small industrial sites requiring pre-heated water. Domestic properties require larger hot water cylinders, and hot water demand can often be insufficient to make retrofitting individual hybrid PV-T systems an economic proposition.

Modern inverters enable PV-T systems to curtail power production and thus the ability to assist in electricity grid balancing similarly to traditional PV only systems. Response time for regulation of PV-T systems is second-based.

Sizes

PV-T systems are modular, and can range in size from a rooftop mounted system supplying an individual domestic dwelling, to large systems which include multiple modules supplying multi-residential or commercial buildings, with heat supplied either directly, through a district heat network, or into earth energy storage supply heat pumps in individual properties.

Individual PV-T modules range in size from around 1.3 to 1.6 m^2 in area. A typical PV-T system serving a single domestic property may comprise 8 modules, approximately 13 m^2 total module area, with a capacity of 2.0 kW_p electric and 5.2 kW thermal. A community hybrid PV-T system could comprise 100s of modules, with a capacity in the 10s or 100s of kW.

Efficiency and loss

The design concept of a PV-T system is to produce heat and electricity as efficiently as possible, maximising the amount of solar energy converted into useful energy. PV-T collectors are capable of reaching overall efficiencies of 70% or higher (electrical plus thermal), with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%, depending on the conditions. Efficiency figures take account of global irradiation losses (panel inclination and orientation), as well as losses from shading and soiling. At the point of use of the electricity and heat generated, further losses are incurred, these include DC and AC losses, and heat utilisation, performance and storage losses. The overall efficiency and performance of a PV-T system depend on the design of the PV-T module, the design of the secondary system (i.e. thermal storage, pumps, pipework etc.), system integration, operation and control.

There is usually a trade off in performance for either heat or electrical production. PV-T panels are designed specifically with an electrical or thermal bias and system flow rate can be controlled to optimise either electrical or thermal efficiencies depending on the load demand and generation potential. However, the technology does have its limits (maximum temperatures, flow rates etc.) with which system designs need to fit within to ensure long term operation.

For domestic systems installed in the UK the total energy output, heat to electricity, is between approximately 2:1 and 3:1.

Potential opportunities for improvement in PV-T system performance are as follows.

- Combined with inter seasonal storage and GSHP systems for space heating in winter.
- Combined with absorption refrigeration for cooling in summer.
- Combined with phase change material (PCM) storage.

Economic parameters

<u>Investment cost:</u>

The total investment cost of a typical large domestic PV-T system including 3 kW_p of PV and a 150-litre storage tank is approximately €11,000, including installation (2017). The cost of the PV-T array and the electrical components (inverter, meter, cables, etc.) accounts for approximately 60% of the total, with the remainder of the costs attributed to the hydraulic components. The approximate split between the cost of hardware and installation is 70% to 30%. The breakdown of the costs (approximate) for an example project are shown in the table below.

	Domestic PV-T system (3 kW_p) (€)
Total investment cost	11,000
PV-T array & electrical components (60%)	6,600
Hydraulic components (40%)	4,400
Equipment (70%)	7,700
Installation (30%)	3,300

The cost of PV-T modules ranges from €1,680–2,520/kW_p, with an average of €1,920/kW_p (2017).

A schematic drawing showing a PV-T system is shown in the figure below.

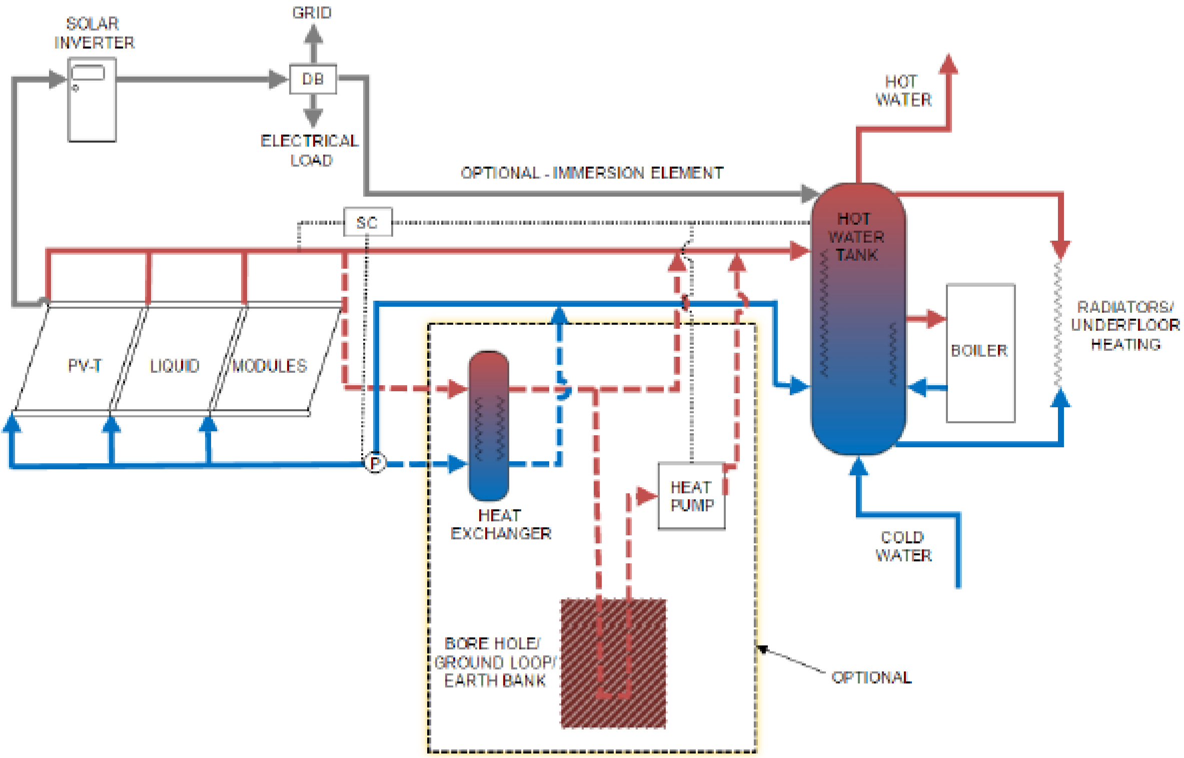

Figure 4: Schematic of PV-T system and a range of alternative heat uses[31].

The main costs of the solar-thermal portion of the system are associated with the storage tank, collectors, solar fluid, pump station (consisting of a circulation pump, a controller and temperature sensors) and the piping and fixings.

The total investment cost of a large scale PV-T system will be influenced by the number of PV-T modules, and which is therefore scale-able to a certain extent based on a domestic system (including economies of scale), however the heat infrastructure aspects including pipework and storage will be dependent on the specifics of the heat demand.

<u>Operation and maintenance costs (fixed and variable):</u>
The annual operation and maintenance (O&M) cost of a domestic scale PV-T system including equipment servicing and replacement is estimated at roughly 2% of the total investment cost. The annual cost of electricity for HW circulation is not included in this figure, as the HW circulation energy will be dependent upon the details of the thermal system served by the PV-T modules.
For larger systems the annual O&M cost is likely to be a lower percentage figure, due to economies of scale. The actual O&M cost however will depend on the details of the PV-T system, and in particular the specifics of the heat demand to be served by the PV-T system, and the details of the hydraulic infrastructure, and whether this is includes diurnal or inter-seasonal storage.

<u>Lifetime:</u>
The lifetime of a PV-T module would be expected to be a minimum of 25 years. Degradation year on year of the PV cells is around 0.4% of the total electricity generated. The lifetime of other components including inverters,

[31] BEIS - Evidence Gathering – Low Carbon Heating Technologies - Hybrid Solar Photovoltaic Thermal Panels

pumps and other mechanical devices will vary, and in any case be expected to be less than 25 years. Other mechanical equipment including pipework and thermal storage would be expected to be over 20 years.

Social acceptance among citizens

Generally, it is considered that solar energy enjoys favourable public acceptance, and that this continues to grow as the uptake of solar energy systems increases and the threat of climate change and the importance of national energy security become more urgent. For solar systems within the built environment social acceptance is considered to be generally high. Building roof mounted solar panels have increasingly become a part of the urban landscape, and a visible feature of community energy sustainability. Planning laws over recent years have evolved to take account of the need to reduce greenhouse gas emissions, improve energy security and reduce the risk of fuel poverty. Solar panels frequently fall under permitted development rights, and this has helped to increase the rate of deployment of rooftop solar systems within communities, both large and small.

Larger scale ground mounted solar systems can be more contentious in terms of social acceptance due to their visual impact, given that these systems are mostly built on greenfield sites, requirement for significant land area which may be considered for other alternative uses, and potential issues over ownership and financial benefit to the local community. In terms of planning, depending on the national and local planning laws, large scale solar farms may be required to be sited a minimum distance from any significant settlement, and may also require some degree of screening.

A survey carried out as part of an MSc in Renewable Energy Systems at International Hellenic University 'Social acceptance issues of Wind and PV projects' determined that a general positive opinion exists considering large scale solar systems, and that solar energy should contribute a greater proportion of the energy mix. In general respondents are not concerned by the aesthetics of solar technologies and would not have a particular problem in living relatively close to a solar farm.

Social acceptance among planners and politicians

It is expected that social acceptance among planners are comparable to that of pure thermal or PV systems.

Appropriateness by scale

Solar systems, and specifically PV-T systems are infinitely scale-able and can be sized to provide for specific local power and heat demands.

PV-T systems are suitable in terms of integration with appropriate energy storage systems. For electricity storage, the options include electrochemical systems (batteries), pumped hydroelectric and compressed air storage, thermodynamic cycle systems and kinetic energy storage (flywheels). For solar power generation operating within the built environment and considering the advantages afforded by electricity storage to even out electricity demand and generation through the 24-hour period, battery type storage is potentially the most suitable technology available. The power capacity of individual building roof mounted PV-T systems is likely to be in the range between approximately 1 and 100kWp. At this scale, Lithium-Ion ('LI') batteries form the basis of the most common form of battery storage system, and continue to undergo technology development, having the effect of reducing costs.

In terms of thermal storage, the size of the storage will be based on the PV-T system capacity, and the heat end use. Domestic HW systems will require short term thermal storage capacity with a charge and discharge period of a few hours. In district energy systems, storage may also incorporate a seasonal charge and discharge as EES, supplying heat to the ground during the summer via a number of boreholes (or via other alternatives), resulting in higher ground temperatures during the winter where heat pumps may extract this heat, and operating at higher efficiencies compared to a situation with no contribution from solar-generated heat.

Roof mounted systems can be designed to provide up to the maximum peak power demand of the building, including other connected power loads where applicable, and where electricity export to the public network is not desired. Alternatively, larger capacity PV-T systems may physically export power to other local loads, either through the public network or via private wire systems. A further alternative is to size a system, either roof mounted or ground mounted, to allow any amount of power to be exported into the public network, however this may be sub-optimal where wholesale power prices are low.

The opportunity and extent of power generation from PV-T systems is dependent on the scale and quantity of local heat demand which may be served by the PV-T system, on the assumption that the vast majority of the heat generated by a PV-T system is used and is not dumped. In this scenario a PV-T system will be sized based on the size of the heat demand and the capacity available for heat storage (both hourly and inter-seasonal storage). The required panel area of a PV-T system serving a typical domestic HW load for a house is generally suitable for the area of the south facing roof of that property. PV-T systems serving other types of heat demands, including non-domestic HW, space heating and process heat, and including hourly or inter-seasonal storage, will be sized based on the specific details of those heat loads and the supporting technologies and infrastructure required to provide for efficient delivery of heat from the PV-T system to the end use. Community PV-T system panels may be roof mounted and/or ground mounted depending on a large number of variables, but, on the assumption that sufficient roof space or land area is available, can be sized specifically to the individual case, with no significant barriers or limitations in terms of the technology.

Key challenges associated with the deployment of PV-T systems include the following:

- Availability of suitable building roof space and/ or land area for PV-T modules.
- Availability of suitable land area for EES system, in the case of a district energy system with inter-seasonal storage.
- Suitability of heat loads to take advantage of low temperature heat from a PV-T system.
- Availability of suitable space for short-term HW storage (individual buildings or district energy system not employing EES.

Market readiness and current deployment

Compared to separate solar PV and solar thermal technologies, installations of PV-T systems are very low. In the UK this ranges from 10 to 100 installations per year and an installed base of around 500 systems (2015). There are approximately 40 European manufacturers of PV-T products (2015). Several thousand domestic PV-T systems have been installed in continental Europe, particularly in countries with high support for PV. Unless low temperature thermal storage becomes common (either via thermal storage tanks or inter-seasonal storage) the technology is likely to remain a niche choice with the application limited to exceptionally low-carbon new build homes. PV-T systems providing HW via a water-glycol mix account for the largest market share in UK domestic installations (2015).

A key market for PV-T installers is domestic PV-T systems for private new build homes or complete refurbishments of existing homes where the home has been designed to be zero or near zero carbon. These properties are exceptionally well insulated with very little space heating requirement, meaning that inter-seasonal storage of solar thermal energy is viable for space heating.

It has been estimated that PV-T systems can cover approximately 60% of the heating demand, and more than 50% of the cooling demand of average residential buildings in southern Europe. In addition, PV-T collectors that heat air can be used for ventilation and space heating, or air pre-heating purposes, and can be integrated into building walls and roofs. Building-integrated modules on facades with a ventilation air gap behind the module create natural ventilation and reduce the heat losses through the wall, providing renewable heating and reducing the energy demand at the same time.

9 Energy conversion - Cogeneration of heat, cooling and power

Leading partner(s) in the technology description: UNIVPM

Technical description

Cogeneration of electricity, heat and cooling is an established technological solution addressing a more efficient use of fuels whose primary scope is electricity generation. For the case of reciprocating engines and turbines a fuel (mostly natural gas) is compressed, burned and expanded within an expander medium (cylinder/turbine) in order to produce electricity. For the case of fuel cells, the electricity is produced by means of a chemical reaction among two elements generating a current between two conductors.

These electricity generation processes generate heat as a by-product, and such heat can be recovered with a heat exchanger. This can be used straight away as heat (Combined Heat and Power, CHP) to satisfy a heating demand, feed a district heating network or produce steam for industrial use. Or else way converted into cooling power by means of an absorption chiller (Combined Cooling Heat and Power, CCHP) for refrigeration or space cooling purposes. CHP and CCHP can both be achieved by means of the same system in settings where user demands have seasonal features and variances, producing heating in one season and cooling in the other, as needed. An example schematic of CCHP systems is shown in the following figure.

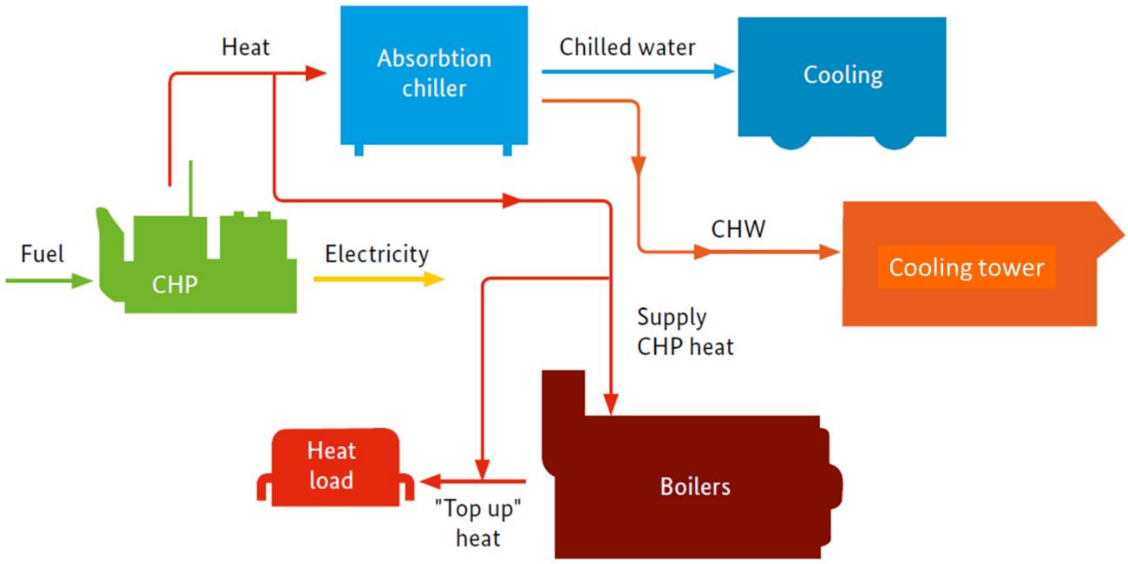

Figure 5: Example of CCHP systems[32].

Sector integration properties

Given the simultaneous generation of different energy vectors, CHP/CCHP systems are an important asset in sector integration, allowing for the coupling of electricity generation with heating and cooling demands from different types of final users. Unlike technologies based on fluctuating solar and wind resources, CHP/CCHP can freely be dispatched when needed and could therefore provide much needed flexibility for energy systems based largely on

[32] GIZ. Cogeneration & Trigeneration – how to produce energy efficiently

renewable. CHP/CCHP technologies also allow for the usage of renewable fuels such as biogas or biomass to substitute natural gas as primary fuel.

CHP/CCHP solutions can typically be regulated very quickly (within seconds) to provide both primary and secondary reserve for grid balancing.

Sizes

The wide span of electricity generation technologies (reciprocating engines, turbines, fuel cells etc.) makes the configurations and sizes of CHP/CCHP systems vary widely. There can be considered within this group both mature technologies such as reciprocating engines and turbines, and others which are still currently undergoing development, such as fuel cells. While remaining in a size range suitable to an urban microgrid scale (gas turbines also represent much of the backbone of centralized electricity production in many countries) systems can have power outputs ranging from as little as tens of kW to multi MW systems.

Efficiency and loss

The efficiency most commonly referred to for CHP/CCHP system is the efficiency of the electricity production. Electrical efficiency depends both on the type of technology and its size. Fuel cell system consist in replicating small units of few kW_e up to the desired total output power of even several MW_e, thus having no significant differences of electrical efficiencies among small and large systems of the same type of fuel cells. This is not the same for reciprocating engines and turbines, here effects of scale incur, and large systems generally have higher electrical efficiencies compared to small systems.

CHP Technology	**Reciprocating Engine**	**Micro Turbine**	**Gas Turbine**	**Fuel Cell (SOFC)***
Rated power [MW]	0.005 - 15	0.03 - 2	1 -50	0.2 - 2
Electrical efficiency [%]	28 - 46	28 - 35	34 - 44	40 - 60
Total Efficiency [%]	80 – 90	80 – 90	80 – 90	80 - 90

*To represent the fuel cell technology a Solid Oxide Fuel Cell (SOFC) has been considered, this due to this particular type being the most market ready for stationary electricity generation applications.

The amount of recoverable heat depends again on the type of technology, the fluid used as a cooling medium and its temperature, with global efficiencies reaching up to 90% for CHP systems.

A CCHP system is achieved by coupling an absorption chiller with the CHP system, with the cooling power produced being proportional to the waste heat supplied by the single performance parameter COP (Coefficient of Performance).

$$P_{cool}^{CCHP} = P_{heat}^{CHP} * COP^{abs\_chiller}$$

The COP for absorption chillers for CCHP applications depends on the particular technology being used and the temperature level of the supplied heat. For single effect chillers water has to be used and its temperature cannot be higher than 90°C, while for double effect also steam or exhaust gases can be used. The COP can be considered to be constant regardless of the size of the system

Technology	**COP**
Single effect absorption chiller	0.65-0.8
Double effect absorption chiller	1.2

Economic parameters

Costs for CHP/CCHP systems vary depending both on the type of electricity generation technology considered and its size, with bigger units generally having a lower specific cost per kW. Adding this economy of scale to the previously described increased electric efficiency for larger system sizes, makes the deployment of less units of larger sizes both energetically and economically convenient when possible.

CHP Technology[33] [34]	Reciprocating Engine	Micro Turbine	Gas Turbine	Fuel Cell (SOFC)
Rated power [MW]	0.065 - 15	0.03 - 2	1 -50	0.2 - 2
Investment cost [1000 €/kW]	1.2 – 2.5	2.1 – 3.9	1 – 2.9	4.2 – 9.6
O&M [€/MW/year]	10,000	15,000	20,000	250,000
Lifetime [years]	25	15	25	20

In order to realize a CCHP system, the investment and O&M costs related to the purchase of an absorption heat pump must be added.

	Single Effect	Double Effect
Rated Power [MW_c]	0.2 – 5+	1 – 5+
Investment Cost [€/kW_c]	600	600
O&M [€/MW_c/year]	2	2
Lifetime [years]	25	25

Social acceptance among citizens

A distinction has to be made between large scale and micro cogeneration. In the first case it is hard to determine. Very few citizens have conscience of the origin of the electricity they consume. Whether it comes from small generation units within a local energy community or from the main national grid. Still efforts are being made in increasing the citizens' awareness of the economic and environmental benefits of co/trigeneration adoption. Micro-cogeneration systems for single domestic users have known a wide deployment in Japan and in a lesser degree in Europe (number of installations in the order of thousands), with driver being mostly in the economic savings achieved by the owners. On this scale the acceptance of the technology seems to be linked to the awareness by the citizens of the economic benefits related to the adoption.

Social acceptance among planners and politicians

CHP/CCHP systems are already a well-recognized technology among policymakers given their potential to help towards decarbonization targets. The potential of reduction of CO_2 emissions is well established, and there is also the possibility to substitute the fuel used for CHP systems (mostly natural gas) with a green one, such biogas. But the policy approach in Europe has been very heterogeneous[35], with countries applying support mechanisms that successfully stimulated investments in the sector: this is the case for example of Germany, Italy, Belgium etc. The barriers to a wider deployment of CHP systems at policy level lie in the lack of focus on the achievable primary energy savings, and consequently on rewarding such achievements. This add risks and costs to potential new investments.

Appropriateness by scale

All of the technologies described have sizes that can range from few kW to multiple MW, both using traditional combustion-based technologies and fuel cells. CHP/CCHP systems are thus adaptable to user demands of any magnitude. There are cogeneration systems which serve the needs of large district heating networks with capacities

[33] U.S. Department of Energy – Combined Heat and Power Technology Fact Sheet Series

[34] Energinet, Danish Energy Agency. Technology data for energy plants for electricity and district heating generation. 2016-2019

[35] CODE2 Project, European Policy Report, 2015

of several MW_t; to micro-cogeneration systems moved by internal combustion engines with sizes starting from 1 kW_e, which can serve the needs of single domestic installations (with generally much lower electric conversion efficiencies).

Market readiness and current deployment

Reciprocating engines and turbines are already mature and widely deployed technologies on a wide variety of sizes and applications both for electricity generation and CHP/CCHP purposes. With applications in different scenarios, such as hospitals, universities and industry, also by means of district heating/cooling networks. For example, in Turin (Italy) a large urban area's demand (around 500,000 people) is entirely met by a district heating network fed with the waste heat of two large CHP plants, powered by natural gas turbines. Electricity is produced with an average efficiency of 39% for a total of 1,200 MW_e, with a waste heat recovery capacity of 740 MW_t totally. Another example of an already deployed solution is a small size CCHP system for the university campus of UNIVPM in Ancona (Italy). In this case the electricity generation asset is a natural gas internal combustion engine of 600 kW_e with a thermal recovery capacity of 693 kW_t. In the summer the heat is fed to four absorption heat pumps of 800 kW_t total to meet the cooling demand. A last example is the system assessing the needs of the town of Osimo (Italy) by means of CHP and district heating, with a gas turbine of 1,200 kW_e which produces electricity with an average efficiency of 42%.

Fuel cell systems on the other hand, while being already a commercially viable solution by some manufacturers, are still undergoing technological development and costs reductions due to economies of scale.

10 Energy conversion – Heat pumps

Leading partner(s) in the technology description: ASTEA

Technical description

Heat pumps use the same thermodynamic cycle of the refrigerators, with a low boiling fluid that vaporizes by absorbing heat from a source (called heat source) at low temperature and giving it to a high temperature well (called heat sink). Hence, the heat pump can be used both to refrigerate (for the heat source), and to heat up (for the heat sink). Heat pumps can be classified under two broad categories based on the technology used to achieve the heat transfer: compression and absorption heat pumps.

Compression heat pumps are activated by means of a compressor, which can be driven by an electric motor or an endothermic engine (using the combustion of a fuel to produce the needed mechanical power). Absorption heat pumps on the other end use a heat source as a driver, thus enabling the exploitation of waste heat to produce cold.

Another distinction between the different types of heat pumps lies in the two fluids responsible of the heat exchange with the refrigerant: the first represents the external source, the second the fluid responsible for the distribution of the heat inside the environment to be heated/cooled.
Under this classification scheme, four types of heat pumps can be identified:

- Air-air
- Air-water
- Water-air
- Water-water

Sector integration properties

Heat pumps are intrinsically a bridge among energy vectors, making possible the integration of the electricity/heating/cooling sectors depending on the technology under consideration, and allowing for the usage of heat sources of different temperature levels. Electric compression heat pumps are ideal to be integrated with large shares of renewables providing climatization capabilities for both cold and warm seasons. Absorption heat pumps allow for the making of CCHP (Combined Cooling Heat and Power) systems, exploitation primary energy resources in the best way possible.

The regulation ability and time responsiveness of heat pumps is currently limited due to long start/stop times and slow adjustment to load changes. If the market for regulation was more desirable, heat pumps could likely be constructed with faster start/stop times, but depending on heat source and outlet temperature etc., efficiency of the heat pumps could be affected.

Sizes

The size of heat pumps depends on the application. It can vary from small sizes, for residential heating/cooling purposes with rated powers of few kW. For large compression high temperature heat pumps, which can also feed district heating networks the capacities can be of several MW.
In Europe there are already a multi MW heat pump systems deployed[36]:

- Denmark: 14 installations of compression heat pump with a combined capacity of 22 MW, 17 installations of absorption heat pumps with a combined capacity of 56 MW.

[36] Helge Averfalk, Paul Ingvarsson, Urban Persson, Mei Gong, Sven Werner; "*Large heat pumps in Swedish district heating systems*"; in *Renewable and Sustainable Energy Reviews*; 2017; pp 1275-1284

- Italy: 2 geothermic heat pumps, installed in Milan, with a combined capacity of 31 MW.
- Norway: 2 heat pumps in Sandvika with a capacity of 13 and 9 MW, 1 heat pump in Oslo with a capacity of 18.4 MW that is the largest unit in the world, 1 heat pump in Drammen with a capacity of 15 MW that is the largest unit in the world using ammonia as refrigerant fluid.
- Finland: A system of heat pumps installed in Helsinki with a total capacity of 90 MW.

Efficiency and loss

The efficiency of a heat pump is expressed by its Coefficient Of Performance (COP), which measures the ratio between the useful effect of heat pump, that's the thermal energy supplied to the heat sink in case of use for heating, or the energy take from the heat source in case of use for cooling, and the electric energy (for the compression heat pumps), or the thermal energy (for the absorption heat pumps) absorbed for its operation.
The compression heat pumps have variable COP, depending on a set of conditions: technology, temperature of the heat source and delivery temperature. Generally, compression heat pumps are less efficient when there is a high temperature difference between heat source and heat sink.

The theoretical coefficient of performance can be calculated as the "Lorenz COP" which relates the mechanical work to temperature differences in power generation, refrigeration and heat pump technology:

$COP_{Lorentz} = \frac{T_{lm,sink}}{T_{lm,sink} - T_{lm,source}}$, where $T_{lm} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)}$ is the logarithmic average temperature, respectively of heat sink and heat source, T_{in} is the entry temperature of the heat sink/source in the heat exchanger and T_{out} the exit temperature.

The Lorenz COP is the theoretical maximum; in practice the COP will be lower due to the thermal and mechanical losses (typically around 40-60% of the theoretical COP); the medium COP for compression heat pumps is usually between 3 and 5.
For absorption heat pumps, the COP is not affected by temperature levels: a difference in temperature is required to proper functioning, but as long as this remains the COP will be around 1.7 and not affected by further temperature increase of the heat source[37].

Economic parameters

Heat pump systems costs vary depending on a set of characteristics of the pump itself: its rated power, the type of refrigerant fluid, the type of heat pump (whether it is a compression or absorption heat pump, or the type of energy source used).
Moreover, for residential application, the cost depends on the heat pump performances: it could be a basic heat pump, two stage heat pumps (with a regulation capacity between 65-100% of the peak power), or a heat pump with variable capacity (with a regulation capacity between 40-100% of the peak power).

	Compr -Small	**Compr – Medium**	**Compr - Large**	**Absorption**
Size [MW_{th}]*	0.05 – 1.5	3	3+	1 – 12
Investment cost [€/kW_{th}]	250-1700	1100	700	600
O&M – Variable [€/kW_{th}/y]	2	2	2	2

[37] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

Lifetime [years]	15	15	25	25

*The size of the heat pump system [MW or kW] refers to the thermal output of the device

Heat pump investment costs can be approximately split in 75% cost of the system, 14% cost of auxiliary equipment, and 11% cost of installation.

Social acceptance among citizens

Heat pumps have a different level of acceptance depending on the scale of the system. They are a common solution for the climatization of newly built tertiary buildings, so they might be considered widely accepted in this context. Regarding smaller applications, while having been a common cooling system for individual households for years, they are not yet as diffused for meeting also the heating demand. In this case the barrier is both on a cultural and economic aspects. On this second aspect this is due mostly to the need to refurbish a large part of the existing building stock, whose heating system is mostly based on radiators fed by heat produced with combustion boilers.

The existing barriers[38] can thus be listed as:

- Requirements to have an acceptable return on investment (often not more than 2 years are accepted); matter which is further complicated by a comparatively low price for fossil energy (the price of fossil fuels does not reflect their environmental impact).
- The perception of heat pumps as a new, unproven technology.
- Limited or no availability of best practises that could increase create trust in this kind of systems.

Furthermore, regarding the implementation of heat pumps within the industrial sector, there are also some specific structural barriers to overcome:

- High transaction cost for the conversion of processes, as many old processes are based on steam.
- Need to integrate competences and responsibilities to realise an optimal system that works efficiently both from energetic that from the economic point of view[39].

Social acceptance among planners and politicians

Heat pumps have a recognized potential for the energy saving and CO_2 emissions mitigation, facilitating the reaching of the European climate targets, especially in countries where the diffusion of this technology is still lacking. A more inclusive policy framework could help in this direction; such policies should be focused on:

- Policy measures intended to penalize the use of fossil fuels (such as carbon taxes).
- Provide low interest rates and loan guarantees to energy efficient investments using low carbon emission technologies such as heat pumps.
- Incentivize research and development on standardized heat pump solutions for the industrial sector.
- Provide more best practise examples.

Appropriateness by scale

Heat pumps can be found in a wide range of sizes, depending on the application. The smaller sizes, in the order of few kW_{th} are used for residential heating and cooling or hot domestic water production (in particular in markets like Italy where the most used are air-air heat pumps for residential cooling). The size increases for heat pumps

[38] Heat Pump Buying Guide- Prices, Reviews and Tax Credits 2019 - https://www.pickhvac.com/heat-pump/

[39] Large Heat Pump in Europe – 2018 – European Heat Pump Association (EHPA) - https://www.ehpa.org/media/studies-reports/

integrated in industrial processes, where sizes can reach hundreds of kW_{th} as an example for recovering low temperature waste heat from industrial processes.

The bigger sizes can be found in systems integrated within district heating networks, especially in central and northern Europe countries, with sizes up to tens of MW.

Market readiness and current deployment

Heat pumps are a mature technology, which especially regarding the compression typology has undertaken a massive market growth. This due to many factors such as the contemporary growth of electricity generated by renewables and the efforts put by many countries towards the electrification of heating demands. In the whole European Union sales increased by 4.4% in 2017, with more than 3.5 million systems sold[40].

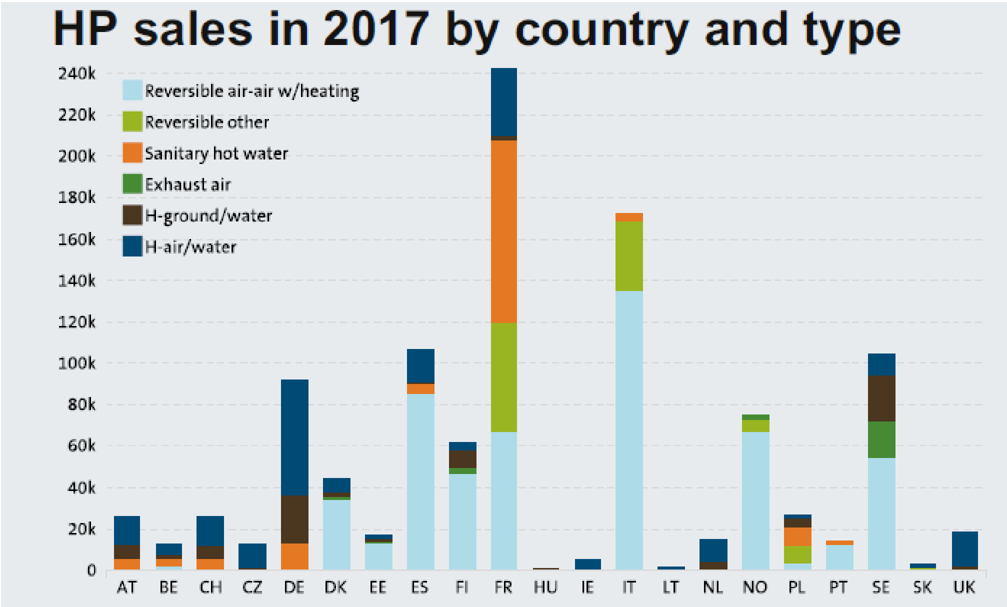

Figure 6: HP sales in 2017[41].

[40] Heat Pumps Barometer – 2018 – EurObserv'ER - https://www.eurobserv-er.org/heat-pumps-barometer-2018/

[41] Maurizio Pieve, Riccardo Trinchieri; *"Heat pump market report for Italy"*; in *Heat Pump Technologies Magazine*; vol.36 n 3/2018

11 Energy conversion – Direct electric heating

Leading partner(s) in the technology description: GDHVI and AAU

Technical description

The basic principle of direct electric heating is to convert electricity to heat and hot water for space heating and domestic hot water respectively, and in some instances hot water for floor heating. For space heating purposes, direct-acting heaters are typically utilised, also known as panel heaters, electric radiators, aluminium radiators or oil-filled radiators, depending on the technology used to house the element. Hot tap water is typically produced by using a hot water tank and an electric heating coil, if needed several water heaters can be installed in a house.

Electric heating can function both as a complementary technology to other heating systems and as the sole source of heating for a household in the form of a complete system. High-efficiency panels are often suitable for new-build and well-insulated properties, or rooms that have low or occasional requirements for use such as bedrooms, studies and light commercial spaces. They are also ideal for use within a building that does not have a dual-rate (off-peak) electric meter.

Modern electric heating systems use intelligent control mechanisms to accurately adjust the temperature of the room and are often also capable of adjusting based on time-of-use tariffs or reducing heat production during the night. Energy storage is in some instances included as part of electric heating solutions, which would significantly increase the potential for flexibility. This potential is further described in chapter 24 on smart electric thermal storage (SETS).

Electric boiler is another designation for electric heating, based on the same working principle as the water heater described previously, available for use in both individual households and in the scale of several MW's for district heating systems. However, this technology description will focus solely on the application of electric heating for small-scale individual household and apartment complexes in the form of panel heaters and water heaters.

Sector integration properties

Electric heating provides a potential for coupling of the heat and electricity sector and integrating renewable electricity, and especially if coupled with heat storage, could utilise peak rate electricity providing flexible demand response[42]. Improved control mechanisms and technological advances of smart grids could increase the relevance and sector integration properties for electric heating. Direct electric heating appears especially relevant for rural households where district heating is infeasible.

Direct electric heating can be regulated very quickly (within seconds) from 0-100%.

Sizes

Direct electric heating systems typically come in sizes ranging from 1-10 kW for one-family household solutions, but upwards of 400 kW for complete systems for apartment complexes.

[42] Electric heating as flexible demand for enhanced network operation - doi: 10.1049/oap-cired.2017.0950

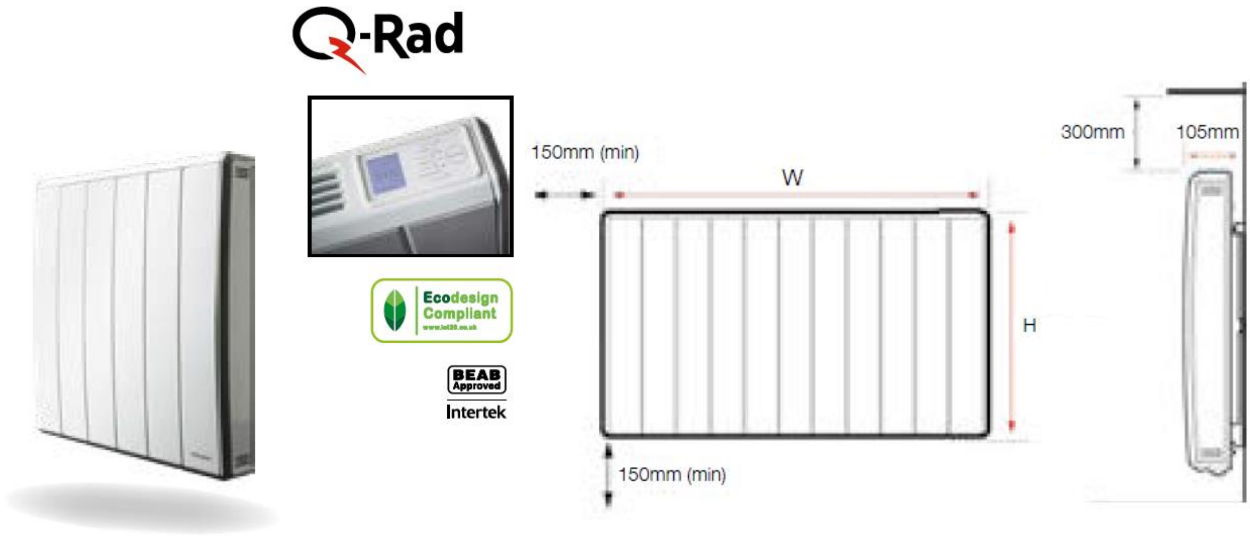

Figure 7: Q-rad panel heater for space heating purposes.[43].

Efficiency and loss

As all losses on the panel heater are resistive – thus heat producing – the efficiency is 100%. However, the use of electricity for heating purposes in direct electric heating does result in high losses of exergy due to the relatively low efficiency compared to for example a heat pump.

Some modern electric heating panels have a self-learning delayed start function, which learns the thermal characteristics of a room and determines how long the appliance needs to be on in order to reach target temperature based on factors such as room size, heat losses and the prevailing weather. Measuring the heat-up and cool-down times of the room and how they vary with external temperature, the heater will work out what time it needs to start heating in order to reach user defined target temperature at a specified time. Inevitably, this minimises wasted energy and can deliver cost savings for users along with improved control, comfort and energy savings.

Economic parameters

Investment and installation costs are generally low for direct heating solutions. The following table provides an overview of costs for two typical installation sizes.

All data are for 2015[44]	**3 kW unit for single family household**	**160 kW unit for apartment complex**
Investment cost	3000 €/unit	106000 €/unit
O&M – Fixed	25 €/unit/year	50 €/unit/year
O&M – Variable	0	0
Lifetime	30 years	30 years

[43] Q-Rad – the intelligent electric radiator https://www.dimplex.co.uk/q-rad

[44] Technology Data for Individual Heating Installations August 2016- Latest update March 2018 - https://ens.dk/en/our-services/projections-and-models/technology-data

For both small units suitable for single family households and larger units for apartment complexes, costs are distributed as approximately 70% equipment and 30% installation.

Social acceptance among citizens

Electric heating is generally a well-accepted technology due to its compliance with typical utilisation practices and, apart from the relatively low efficiency, no unwanted side-effects such as noise, pollution or use of fossil fuels.

Social acceptance among planners and politicians

While electrification of sectors, including the heat sector, is widely accepted and agreed upon as an important step towards future renewable energy systems, excessive use of direct electric heating is not without challenges. The electricity consumption of direct electric heating is high, and if installed in large scale could result in significant increases to electricity peak load demand. For this reason, installing direct electric heating is banned or at least restricted in several countries including Sweden[45], Denmark[46], Germany, and Switzerland[47] due to the excessive demand for peak-load electricity production capacity. However, with the increasing share of renewable electricity production this appears to be changing, and direct electric heating might even be an important source of flexibility and consumption in hours of high electricity production.

A large-scale research project involving 800 households on the Danish island Bornholm investigated the potential for operating heat pumps and direct electric heating flexible to reduce local peak loads and provide ancillary services to the TSO by using aggregators. In this project direct electric heating proved to provide greater flexibility compared to heat pumps[48].

Appropriateness by scale

Direct electric heating is primarily appropriate for single family households either as a complementary heating source for especially cold rooms or as a heat source in vacation houses with limited heat demands. However, for new energy efficient building direct electric heating could function as a complete heating solution.

Market readiness and current deployment

Electric heating is a commercially available technology widely utilised throughout the world, in the European Union alone more than 100 million electric panel heaters are installed[49]. In Europe electric heating is most prevalent in Sweden where approximate 30% of heating supplied by electric heating, followed by Finland and Spain with approximately 25%[50]. The countries with high shares of electricity for heating are also where Smart Electric Thermal Storage solutions are most relevant going forward; more on this in Chapter 24.

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[45] IEA - Building Performance Standards (Building Regulations) Sweden - https://www.iea.org/policiesandmeasures/pams/sweden/name-22078-en.php

[46] Danish Ministry of Energy - Lov om ændring af lov om varmeforsyning nr. 96 af 9. Februar 1994

[47] Mapping the policy variables affecting the role of concentrating solar power in the European Union, 2018 - http://mustec.eu/sites/default/files/reports/LilliestametalMUSTECdeliverable7.1_final.pdf

[48] EcoGrid – a New Real-time Market for Small-scale Electricity Consumers http://www.eu-ecogrid.net/

[49] Potential for Smart Electric Thermal Storage - Contributing to a low carbon energy system, February 2013, DNV KEMA Energy & Sustainability.

[50] Role of SETS in evolving European energy system - http://www.realvalueproject.com/images/uploads/documents/Role_of_SETS_in_Evolving_European_Energy_System.pdf

12 Energy conversion – Electrofuels

Leading partner(s) in the technology description: AAU

Technical description

Electrofuels (also often referred to as power-to-X) is the designation for an emerging class of carbon neutral energy sources made by storing electricity in chemical bonds of liquid or gas fuel. The categorisation of electrofuels is broad and includes an array of different technologies with multiple inputs and outputs, including fuels/feedstocks, electricity and excess heat. Examples of the most common targets are methanol, butanol, biodiesel, hydrogen, and carbon-containing gasses such as methane and butane.

The different types of electrofuels have different applications and purposes to fulfil in future energy systems, in addition to different manufacturing processes. Therefore, to delimit this technology description, the focus is to describe the production process and application of hydrogen and methanol, as opposed to including all variations of electrofuels/power-to-X technologies.

The most common production method for hydrogen is electrolysis. This involves running electricity through water to separate hydrogen and oxygen. Hydrogen can then be compressed/cooled and either stored or transported, while the excess oxygen can be utilised in nearby industry or biogas plants. This is a power intensive process, and renewable energy sources such as wind, solar, or hydro power, among many others, can be utilised. Applications for hydrogen include use in combustion- or fuel cell engines for either buses, trains or cars, or for electricity production in fuel cells. Three dominant types of electrolysers appear to be emerging: Alkaline cells (AEC), Polymer cells (PEM), and Solid Oxide Cells (SOEC), with differences in operating temperature, pressure, and electrical efficiency[51].

Hydrogen is also a core component in the power-to-methanol process, which resembles the process of producing pure hydrogen, but includes additional steps. Producing methanol involves combining hydrogen and CO_2, typically obtained from either carbon capture technologies or as a by-product from biogas plants. Hydrogen and CO_2 can be combined through processes of compression, methanol synthesis, and methanol distillation, with a final output of methanol and water. Methanol produced through the described process of combining hydrogen and CO_2 is sometimes denoted as MefCO2. Methanol can be used directly as a fuel for internal combustion engines, for example in vehicles, or indirectly by mixing with gasoline. The energy content of methanol is, however, about half of traditional gasoline. Methanol is easier to store than hydrogen due to it being a liquid and not a gas. Methanol is poisonous to humans and therefore significant security measures and research of long-time effects must be undertaken.

Sector integration properties

Electrofuels have large potentials for sector integration in future renewable energy systems due to their ability to couple the electricity, transport and heating sector. Especially the ability to supply transport fuel for heavy-duty and long-distance travel could prove to be a very important quality of electrofuels in future 100% renewable energy systems[52].

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[51] Technology Data for Renewable Fuels - Catalogue first published 2017 - Latest update 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

[52] A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system - https://doi.org/10.1016/j.energy.2014.05.104

Electrolysers can respond quickly to load changes and ramp up from minimum to maximum load within a minute, and down regulation be done within a second. The very strong regulation ability of electrolysers could be an important flexibility component of future energy systems, providing valuable grid balancing[53 54].

The production of electrofuels relies heavily on the use of electricity and as such could prove to be very beneficial in the integration variable electricity production from e.g. wind turbines and solar photovoltaics. The production of electrofuels result in a bi-product of oxygen as well as excess heat, which can be utilised by nearby industries or district heating, if available.

An important quality of electrofuels, such as hydrogen and methanol, is the ability to convert electricity to other fuels, and thus in essence store electricity. While it is not easy to store hydrogen due it being a very diffuse gas with a low volumetric calorific value in its gaseous phase, it can be done, and studies and pilot projects are being undertaken on how best to do so. One example is a project from Denmark exploring the potential for storing hydrogen in existing salt caverns, which could enable large-scale storage options for the future[55]. Transporting hydrogen is possible, but in many cases infeasible due to the high pressure necessary to transport meaningful amounts.

Sizes

Typical plant sizes depend significantly on the specific type of technology. As the most mature technology, AEC plants exists in the widest range of capacities, from 4 kW_e-100 MW_e. Existing PEM plants range from 1-10 MW_e, however sizes upwards of 100 MW_e are expected and have been announced by manufacturers such as Siemens[56].

For power to methanol plants, the EU funded project MefCO2 projects business cases from 4000-50000 tons methanol/year which would be equal to approximate electrical capacities of 2.4-30 MW_e, but larger sizes could be feasible depending on available electrolysers and access to CO_2[57].

Efficiency and loss

AEC and PEM hydrogen electrolysers have a hydrogen output ranging from 50-65% in addition to an excess heat production of 0-15% (both based on lower heating value) based on 100% input of electricity. Power to methanol plants have an output of about 60% methanol and 25% excess heat[58].

Economic parameters

Significant price reductions can be expected for both electrolysers and power to methanol plants in the near future as production volumes increase and the technologies mature. The table below shows a cost comparison for three different technologies; AEC and PEM electrolysers producing only hydrogen (and excess heat), and a power to methanol plant producing methanol (and excess heat). SOEC electrolysers are omitted from this table due to the early stage of development and resulting cost uncertainties.

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[53] On the ability of pem water electrolysers to provide power grid services - https://doi.org/10.1016/j.ijhydene.2018.11.186

[54] The role of electrolysers in energy system: Energy markets, grid stabilisation and transport fuels - https://vbn.aau.dk/da/publications/the-role-of-electrolysers-in-energy-system-energy-markets-grid-st

[55]Hydrogen Valley Hvad er kaverner? - http://hydrogenvalley.dk/hydrogen-valley/groenne-gasser/hvad-er-kaverner/

[56] Green hydrogen (Siemens) - https://www.siemens.com/customer-magazine/en/home/industry/process-industry/pem-electrolysis.html

[57] Green methanol for a green future - http://www.mefco2.eu/pdf/MefCO2_Brochure_00.pdf

[58] Technology Data for Renewable Fuels - Catalogue first published 2017 - Latest update 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

All data are for 2015[59]	**10 MW_e Alkaline electrolyser cell**	**1 MW_e PEM electrolyser cell**	**3 MW power to methanol plant**
Investment cost	1.07 M€/MW_e	1.9 M€/MW_e	4.51 M€/$MW_{methanol}$/year
O&M – Fixed	53500 €/MW_e/Year	95000 €/MW_e/Year	0.053 M€/$MW_{methanol}$/year
O&M – Variable	0	0	6.27 €/MWh
Lifetime	25	15	25

Costs for AEC plants are distributed as 84% equipment 16% installation costs, PEM plants 84% equipment 16% installation, and power to methanol plants 75% equipment 25% installation.

Social acceptance among citizens

For most citizens, electrofuels will likely be most relevant as a fuel for transportation. A study from Belgium found that major obstacles for increased adoption of biofuels are related to the availability of biofuels and price. Other areas of importance include the potential level of engine modifications needed, environmental friendliness, quality, and performance[60]. The refuelling times are generally short for electrofuels such as ethanol due to it being a liquid fuel, and as such compatible with typical utilisation and practices.

A survey conducted in Spain on social acceptance of hydrogen for transportation found a high level of hydrogen awareness and a favourable public perception of hydrogen technologies, and overall respondents indicate willingness to accept hydrogen as a key component of future energy systems and especially the transport sector[61].

Social acceptance among planners and politicians

The ability to integrate sectors and utilise renewable electricity is important for future renewable- and smart energy systems, however plant capacities will need to be very large to have any actual influence in balancing electricity fluctuations, which places severe demand for safety of such facilities.

Brazil has historically been one of the largest markets for ethanol where it is used extensively as a transport fuel, this is partly a result of the large sugarcane industry in Brazil, but also a result of favourable government policy, including R&D funding and beneficial fiscal policies[62].

Storing and transporting electrofuels, and especially hydrogen present several challenges and relies on infrastructural developments e.g. new fuel stations or use of the existing gas grid for transportation.

Planning for electrofuel plants could prove to be challenging due to the many possible synergy effects, of which important to consider and mention include:

- The capacity of the grid connection
- Whether the excess heat produced can be utilised in district heating
- Whether the excess oxygen can be used in industry or biogas plants nearby

[59] Technology Data for Renewable Fuels - Catalogue first published 2017 - Latest update 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

[60] Perceived importance of fuel characteristics and its match with consumer beliefs about biofuels in Belgium - https://doi.org/10.1016/j.enpol.2009.04.022

[61] Assessing the social acceptance of hydrogen for transportation in Spain: An unintentional focus on target population for a potential hydrogen economy - https://doi.org/10.1016/j.ijhydene.2016.01.139

[62] Exploring policy options to spur the expansion of ethanol production and consumption in Brazil: An agent-based modeling approach - https://doi.org/10.1016/j.enpol.2018.09.015

- Whether large amounts of CO_2 are available nearby, for example from a biogas-upgrading plant

Appropriateness by scale
While hydrogen can be produced at small plants sizes, for public supply of electrofuels, production is mostly relevant at larger plants, typically in excess of several MW's. Also, when addressing the more complex forms of electrofuels like methanol, these are envisioned made in large-scale due to the combination with CO_2 sequestering and excess heat supply for district heating systems. In the future sizes are expected to continue increasing due to economy of scale effects and more attractive business models for increased production.

Market readiness and current deployment
In general, electrofuel production can be considered to be in the early stages of development; there are many on-going pilot projects but limited full-scale applications and experiences. The technology is, however, proven to work through several demonstration projects.

Hydrogen production is a well-established technology as hydrogen has non-fuel purposes in industry including e.g. surface treatment of metals. Here there is a well-established infrastructure at for such purposes. Currently only AEC plants are at a development stage where it can be considered a commercial technology, though. PEM electrolysers are on the edge of transitioning from pilot stage to a commercial technology, and while most pilot projects are around 1 MW_e, sizes are expected to increase to above 10 MW_e. One of the largest hydrogen plants in Europe is located in Denmark; a 1.2 MW PEM plant capable of producing 500 kg of hydrogen per day[63].

The global installed capacity of water electrolysis plants for hydrogen production is more than 10 MW_e for AEC plants, and more than 8 MW_e for PEM plants[64].

As for methanol, the scientific literature has more examples of assessment of methanol production[65] [66], however actual applications are sparse, including for instance a 1 MW pilot plant in Lünen, Germany[67].

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[63] Nu har Danmark et af Europas største brintanlæg - http://www.biopress.dk/PDF/nu-har-danmark-et-af-europas-storste-brintanlaeg
[64]Future cost and performance of water electrolysis: An expert elicitation study - https://doi.org/10.1016/j.ijhydene.2017.10.045
[65] Methanol synthesis from flue-gas CO2 and renewable electricity: a feasibility study https://doi.org/10.1016/S0360-3199(02)00082-4
[66] Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment https://doi.org/10.1016/j.apenergy.2015.07.067
[67] Coal plant provides CO2 for methanol production https://www.powerengineeringint.com/articles/2015/06/coal-plant-provides-co2-for-methanol-production.html

13 Energy conversion – Gas boilers

Leading partner(s) in the technology description: AAU

Technical description
Gas boilers produce heat through combustion of gas, mainly natural gas or biogas, but as opposed to gas combined heat and power plants, the output is solely heating and not electricity. The energy from the combustion process is transferred to water as a result of radiation (and convection) The hot water can then be circulated through the heating system of a house - possibly through a district heating system or used for domestic hot water. The water may be stored in a heat storage tank if required.

The fuel input can be either natural gas, biogas or LPG gas (with some minor modifications to the boiler). It is also possible to mix smaller amounts of biogas with natural gas in the distribution grid. The heating value of biogas is, however, lower than natural gas due to the high CO_2 content of biogas.

Gas boilers have been applied in district heating systems for decades but are today mostly utilised as a source of low-cost back-up capacity due to the low capital cost per thermal capacity.

Sector integration properties
Gas boilers do not on their own have sector integration properties but are nevertheless an integral part of current energy systems and will likely also fulfil an important role in future renewable and smart energy systems. This could be in combination with other technologies such as heat pumps or solar thermal heating which are suitable for covering hot water demand during the summer or baseload heat demand of a district heating system, but expensive if used as a sole heat source or reliant on excessive storage capacity. The low capital cost of gas boilers makes them suitable for covering peak load periods, or as back-up capacity.
The comparably lower CO_2 emissions of natural gas compared to other fossil fuel options such as coal or petroleum, means that natural gas is viewed by some as a bridge fuel in the transitions towards renewable energy systems.

While not strictly related to the gas boiler itself, the existing natural gas infrastructure can also be utilised in renewable energy systems for transportation of biogas, or biogas can be mixed with the natural gas, providing an alternative with less green-house gas emissions than natural gas by itself.

Gas boilers can be regulated within a few minutes if already in operation, cold start up time is around 30 minutes. Gas boilers are not connected to the electricity grid and thus provide no potential for electricity grid balancing.

Sizes
Typical sizes for gas boilers for use in households are 5-20 kW_{th}, with capacities in the lower end of the range being sufficient for most households if combined with hot water storage, whereas a capacity of about 20 kW is needed for most if not.

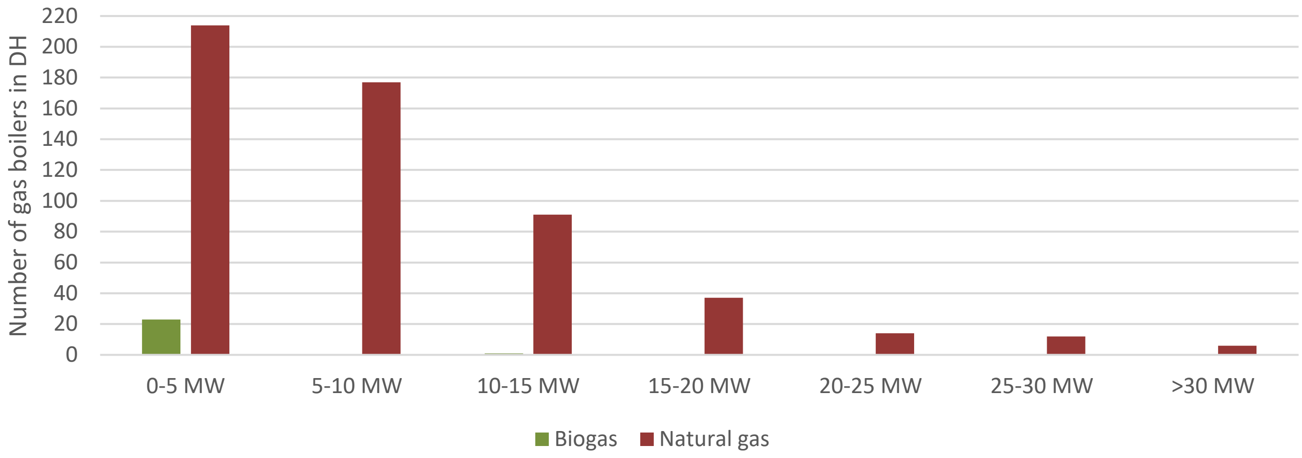

Figure 8: Installed gas boilers in Danish district heating.

District heating natural gas boilers have capacities from 0.5-20 MW_{th} typically, with the average being 8.2 MW_{th} in Danish district heating systems[68]. Biogas boilers are not nearly as widely applied, and the average capacity is lower as well at 1.9 MW_{th}.

Efficiency and loss

Upwards of 97% (based on lower calorific value) for small household gas boilers. If operated at low return temperatures of 30-35°C, district heating gas boilers can achieve efficiencies of upwards 107% when including flue gas condensation; without the efficiency will be around 93%.

Economic parameters

Smaller gas boiler capacities (<35 kW) are generally not exposed to economy of scale effects, meaning that the price is not linearly increasing with capacity. Instead the price is mostly a result of material selection and other features. Further technological advancements and price decreases gas boilers are expected to be limited and only of incremental nature due to e.g. increased productivity.

All data are for 2015[69] [70]	**10 kW natural gas boiler one family house**	**0.5-10MW_{th} district heating natural gas boiler**
Investment cost	3,200 €/unit	0.06 M€/MW_{th}
O&M – Fixed	209 €/unit/Year	2,000 €/MW_{th}/year
O&M – Variable	0	1.1 €/MWh_{output}
Lifetime	20	25

Costs for small household gas boilers are distributed as 66% equipment costs and 33% installation costs. Larger district heating gas boilers have costs distributed as 66% equipment and 33% installation.

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[68] Energiproducenttælling 2017. Danish Energy Agency

[69] Technology Data for Individual Heating Installations August 2016 - Latest update March 2018 - https://ens.dk/en/our-services/projections-and-models/technology-data

[70] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

Social acceptance among citizens
Due to natural gas being a fossil fuel, the use of natural gas boilers can be a source of controversy among advocates for renewable energy.

Local environmental effects are limited though whereby local acceptance of gas boilers is often merely an issue of economy.

Biogas, and especially the biogas plants required to produce biogas, is known to be a source of arguments and have challenges related to social acceptance, but existing studies also find that this is something that differs in different countries[71]. A study in Switzerland found relatively high acceptance of biogas plants, and that acceptance levels were mostly influences by perceived outcomes and citizens' trust[72]. Other factors such as information, smell perception and participation also influenced local acceptance.

Social acceptance among planners and politicians
The role of natural gas and use of existing infrastructure in future energy systems derives a lot of arguments among planners and politicians. Some argue that the use of natural gas as a bridging fuel will result in unnecessary delays for the needed transition to renewables[73] [74], while others consider it necessary, and an improvement compared to other fossil fuel alternatives such as coal and oil.

Appropriateness by scale
Historically, gas boilers have played a major role in heat production internationally, as the primary heat solution for single family dwellings, apartment complexes and district heating systems. The role in future renewable energy systems might however be limited to back-up capacity, depending on the future progress and development of biogas production and distribution.

Market readiness and current deployment
Gas boilers are a commercial technology with extensive deployment internationally for both individual and district heating purposes. In Europe natural gas boilers comprise an estimated 40% of heating technology stock[75].

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[71] Local Acceptance of Biogas Plants: A Comparative Study in the Trinational Upper Rhine Region - https://doi.org/10.1016/j.enpol.2018.11.032
[72] Local acceptance of existing biogas plants in Switzerland - https://doi.org/10.1016/j.enpol.2013.06.111
[73] The Influence of Shale Gas on U.S. Energy and Environmental Policy - www.jstor.org/stable/26189414
[74] Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems - https://doi.org/10.1016/j.apenergy.2015.10.016
[75] Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables) - https://ec.europa.eu/energy/sites/ener/files/documents/Report%20WP2.pdf

14 Energy conversion – Biomass boilers

Leading partner(s) in the technology description: AAU

Technical description

Different types of biomass fuel such as wood chips, pellets, or straw can be used for combustion in a biomass boiler to produce hot water or low-pressure steam. The process differs from biomass combined heat and power plants and organic Rankine cycle plants, which are also fuelled by biomass, in that there is no electricity production. The produced hot water can be utilised directly for hot water supply, in district heating or stored for later usage in a storage tank. Typical applications for biomass boilers include individual households, apartment complexes, and district heating systems.

Sector integration properties

Biomass boilers do not as such enable sector integration but could still have an important application and role in future renewable- or smart energy systems. This could be for peak load capacity or as an alternative renewable heat source for scattered rural households where district heating is infeasible. Biomass boilers can function both as a stand-alone solution and in combination with solar thermal collectors supplying the hot water demand during the summer while the biomass boiler ensures space heating during the winter.

Extensive deployment of biomass boilers could however prove to be detrimental to the future integration of renewable energy in 100% renewable energy system, since biomass boilers are unable to utilise the increasing variable renewable energy production as indicated in a study comparing district heating supplied primarily by electrical heat pumps to biomass boilers[76].

Biomass boilers can be regulated within in a few minutes if already in operation, cold start up time is around 30 minutes. Biomass boilers are not connected to the electricity grid and thus provide no potential for electricity grid balancing.

Sizes

Typical sizes range from a few kWs for small household installations to MW size units for district heating or industrial use. A biomass boiler capable of heating a single-family household is typically 8-15 kW depending on heat demand, while typical capacities for biomass boilers in district heating systems range from 1-50 MW_{th}[77]. In Danish district heating systems, most biomass boilers are below 10 MW_{th}, with the largest existing units being 25 MW_{th}[78] (See bar chart below).

[76] Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems - https://doi.org/10.1016/j.renene.2019.02.140

[77] Technology Data for Individual Heating Installations August 2016 - Latest update March 2018 - https://ens.dk/en/our-services/projections-and-models/technology-data

[78] Energiproducenttælling - Stamdata anlæg 2017. Danish Energy Agency.

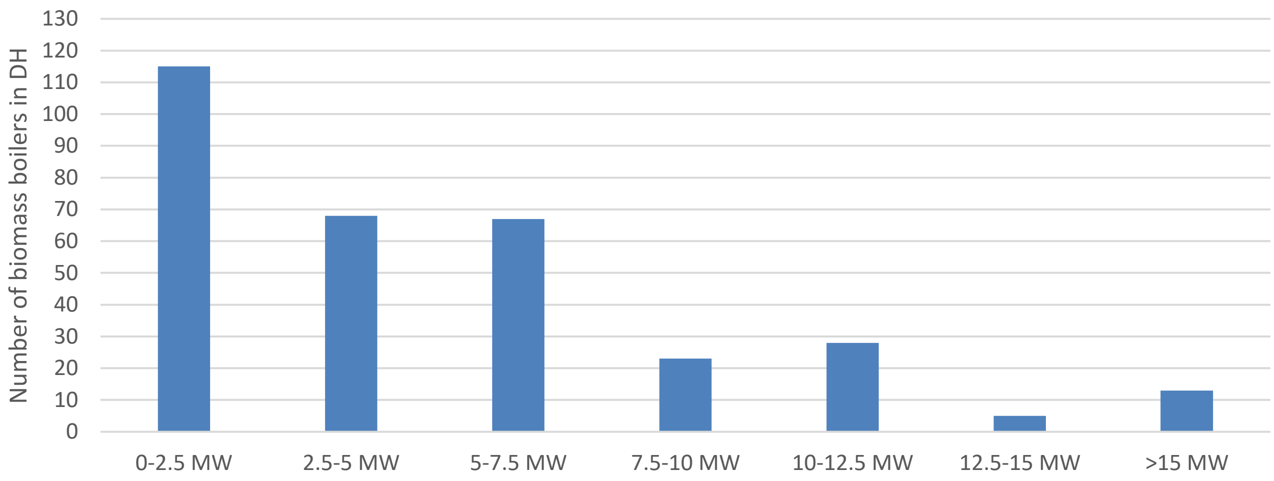

Figure 9: Biomass boilers in Danish district heating.

Efficiency and loss

Efficiency of district heating biomass boilers range from 95-100% (based on lower calorific value) but can be increased to upwards of 108% with flue gas condensation, and 115% with both flue gas condensation and absorption heat pumps installed. Flue gas condensation is mostly relevant for boilers above 1-2 MW_{th} due to increased investment and O&M costs. Efficiencies also depend on local context including moisture content of the biomass fuel and return temperature for district heating; lower temperatures result in higher efficiencies.

Smaller biomass boilers for households or apartment complexes generally have efficiencies ranging from 75-80%.

Economic parameters

Economy of scale effects for district heating boilers below 20 MW_{th} are quite substantial, due to wood chips boilers being almost serial produced, reducing investment and O&M costs.

All data are for 2015[79] [80]	**12 kW_{th} biomass boiler single family house**	**6.9 MW_{th} district heating boiler wood chips**
Investment cost	7000 €/unit	0.7 M€/MW_{th}
O&M – Fixed	516 €/unit/Year	32800 €/MW_{th}/year
O&M – Variable	0	1 €/MWh_{output}
Lifetime	20	25

Costs for a household biomass boiler are distributed as 80% equipment and 20% installations costs. For a district heating biomass boiler costs constitute 58% equipment and 42% installation costs.

Social acceptance among citizens

The social acceptance of biomass boilers is likely to relate to the exploitation of biomass resources and individual perception of sustainability and environmental issues of bioenergy, with examples of potential conflicts including biodiversity, land use conflicts, greenhouse gas emissions, and the use of arable land for food production[81].

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[79] Technology Data for Individual Heating Installations August 2016 - Latest update March 2018 - https://ens.dk/en/our-services/projections-and-models/technology-data

[80] Technology Data for Energy Plants for Electricity and District heating generation August 2016- Latest update February 2019 - https://ens.dk/en/our-services/projections-and-models/technology-data

[81] Is energy cropping in Europe compatible with biodiversity? – Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes - https://doi.org/10.1016/j.biombioe.2012.09.054

Another potential area of conflict is the smoke produced from large biomass boilers, for example when included as part of a district heating system, mostly due to health and environmental concerns, as indicated in a study from Sweden[82]. This can, to some extent, be mitigated by high environmental standards to ensure the trust of the local community.

The social acceptance of biomass plants among citizens is generally high with a stable positive attitude among the local community. This was determined in a survey-based study from Germany, in which the development of public acceptance of biomass plants was monitored over a three-year period[83]. However, the study also concluded that acceptance is not a fixed entity, and that acceptance depends significantly on local experiences.

For some consumers, switching to biomass-based DH provides an economically attractive alternative, which all things equal, should increase the social acceptance among citizens.

Social acceptance among planners and politicians

The sustainability and appropriate future usage of biomass for heating, as well as the extent of which biomass fuel can be considered a renewable energy source is avidly discussed among planners and politicians, and the ethical and political issues mentioned previously applies to planners and politicians as well. One study argues how biomass fuel should be prioritized in other sectors before heating, including electricity and transportation due to the variety of options available for renewable heat production[84].

A different study investigated how biomass consumption for heating can be reduced and determines that future energy systems with increased utilization of district heating and electrical heat pumps are preferable to excessive use of biomass for heating purposes[85].

In Denmark, district heating biomass boilers have for several years presented a business economically attractive investment due to tax exemption of biomass fuels, exemplifying the significant influence taxes and framework conditions have on the deployment of technologies. It is not possible to give a solid assessment of this worldwide, however it is likely that this situation is also reflected elsewhere.

Appropriateness by scale

Biomass boilers are widely applied globally for both households, apartment complexes and district heating systems, making it a relevant technology in both rural and urban settings.

Market readiness and current deployment

Biomass boilers are a well-known technology with large commercial deployment globally, thus improvements can be expected only incrementally. Global capacity for modern biomass fuelled amounts to 314 GW_{th}[86].
In Danish district heating the installed capacity for biomass boilers amounts to 1572 MW_{th}.

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[82] The conundrum of combustible clean energy: Sweden's history of siting district heating smokestacks in residential areas - https://doi.org/10.1016/j.enpol.2018.05.059
[83] Acceptance of biomass plants – Results of a longitudinal study in the bioenergy-region Altmark - https://doi.org/10.1016/j.renene.2015.04.059
[84] Priority order in using biomass resources – Energy systems analyses of future scenarios for Denmark - https://doi.org/10.1016/j.energy.2013.10.005
[85] Limiting biomass consumption for heating in 100% renewable energy systems - https://doi.org/10.1016/j.energy.2012.07.063
[86] Renewable 2018 Global Status report - http://www.ren21.net/gsr-2018/

15 Power control and conversion - Chargers for electrical vehicles - vehicle-to-grid/home power converters

Leading partner(s) in the technology description: SCAME and DUFERCO

Technical description

Charging stations for electric vehicles consist of an electrical panel or a pillar containing protection equipment, an electricity meter to measure the energy supplied to the vehicle, a vehicle/station communication system and a special socket/connector provided with power and signal contacts.

The purpose of the charging station is to charge the batteries on board the vehicle and to establish digital or analogue communication to the vehicle. The communication scope is to guarantee electrical safety during charging.

The charging stations can be based on alternating current to power a battery charger on board the vehicle or on direct current to directly charge the batteries on board the vehicle. In the latter case the charging station will be also equipped with an AC/DC converter.

It is essential that the charging stations are connected to the power grid management systems to realize the vehicle-to-X (V2X) functionality, so chargers can become a staple element in integrated or smart energy systems scenarios. Three identities are necessary to install, control and manage the charging stations (defined as groups of one or more charging points (CP)):

- Asset Owner: the investor of the charging station;
- Charge Point Operator (CPO): the point of delivery (POD) owner and the entity in charge of managing the charging station through an IT platform which gives access to multiple MSPs to the CPs;
- Mobility Service Provider (MSP or EMP): the interface between the customer and the CPO.

The IT system (CPO back-end) communicates with the charging stations with the “de facto” standard protocol OCPP. Currently the purpose of the communication between the charging station and the IT system ensures the continuous monitoring and remote control of the charging station.

However, the flexibility and the power of the IT system enables the possibility to enhance the control of the charging station and convert the vehicles connected to the grid to a dynamic storage. A smart management of the charging point and an integration of a Smart Energy Building can increase the self-consumption of the building in a system called Vehicle to Building (V2B) or increase the stability of the grid in a system called Vehicle to Grid (V2G).

The state of the art already makes it possible to have a vehicle charged in a scheduled way or in a real-time modulation as if it were a programmable consumer. The possibility to upgrade to a bidirectional behaviour of the EV storage to the building/grid is investigated in the MUSE GRIDS project.

Sector integration properties

The charging stations are the connection between the batteries of the electric vehicles and the grid. Therefore, the connection between advanced power management algorithms inside the IT system of the charging stations and the energy management systems of the grid represent a basic requirement for an integrated management of the energy inside the vehicles’ batteries. In essence, charging stations are prerequisites for renewable electricity-based transportation systems as envisages in several energy scenarios addressing holistic smart energy systems.

Service Providers represent the actors who can enable the abovementioned interaction between the grid and the charging stations.

The result of the integration is a creation of a diffused network of storage systems and all the benefits that result from it.

To this day the magnitude of the economic benefits with the introduction of the bidirectional interaction between electric vehicles and the grid are uncertain. On the other hand, there are a wide range of technical benefits: improving energy efficiency of the system due to the reduction of electric energy circulating in the grid (less losses due Joule's First Law); better management of the grid in terms of safety and quality. Furthermore, vehicles' energy storages can act as a backup reserve for non-dispatchable energy resources allowing the temporal decoupling between production and utilization.

There may be sectors that integrate the recharging stations in an energy system, for example the photovoltaic panels can power the charging stations and realize a real recharge of electric vehicles from renewable energy sources.

The storage capacity from the batteries of electric vehicles provide another prominent potential for sector integration and for balancing the fluctuating renewable electricity production from e.g. solar and wind resources. This allows the produced electricity to be used more efficiently and enables coupling of the electricity and transport sector.

As for the vehicle to grid function, the charging stations can act as an "interface" between the vehicle and the home or between the vehicle and the grid, in order to use the energy stored in the vehicle's batteries for domestic use or to use the batteries of the vehicle as regulators of the electrical parameters of the network (voltage and frequency).

Chargers for EVs have low response times are can be regulated up and down within seconds.

Sizes

The charging stations can have dimensions comparable to an electrical panel for domestic use (consumer unit), or the dimensions of a distribution board containing the power circuits and the power cables for charging vehicles.

The rated power of charging stations varies depending on size and application; however, some general figures are presented below.

- 3-22 kW for Domestic use (Slow charging: 6-8 Hours)
- 22- 100 kW for Public use (Fast Charging: 30-60 minutes)
- 100-350 kW for public use (Ultra-fast charging: 15 minutes)

Domestic Charger | Industrial–Public Chargers | Public Chargers

Figure 10: Chargers for electric vehicles.

The smart charging algorithms at different scale of automation and "intelligence" will be developed at the same time the technological maturity of charging stations and electric vehicles will be reached. During the same period,

dedicated partied will draft the appropriate regulation of the demand-response systems needed for the communication between charging stations and the grid.
The development of this technology will require three main steps:

- Smart Power Management: currently the IT system is already being developed for the control in real-time of the energy flow provided by the charging stations;
- Vehicle to Building (V2B): consider vehicle-building system and represent intermediate scale of development of computer system for integrated management of the vehicle within the building electric distribution;
- Vehicle to Grid (V2G): the development of vehicles' energy storage management systems, even when aggregate under Virtual Power Plant (VPP) concept, represent major scale implementation of electric demand control logics.

Efficiency and loss
The alternating current charging stations are similar to electrical power supply panels, so the efficiency is very high since the losses of the electromechanical components are due to the heating of current in the conductors.
The PCBs inside the station have a loss but the value is negligible compared to the loss in the electromechanical components (circuit breaker, relay, energy meter etc).

Lead batteries have so far primarily been used to ensure power supply of the electronic circuits. However, supercapacitors are currently being developed and tested to replace lead batteries, and once implemented should result in reduced losses. This solution consists of an electronic board with capacitors that recharge completely independently and take over in the event of a power failure.

The direct current charging stations are built with an AC/DC converter with latest resonant technology and high efficiencies, up to 98%.

The CANbus control interface allows the complete integration with the charger central controller so the power output is controlled and limited.

Economic parameters
The economic parameters depend on the type of charging station; the table below provides an overview of different system solutions.

All data are for 2018	**Domestic charger 3-7 kW AC**	**Industrial public charger 22 kW AC**	**Fast charger 100 kW DC**	**Ultra-fast Charger 350 kW DC**
Investment cost	500-1000 €/unit	4000-6000 €/unit	30000-40000 €/unit	50000-60000€/unit
O&M – Fixed	0-300 €/year	300-500 €/year	1000-1550 €/year	1000-1500 €/year
Lifetime	10 Years	10 Years	20 Years	20 Years

Permitting, connection to the distribution grid, installation, testing and commissioning, costs vary quite significantly based on local context, but the following table provides some general estimates. These costs primarily depend on the masonry works and the electric line to be built.

Domestic charger 3-7 kW AC	**Industrial public charger 22 kW AC**	**Fast charger 100 kW DC**	**Ultra-fast Charger 350 kW DC**
1500-3500 €	5500-8500 €	15000-20000 €	90000-120000 €

Social acceptance among citizens

Almost 1.2 million electric cars were sold worldwide in 2017, 57% more than in 2016. In December 2017, a record 170,000 cars were sold, reaching 2% of the total registrations for the month.

The positive trend continued in 2018 with 2 million electric vehicles sold worldwide. China being the biggest market, followed by Europe, and then the United States.

The numbers indicate a great interest from citizens for electric or hybrid vehicles, but there are still barriers that must be overcome before large-scale adoption can be expected to take place. The major barriers to adoption as indicated in study from 2018[87] include vehicle performance, high cost of vehicles, limited diffusion of the charging network and access to charging stations, and limited autonomy.

Electric vehicles currently mostly fulfil a role as a means of transportation for the journey from home to work and for short trips, but the release of new vehicles and the establishment of public charging points are expected to decrease the user's anxiety range.

Fear of change and new behavioural patterns are often perceived as barriers to the acceptance of new technologies. Hence, the main characteristic behind a decentralized management systems of charging stations is improving the consumer experience during the use of the charging service.

Afterward the power management allows to optimise the sizing of the electrical wiring and to avoid blackouts due to exceeding the maximum load capacity of the POD. The power management can guarantee the respect of definite parameters set up by user (e.g. minimum State of Charge).

There are also potential benefits derived from the time decoupling between production and utilization of electric energy from "domestic" renewable sources.

Future possible developments of the charge/discharge management algorithms could avoid early battery degradation.

For the charging stations itself, no acceptance issues are identified. If any, these will more likely relate to performance than existence.

Social acceptance among planners and politicians

Politics plays a fundamental role in the development of electric vehicles, and support schemes and measures can be used as a way of making electric vehicles a more attractive investment. In a study from Austria it was determined that early adopters of electric vehicles were inclined to live in countries with policy incentives[88], indicating that government policy have the potential to influence adoption rates of electric vehicles. Some examples of policy measures include:

- Tax reductions
- Free access of VE to restricted traffic areas
- Possibility to park for free in the cities
- Economic incentives to purchase an electric car

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[87] A dynamic model of electric vehicle adoption: The role of social commerce in new transportation - https://doi.org/10.1016/j.im.2018.05.004

[88] Predictors of electric vehicle adoption: An analysis of potential electric vehicle drivers in Austria - https://doi.org/10.1016/j.enpol.2018.07.058

It is also important to decide to prohibit the circulation of vehicles with a thermal engine inside urban areas to reduce pollution from fossil fuels.
Finally, the installation of an efficient charging infrastructure must be the first objective of the sustainable e-mobility policy.

The support from planners and politicians are essential to the success of the more environmentally friendly electric vehicles and advanced mobility solutions.
The diffusion of the V2X depends on the future tests and cost of this technology. However, the current regulation has to be updated facilitating the authorisation procedure for the installation of new charging stations.

Appropriateness by scale
The charging stations up to 11 kW of power are mainly for domestic use, the stations from 22 kW up to 50 kW have a public use while the stations from 100 kW up to 350 kW will be installed either in service stations or along large motorways connection.

At national level, some policies drive the development of the sustainable mobility setting objectives of growth and penetration of charging stations passing from today's 2,900 stations to 6,500 in 2020 (PNIRE, Italian regulation).
With the diffusion of charging points, the aggregation of smart charging points under a Virtual Power Plant (VPP) represent a relevant opportunity for future development of electric system.

Market readiness and current deployment
The car market is ready to offer electric vehicles to consumers. The automotive industry is increasingly moving towards electricity, and by 2030 almost 30% of newly registered cars are expected to be electric.

The main automotive brands have an offer for all classes of use in the catalogue and in the next 3 years the automotive industry will invest about € 60 billion for electric or hybrid cars.

With the increased sales volume, economy of scale effects will allow for cost reductions, and considerable development of batteries with increased energy density which will allow for higher autonomy of electric vehicles, making electric vehicles comparable to thermal vehicles in terms of cost and distance.

Moreover, the V2X technology will be made possible only after a widespread diffusion of smart meters, monitoring and remote-control components. The data shared between the sources of the Buildings or the DSO will enable the capillary control of the charging stations with decentralized algorithms on the IT back-end of the CPO.

Today there are many examples of battery storage systems adopted to support the grid to be more stable and reliable. The scale of these projects goes from a domestic battery system that allows to maximize the self-consumption of the solar energy, to batteries integrated directly in the grid.

16 Power control and conversion – Control systems

Leading partner(s) in the technology description: CAR

Technical description

Control systems for hybrid and RES energy systems refer, in the scope of this report, to the hardware and software that is in charge of the management of the different energy assets in a restricted area so they can provide the required energy attending to the demand or operator requirements.
The different grids (electrical, thermal, gas, hydrogen, water etc.) present in a local area have very different requirements of operation and are usually managed by different operators. Therefore, depending on the grid, there will be a variety of strategies to be applied to guarantee the service for the users. That is why the integration of the grids for a cooperative use of the energy is not a simple matter, and a new generation of smart controllers is required to solve this problem.

Focusing on electrical grids, there is another thrilling paradigm change that needs to be covered by the smart controllers. It is the change between centralized and predictable generation of energy in power plants (nuclear, thermal, hydroelectric etc.) and distributed energy production based on unpredictable renewable sources of high variety of power scale (domestic, district, high power etc.). In the old electric grid, the operator used to have the control of all generation assets and his main objective was to guarantee the voltage and frequency along the network. But in the new smart grid the operator must take into account a huge number of producers with different objectives, and he will need to develop smart strategies to manage the grid.

Since the point of view of small producers, municipalities or local energy grid operators, the smart controller will manage the generation and storage energy systems they own trying to (among others): 1) maximize the use of renewable energy, 2) maximize the efficiency of the whole system from an economical or energy point of view, 3) minimizing the waste of energy in the different grids, 4) exchange energy among the grids to guarantee users demand and 5) attend main grid operator requirements. This smart controller could be seen as a central brain that collects information of the state of the grid and the energy systems and make the best decision according to the different objectives mentioned before.

Advanced smart controllers can also include prediction tools to improve the decision-making strategies, focusing not only in the state of the grid in that moment but also in the expected production or demand, especially relevant when storage systems have to be managed.

Sector integration properties

Control systems are a key component for sector integration as they oversee energy exchange among different grids. Connection of the different grids will be possible thanks to the conversion technologies and the way these technologies are combined.

Usually the different grids are controlled according to their own objectives and limited to the systems integrated in that grid. Smart control systems are able to manage in an optimal way global objectives for an area including (and balancing) objectives of different grids, producers or consumers. Sometimes there exist conflicts among the local objectives of different grids or actors. The smart control system allows making a decision in an automatic way trying to fulfil or maximize the partial objectives according to global specifications that can be seen as an arbitration system when the local objectives cannot be achieved.

Control systems are generally able to regulate within seconds.

Sizes
Control systems can be applied to domestic users, small producers and to high power assets (local or distributed). In the first two levels the control system is usually provided for one single vendor as a part of a whole system including equipment, controller, software and user interfaces. But in the case of microgrids, control systems are mainly ad-hoc solutions for every case as they usually integrate assets and equipment from different vendors, and also the installation and auxiliary equipment (e.g.: communication, measurement...) depend on the operator/owner requirements. The commercial solutions (see below) always need to be integrated and adapted to the specific configuration of the renewable energy systems in every situation.

In the next sections, specific technical descriptions will be included for home management systems and virtual power plants. Even though all of these control/management systems have a common paradigm for integrating different production and demand assets with very similar objectives (increase of renewable energy use, cost reduction, use of flexibility in the demand etc.) specific solutions should be developed depending (among others) on the power size of the assets, their flexibility for energy exchange with the grid or the way they are distributed in a local or wide area.

Efficiency and loss
There are no efficiencies or losses as such related to the use of control systems. However, control systems are an integral component of modern energy systems and have an important role in ensuring optimal system operation, which arguably has the potential to increase the efficiency of the entire energy system.

Economic parameters
The investment needed for the integration of the control system in a hybrid power plant or microgrid is not easy to assess in a generic way. It depends on the number of devices/generation plants that will be controlled, the hardware structure needed for communication and the ad-hoc programming for the integration of different providers' assets. For example, the investment cost will be lower if the generation plants and control system are provided for the same vendor and it is not needed to develop new communication modules.
The investment cost could be divided in:

- Hardware: including real-time controller, communication devices, HMI, wiring etc. The estimated cost for a standard system is around 10,000 €.
- SCADA: including data base, software for supervision and control and specific developments for the plant. This could have an estimated cost of 20,000 €.
- Control software: this is the cost more difficult to estimate because it depends on the functions included in the control and the requirements of the user/owner of the plant. Even in the commercial solutions a specific deployment is always needed and mainly related with the number of generation/storage assets.

Social acceptance among citizens
The control system is transparent for the citizens as it is an advanced technological development that cannot be easily perceived or understand in deep. Citizens will be aware of the advantages and disadvantages of the different technologies controlled but not of the controller itself. Even though when the effects of the control systems can be noticed (e.g.: blackout) it is not easy for the normal citizen to discern that the origin of that effect is the controller, and usually they will relate these effects with the operator and not with the technology associated with the management system.

Social acceptance among planners and politicians
As the planners and operators of the grid are responsible of its stability and also of the economic exploitation costs, it is expected a high acceptance of any technological development that can help in these two objectives. Nevertheless, the complexity of the electrical grid makes that these controller developments are restricted to the

operation of microgrids or isolated systems. Their connection to the grid will be done under strict restrictions of the operator what sometimes limit their capability of maximizing the renewable use.

Appropriateness by scale

Control systems are relevant and appropriate in all scales; ranging from small scale residential household control systems to national grid management.

Market readiness and current deployment

Commercial solutions are mainly focused on the control of electrical microgrids, where a set of renewable energy generators (PV, wind etc.) and electric storage devices (batteries) have to be managed as a whole to guarantee the balance between generation and demand. In some cases, depending on the connection to the main grid, the microgrid can be seen as a generation plant with different renewable resources and the management is restricted to maximize renewable energy production.

By now, there no exist commercial software solutions for the simultaneous control of multiple grids taking into account the different objectives of every grid and the conversion technologies for the interaction of the grids.

Some of the existing commercial control systems are:

Vendor	Description
Siemens Gamesa Renewable Energy	Hybrid Plant Controller (HPC) is a real-time controller whose objective is to reduce the LCoE in hybrid plants to achieve the maximum integration of RES in optimal conditions. It is able to manage different generation plants (wind farm, photovoltaic, thermal etc.) and storage systems being the whole plant connected or disconnected to the grid.
Siemens	Siemens Microgrid Controller. It is able to plan and control the use of different energy sources and to manage the use of batteries.
General Electric	GE's Advanced Distribution Management Solutions is suitable for addressing distribution grid issues.
Schneider	EcoStruxure Grid is an open, interoperable, IoT-enable system architecture and platform. It is able to manage all elements in a microgrid to attain economic, environmental and technical objectives.
Eaton	Power Grid Xpert Energy Optimizer is programmed to maintain overall microgrid stability, shave peak demand, shift loads, manage black starts, achieve lowest total cost of operation, maximize renewable energy contribution and provide utility demand response functionality.

17 Power control and conversion – Communication in SES

Leading partner(s) in the technology description: RINA-C

Technical description

The necessity of modelling different energy carriers, developing multi-generation systems and integrating various energy infrastructures involves the need to introduce a concept called Smart Energy Systems (SESs), that is a generalized concept of the smart grid in which the different energy vectors (electricity, heating & cooling, water, gas, etc.) are combined with storage technologies and users. Several synergies can be achieved by adopting a coherent approach to the complete smart energy system compared to looking at only one sector. This applies not only to finding the best solution for the total system, but also to find the best solutions for each individual sub-sector.

This means that there are many connections between all the SES components, and it leads to the need to process and exchange large volumes of information/data in order to solve the optimal management problem in such a system. In such a framework, the use of concepts similar to the smart grid is essential for collecting, exchanging, and processing data, sending control signals and intelligent interactions between system controllers and agents.
The use of the Internet in conjunction with Web-based technologies, Information and Communications Technology (ICT) and Advanced Metering Infrastructure (AMI) provides potentials for optimizing the operation of distributed energy systems.

The existence of these systems allows the bidirectional information exchange between subscribers and the system operator or the autonomous control, which facilitates the real-time management over the entire network. Both services providers as well as consumers benefit from innovations in information and communication technologies (ICT). By communicating all relevant processes, like meter reading, grid monitoring and management, to the multi energy grids' endpoints, an overall smarter energy market can be established.

Today, with the development of ICT and the need for intelligent performance of the various components of the system, the development of concepts such as the smart energy system for the automatic and intelligent operation of the grid is inevitable.

In different segments of a grid, different communication technologies are applied to meet the unique specific requirements. Thinking for example to the power grid, in a power transmission segment, wired communications over power lines or optical fibre cables are adopted to ensure robustness of the backbone. However, in power distribution segment, that provide power directly to the end users, both wired and wireless communications should be considered, e.g. DLC, GSM, LTE, 5G, etc.

In order to achieve a cost-effective and flexible control and monitoring of the end devices, efficient dispatching of services and dynamic integration of distributed multi energy resources with the grid, wireless communications and networking functionalities must be embedded into various equipment. There may be a need to control heat and/or gas, EVs over a common communication system. Capability of wireless networking among various electric equipment is one of the key technologies that drive the evolution of a conventional distribution network into a SES.

Nowadays, heterogeneous networks achieve end-to-end integration of the corresponding technologies by using sensor network architecture. Defining the interoperability with next-generation network (NGN) as the SES backbone is of importance, too. The main component of the SES is the sensor network, which consists of a system of distributed nods that interact among themselves and with the infrastructure in order to acquire, process, transfer and provide information extracted from the physical world.

Sector integration properties

Simulation, design and operation strategies of SESs calls for tools and models that extend across all parts of the energy system with focus on electricity, heating, cooling and transportation and thus across infrastructures connected by electric, thermal and gas grids [89].

The components of each of these entities will need a way of communicating that will be independent of the physical medium used and also independent of manufacturers and the type of devices.

To allow these connections it is essential to standardize each communication by applying protocols as use of too many different protocols could lead to problems in understanding each other. For this reason, some organizations have decided to create STANDARD rules to regulate the introduction of new protocols and to guarantee interoperability between parties.

The main organizations providing communication standards are:

- Telecommunication: ITU (worldwide), ETSI (Europe).
- Information: ISO (worldwide), CEN (Europe), NIST (USA)
- Electrotechnics: IEC (worldwide), CENELEC (Europe)
- Others: SGIP (smart grid in US), IETF (internet worldwide).

Therefore, multiple communication technologies and standards coexist in different parts of the system. For example, communications in short-range wireless such as Bluetooth (IEEE 802.15.1) or UWB could be used for the interface between meter and end customer devices; ZigBee (IEEE 802.15.4) and Wi-Fi (IEEE 802.11) could be used for smart meter interfaces in the home and local area network; cellular wireless (e.g. GPRS, UMTS, or 4G technologies like 802.16mand LTE) could be used for the interface between meters and the central system.

Machine-to-machine (M2M) communication is seen as a form of data communication among machines without (or only limited) human intervention. As suggested by its name, M2M comprises three core components:

- Machine - On one end, there is a device (e.g., electricity meter) which is monitored by means of a sensor (in 'uplink's) or a device (e.g., a switch) which is instructed to actuate (in 'downlink')
- 'To' - This is the networking part which facilitates seamless and autonomous end-to-end connectivity between machines
- Machine - On the other end of the communication link, there is a device (e.g., a computer) which extracts, processes and displays the information gathered from the monitoring devices in order to make decisions and, possibly, send instructions to the actuators to perform some task(s)

The design and growth of M2M system has been driven by the following high-level requirements:

- Number of nodes: Possibly the strongest differentiator with regard to current systems is the need and ability to support a large number of devices, which stretches well beyond the currently used cellular or Wi-Fi users
- Dispersive applications: These devices are being driven or driving a very wide spectrum of applications, some of them being critical in delay, others critical in security, etc. For example, automated meters may only need to report their non-critical readings every few minutes, whereas phasor monitoring needs to be done several times per second and data delivery ought not to fail
- Affordable cost: None of the above can be accomplished if cost is not kept to a minimum: it implies that M2M technology must be more affordable at the same or better technical characteristics than any alternative approach

[89] H. Lund, P. A. Østergaard, D. Connolly, B. Vad Mathiesen, "*Smart Energy and Smart Energy Systems*", May 2017

- Autonomous operation: Need to facilitate a truly autonomous operation due to the fact that the large number of devices cannot be serviced by humans as is traditionally done in human-centric networks. Autonomy here includes auto-configuration, auto-optimization, auto-healing, scalability, etc.
- Mobility and remote operation: The system must support some degree of mobility and must be usable in remote regions. Cellular operators see an enormous opportunity, at the caveat of requiring a major technical overhaul of their cellular networks
- Comparably low rate: The very large majority of M2M applications requires low communication rates, rarely exceeding hundreds of kilobits per second (kbps). This contrasts very much with current trends in human-centric communication networks, where capacity densities of 1 Gbps/km2 are needed
- Critical delay requirements: Some applications are very critical in delay, i.e., the M2M readings need to be delivered with a hard-delay constraint. For instance, phasor readings in the grid are considered critical and need to be reported within tens of milliseconds (ms) to be able to react meaningfully to any impeding outage
- Highly energy efficient: Due to the unattended field deployment, power supply is not always guaranteed and, if it is not, batteries cannot be replaced on a regular basis. A major design driver is hence the energy efficiency of the communication system.
- Highly secure: Due to unattended and remote field deployments, the devices as well as the communication links must be highly secure. For instance, to avoid false outage reports from the phasor monitors in the grid, security is one of the major technical design drivers.

In general, the described communication systems function on second-based operation, and in most instances less than one second.

Sizes

The communication infrastructure is envisioned as a collection of interconnected networks. A variety of technologies, network topologies and communication protocols are considered. There are several important issues in communication network design, such as:

- Which communication technologies should be used to establish links between devices?
- Which network topologies are applicable in the context of electric grid infrastructures, and how communication technologies and grid geography affect the topology of the network?
- Which networking and transport protocols are the most appropriate for meeting the requirements of smart grid communications?

There is a general agreement that it is not possible to give a unique answer to the above questions because SESs will operate in different environment with different sizes and different use cases.

Taking in account the volumes of parties involved in SESs, such as electricity, heating & cooling, water, gas, EVs, etc., large amount of information/data are exchanged in order to manage entire needs of the system. During the "2015 IEEE International Conference on Smart City"[90], it was shown that only in the electricity grid, data generated by an end-user each day is approximately 0.5MB, comparable to that of an average Facebook user. This is a good data starting point to understand how, merging multi-energy grids, the amount of data is relevant and consistent.

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[90] The Hien Dang Ha, Roland Olsson, Hao Wang, "*The Role of Big Data on Smart Grid Transition*", 2015 IEEE International Conference on Smart City (IEEE Smart City 2015), December 2015

The bulk of SES technologies are already used in other applications such as smart grids[91].

- Integrated communications: Areas for improvement include: substation automation, demand response, distribution automation, supervisory control and data acquisition (SCADA), energy management systems, wireless mesh networks and other technologies, power-line carrier communications, and fiber-optics.[92] Integrated communications will allow for real-time control, information and data exchange to optimize system reliability, asset utilization, and security.[93]
- Sensing and measurement: Core duties are evaluating congestion and grid stability, monitoring equipment health, energy theft prevention, [94] and control strategies support. Technologies include: advanced microprocessor meters (smart meter) and meter reading equipment, wide-area monitoring systems, dynamic line rating (typically based on online readings by Distributed temperature sensing combined with Real time thermal rating (RTTR) systems), electromagnetic signature measurement/analysis, time-of-use and real-time pricing tools, advanced switches and cables, backscatter radio technology, and Digital protective relays.
- Smart meters.

Efficiency and loss

The existing electricity, heating, cooling and transportation infrastructure can be substantially improved by automation and information management. It is believed that the biggest return on the investment may be achieved by improving distribution automation that will provide a fast-increasing capacity over time: “blind” and manual operations with electromechanical components in the distribution grid need to be transformed into a “smart grid”.[95]

Such transformation is also necessary to meet environmental goals, to provide a greater emphasis on demand response (DR), and to support plug-in and hybrid electric vehicles.

Thanks to the integration of internet communication, SES can provide many technical, economic, and environmental benefits, including increasing efficiency, reducing energy consumption, reducing emissions and losses, increasing reliability, real-time control, facilitating the integration of RES and reducing system costs.

The maximum theoretical throughput that can be achieved with Bluetooth V2.1+EDR is 3Mbit/s, but the practical data transfer rate is 2.1 Mbit/s.[96] Moreover, it should be noted that the Bluetooth protocol has always suffered from signal interferences. As Bluetooth operates in the 2.4 to 2.4835 GHz electromagnetic band, problems may appear if a Zig-Bee3 or any other IEEE 802.15.44 based protocol is running nearby. In addition to that, in [Intel,

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[91] U.S. Department of Energy, National Energy Technology Laboratory, Modern Grid Initiative, http://www.netl.doe.gov/moderngrid/opportunity/vision_technologies.html Archived July 11, 2007, at the Wayback Machine

[92] Berger, Lars T.; Iniewski, Krzysztof, eds. (April 2012). Smart Grid - Applications, Communications and Security. John Wiley and Sons. ISBN 978-1-1180-0439-5.

[93] F.R. Yu, P. Zhang, W. Xiao, and P. Choudhury, "Communication Systems for Grid Integration of Renewable Energy Resources," IEEE Network, vol. 25, no. 5, pp. 22-29, Sept. 2011.

[94] Buevich, Maxim; Zhang, Xiao; Schnitzer, Dan; Escalada, Tristan; Jacquiau-Chamski, Arthur; Thacker, Jon; Rowe, Anthony (2015-01-01). Short Paper: Microgrid Losses: When the Whole is Greater Than the Sum of Its Parts. Proceedings of the 2Nd ACM International Conference on Embedded Systems for Energy-Efficient Built Environments. BuildSys '15. New York, NY, USA. pp. 95–98. doi:10.1145/2821650.2821676. ISBN 9781450339810.

[95] Ali Ipakchi, Farrokh Albuyeh, “*Grid of the future*”, IEEE Power and Energy Magazine 7(2):52 – 62, May 2009

[96] Kewney, G. (2004). “*High speed bluetooth comes a step closer: enhanced data rate approved*.” http://www.newswireless.net/index.cfm/article/629.

2012][97] it is claimed that USB 3.0 devices, ports and cables have been proven to interfere with Bluetooth devices due to the electronic noise they release falling over the same operating band as Bluetooth. This issue should be considered when designing and performing the tests of the present project.

Different versions of Wi-Fi exist, with different ranges, radio bands and speeds. Wi-Fi most commonly uses the 2.4 GHz (12 cm) UHF and 5 GHz (6 cm) SHF ISM radio bands; these bands are subdivided into multiple channels. Each channel can be time-shared by multiple networks. These wavelengths work best for line-of-sight. Many common materials absorb or reflect them, which further restricts range, but can tend to help minimise interference between different networks in crowded environments. At close range, some versions of Wi-Fi, running on suitable hardware, can achieve speeds of over 1 Gbit/s.

5G systems in line with IMT-2020 specifications[98] are expected to provide enhanced device and network-level capabilities, tightly coupled with intended applications. The following eight parameters are key capabilities for IMT-2020 5G:

Capability	Description	5G target
Peak data rate	Maximum achievable data rate	20 Gbit/s
User experienced data rate	Achievable data rate across the coverage area (hotspot cases)	1 Gbit/s
	Achievable data rate across the coverage area	100 Mbit/s
Latency	Radio network contribution to packet travel time	1 ms
Mobility	Maximum speed for handoff and QoS requirements	500 km/h
Connection density	Total number of devices per unit area	10^6/km^2
Energy efficiency	Data sent/received per unit energy consumption (by device or network)	Equal to 4G
Spectrum efficiency	Throughput per unit wireless bandwidth and per network cell	3–4x 4G
Area traffic capacity	Total traffic across coverage area	1000 (Mbit/s)/m^2

Satellite Internet access is Internet access provided through communications satellites. Modern consumer grade satellite Internet service is typically provided to individual users through geostationary satellites that can offer relatively high data speeds, [99] with newer satellites using Ku band to achieve downstream data speeds up to 506 Mbit/s.[100]

Capability	Satelite target
Medium	Air or Vacuum
License	ITU
Maximum **downlink** rate	1000 Gbit/s
Maximum **uplink** rate	1000 Mbit/s

[97] Intel (2012). "*Usb 3.0* radio frequency interference impact on 2.4 ghz wireless devices*." http://www.usb.org/developers/whitepapers/327216.pdf.
[98] "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond" (PDF).
[99] "Satellite Internet: 15 Mbps, no matter where you live in the U.S." Ars Technica. Retrieved 5 September 2013.
[100] End-to-End Efficiency for Trunking Networks, Newtec IP Trunking, 2013

Average downlink rate	1 Mbit/s
Average uplink rate	256 kbit/s
Latency	Average 638 ms[1]
Frequency bands	L, C, Ku, Ka
Coverage	100–6,000 km
Additional services	VoIP, SDTV, HDTV, VOD, Datacast
Average **CPE**price	€300 (modem + satellite dish)

Economic parameters and Appropriateness by scale

SES is a concept that can cover all energy technologies and systems. Depending on the scale of the system, SES can use different communication technologies and consequently can come across various economic aspects. The following table tries to briefly summarize the costs and scale for the main communications technologies involved.

Communication technology	Cost level (1-Low, 4-High)	Communication Scale
Bluetooth[101]	1	Information are exchanged between different devices through a short-range secure radio frequency that can search for devices covered by the radio signal within a range of a few tens of meters by connecting them together. It involves small amounts of data exchange.
Wi-Fi	2	Information are exchanged between different devices in less delocalized areas, such as in urban areas. It could involve large amounts of exchanged data. Wi-Fi operational range depends on factors such as the frequency band, radio power output, receiver sensitivity, antenna gain and antenna type as well as the modulation technique. In addition, propagation characteristics of the signals can have a big impact. At longer distances, and with greater signal absorption, speed is usually reduced.[102]
5G[103]	3 – both CAPEX and OPEX are more expensive respect to Wi-Fi communication	Information are exchanged between different devices in delocalized areas, such as in rural or isolated mountain areas where WI-Fi communication is limited. It could involve large amounts of exchanged data. 5G performance targets high data rate, reduced latency, energy saving, cost reduction, higher system capacity, and massive device connectivity.[104]
Satellite	4	It is used to put in communication an isolated elements or areas or one that needs an effective and reliable communication and cannot use other. It could involve large amounts of exchanged data. Communications satellites use a wide range of radio and microwave frequencies.[105]

[101] bluAir. "Bluetooth Range: 100m, 1km, or 10km?". bluair.pl. Retrieved 4 June 2015.
[102] "*802.11n Data Rates Dependability and scalability*". Cisco. Archived from the original on 2017-07-05. Retrieved 2017-11-20.
[103] "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond" (PDF).
[104] Segan, Sascha (14 December 2018). "What is 5G?". PC Magazine online. Ziff-Davis. Retrieved 23 January 2019.
[105] "Military Satellite Communications Fundamentals | The Aerospace Corporation". Aerospace. 2010-04-01. Retrieved 2016-02-10.

Social acceptance among citizens, planners and politicians

Services based on open and standardized Internet protocols have revolutionized information and communication technology and provided new business opportunities that have led to a huge increase in productivity in telecommunications and multimedia field. Today's energy management systems can greatly benefit from this development. With extensive network coverage across various interoperable infrastructures and growing support for communication in the energy system components (e.g. smart meters, home appliances, power generators), current cutting-edge technologies provide the basis for a broad supply relative energy value-added services. This offer is beneficial for both service suppliers and customers: vendors take advantage of distributed and self-organizing communication algorithms, thus enabling intelligent resources distribution and thus reducing peak loads and the risk of failure. Customers, on the other hand, benefit from fast and secure data exchange, up-to-date knowledge on family consumption and value-added services for home appliances, which ultimately contribute to reducing overall energy consumption/costs and polluting emissions.

Smart Energy System could be vulnerable to various threats and challenges. Various cyber security challenges are addressed:

- Connectivity: The communication network in the Smart Energy System is sophisticated as it combines a large number of devices that interoperate. Given the nature of the Smart Energy System environment being decentralized, the systems require a high level of protection against attacks and vulnerabilities. Attacks can lead to physical damage, black-outs and lack of efficiency. This is because, attackers gain control of the system.[106]
- Customer's Privacy: Ensuring consumer's privacy is an important aspect in any system including the Smart Energy System that should be well protected and preserved. The introduction of smart meter into the Smart Energy System could bring many challenges related to user's information privacy. Besides reporting back some essential information about user's power consumption, smart meter could compromise the user's privacy which is a critical. Since it could use the information received at the service provider to infer the behaviours of the users. The collected data about customers include information about the time they are available at home or travelling. It can even extract information about some daily activities such as sleeping, watching television or even what appliances they are using. Criminals who plan to commit a crime, business, marketers who want to advertise or even competitors are interested in the extracted data. So, data should be protected during the transmitting and the storage process to prevent unauthorized access to data in order to protect the user's privacy.[107]
- Software Vulnerabilities: Software suffers from a wide variety of vulnerabilities that include malwares. Supervisory control and data acquisition (SCADA) systems composed of general-purpose technology that introduces the risk of malwares and malicious updated. General purpose systems suffer from various well-known vulnerabilities that should be patched to ensure that the system stay updated. On the other hand, patching is considered a difficult process especially in critical systems like the smart grid because it is very expensive, and it could lead to downtime.[108]

High level of securing a Smart Energy System network is by providing data protection and object authentication.

This is possible considering cryptography methods and algorithms used to encrypt data, in order to secure communication, protect user information, and to authenticate users in order to prevent attacks against data integrity. In encryption, both Symmetric Key encryption and Public Key encryption are used in smart grid networks. While symmetric key requires lower computing capabilities, public key has been proven to be more secure and is

[106] M. B. Line, I. A. Tondel and M. G. Jaatun, "Cyber security challenges in Smart Grids," in 2nd IEEE PES International Conference and Exhibition, Innovative Smart Grid Technologies (ISGT Europe), Manchester, 2011.

[107] H. Khurana, M. Hadley, L. Ning and D. A. Frincke, "Smart grid security issues," IEEE Security & Privacy, 7(1), pp. 81-85, 2010.

[108] M. B. Line, I. A. Tondel and M. G. Jaatun, "Cyber security challenges in Smart Grids," in 2nd IEEE PES International Conference and Exhibition, Innovative Smart Grid Technologies (ISGT Europe), Manchester, 2011.

easier to implement when it comes to key management. However, due to the variation of computational capability of devices, which range from simple sensors to smart phones and computers, both types of encryption are used.

Market readiness and current deployment

Energy is the key to tackling the most important issues of today and tomorrow such as climate change, sustainable development, health and environment, global energy and food security, and environmental protection. Thanks to the already mature communication technologies, the deployment of SES can be facilitated. For the integration between the parties, installation of sensors and hardware devices is required to allow the use of internet communication channels.

In Europe, there are many countries' ambitions to install smart meters. This an important mission to improve the Advanced Metering Infrastructure (AMI) and consequently permit the dispatching of Smart Grids and Smart Energy Systems. It could consider for example Denmark that in 2013, then Climate, Energy and Building Minister Martin Lidegaard decided that all Danish homes are to have smart electric meters recording hourly consumption by 2020. In 2013 about half of the homes in Denmark had a smart meter installed – these were accounting for about three-quarters of the consumption. With the signing of a new executive order by Minister Lidegaard, the rollout would be completed to the remainder of the homes.

According to a ministry statement, the investment in the smart meters would be quickly recovered. The ministry anticipated a reduction in power consumption by 2 percent, which corresponds to a saving of DKK 180 (US$32) per year for an average homeowner. Further, hourly settlement would lead to increased competition in the electricity market, which could give the homeowner a further saving of over DKK100 (US$18) per year.

18 Power control and conversion – Wider area network (WAN) system

Leading partner(s) in the technology description: RINA-C

Technical description

Communication infrastructures (or networks) are widely used around the world to provide the connectivity service among individual electric devices or entire grid sub-systems. Data networks can be connected to allow users seamless access to resources that are hosted outside the particular provider to which they are connected. Terminals connected to TCP/IP networks are addressed using IP addresses. TCP/IP are the fundamental protocols that provide the control and routing of messages through the data network.

There are several network structures that the TCP/IP protocol can use to effectively route messages, for example:

- wide area networks (WAN)
- metropolitan area networks (MAN)
- local area networks (LAN)
- personal area network (PAN)
- body area network (BAN)

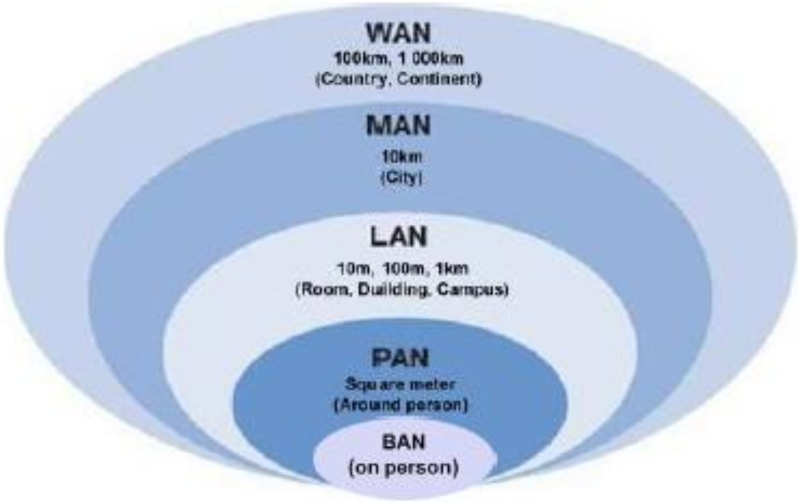

Figure 11: Illustration of ranges for different network infrastructures.

A body area network (BAN) is a wireless network of wearable computing devices; BAN devices may be embedded inside the body, implants, may be surface-mounted on the body in a fixed position Wearable technology or may be accompanied devices which humans can carry in different positions, in clothes pockets, by hand or in various bags[109].

A personal area network (PAN) is a computer network for interconnecting devices centred on an individual person's workspace[110]. A PAN provides data transmission among devices such as computers, smartphones, tablets and personal digital assistants.

A local area network (LAN) is a computer network that interconnects computers within a limited area such as a residence, school, laboratory, university campus or office building[111].

A metropolitan area network (MAN) is a computer network that interconnects users with computer resources in a geographic area or region larger than that covered by even a large local area network (LAN) but smaller than the

[109] Poslad, Stefan (2009). Ubiquitous Computing Smart Devices, Smart Environments and Smart Interaction. Wiley. ISBN 978-0-470-03560-3. Archived from the original on 2012-02-15. Retrieved 2014-06-23.

[110] Gratton, Dean A. (2013). The Handbook of Personal Area Networking Technologies and Protocols. Cambridge University Press. pp. 15–18. ISBN 9780521197267. Retrieved 12 December 2018.

[111] Gary A. Donahue (June 2007). Network Warrior. O'Reilly. p. 5.

area covered by a wide area network (WAN). The term MAN is applied to the interconnection of networks in a city into a single larger network which may then also offer efficient connection to a wide area network[112].

A wide area network (WAN) is any telecommunications network that extends over a large geographical distance/place and it is the core tier of the smart grid communication system. [113] Such high-capacity communication backbone is used to deliver the large amounts of data collected by the highly dispersed AMI systems and Field Area Networks (FANs) to remote control centres over long distances. WANs often connect multiple smaller networks, such as local area networks (LANs) or metro area networks (MANs). The key difference between WAN and LAN technologies is scalability. WAN must be able to grow as needed to cover multiple cities, even countries and continents.

There are two types of WAN: Switched WAN and Point-to-Point WAN.

1. A switched WAN network is used to connect multiple end nodes through a common WAN network. The end nodes connect to a switched WAN network either to reach other nodes connected to the switched network or to connect to the public Internet. X.25, Frame Relay, ATM, MPLS, VPN are examples of popular switched WAN protocols.
2. A point-to-point link provides a single, pre-established WAN communications path from the customer premises through a carrier network to a remote network. Point-to-point lines are usually leased from a carrier and thus are often called leased lines.

A set of switches and routers are interconnected to form a Wide Area Network. The switches can be connected in different topologies such as full mesh and half mesh. A wide area network may be privately owned or rented from a service provider, but the term usually connotes the inclusion of public (shared user) networks.

Both packet switching and circuit switching technologies are used in the WAN. Packet switching allows users to share common carrier resources so that the carrier can make more efficient use of its infrastructure. In a packet switching setup, networks have connections into the carrier's network, and many customers share the carrier's network. The carrier can then create virtual circuits between customers' sites by which packets of data are delivered from one to the other through the network.

Circuit Switching allows data connections to be established when needed and then terminated when communication is complete. This works like a normal telephone line works for voice communication. Integrated Services Digital Network (ISDN) is a good example of circuit switching. When a router has data for a remote site, the switched circuit is initiated with the circuit number of the remote network.

A Smart Energy System communications infrastructure allows utilities to communicate with one another in regional grids, as well as with customers and distributed power generation and storage facilities. To achieve the full vision of the Smart Energy System, individual utilities will need to support multiple networks: the Home Area Networks (HANs) for consumer energy efficiency; the Neighbourhood Area Network (NAN) for advanced metering applications; and the Wide Area Network (WAN) for distribution automation and the backbone of the Smart Energy System. Therefore, inside SESs panorama, WAN is a one of the most important way involved to implement communication.

[112] IEEE Std 802-2002, IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture, page 1, section 1.2: "Key Concepts", "basic technologies" http://www.apposite-tech.com/blog/wp-content/uploads/2017/09/IEEE-Std-802-Metropolitan-Area-Networks.pdf

[113] A WAN Is a Wide Area Network. Here's How They Work". Lifewire. Retrieved 2017-04-21.

Sector integration properties
A WAN connects multiple distribution systems together and acts as a bridge between neighbourhood area networks (NANs), home area networks (HANs) and the utility network, providing a backhaul for connecting the utility company to the customer premises.

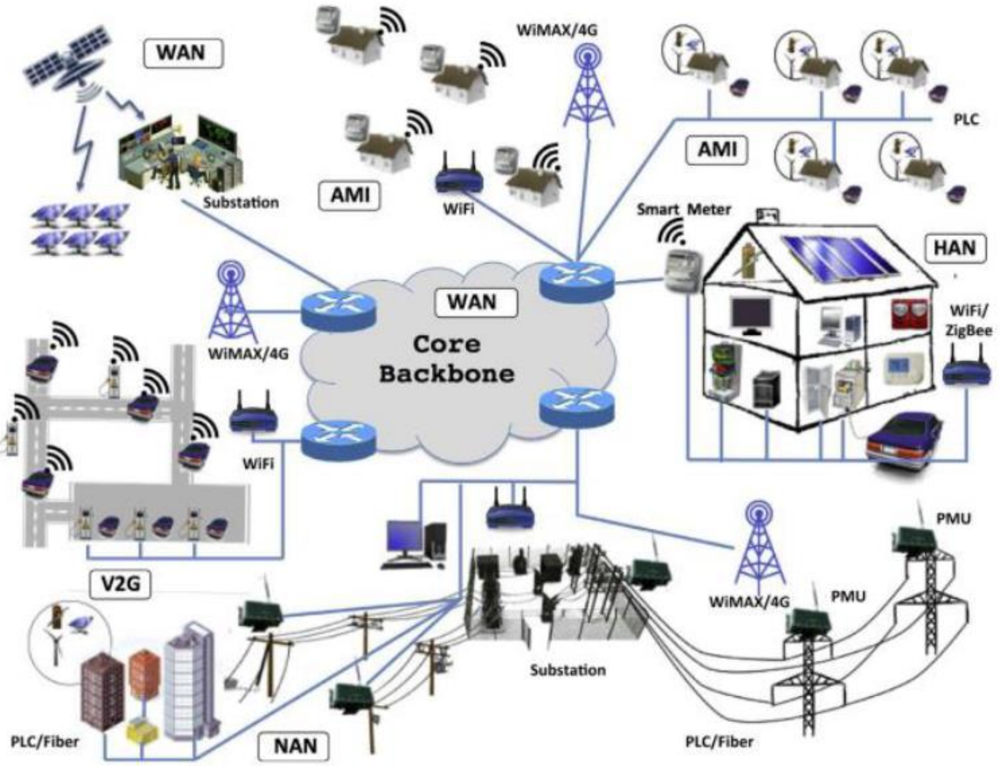

Figure 12: graphic illustration of WANs and their connection and correlation to surrounding infrastructure[114].

Generally, a backhaul can adopt a variety of technologies to transfer the information extracted from the NAN to the utility local offices.

Since information privacy and reliability are the major concerns for the customer, security and fault tolerance of these communication technologies are crucial issues. For these reasons, the various parts of the WAN could be connected using a virtual private network (VPN). This provides protected communications between sites, which is necessary given that the data transfers are happening over the internet.

Many technologies are available for wide-area network links. Examples include circuit-switched telephone lines, radio-wave transmission, optic fibre, Ethernet, cellular network, or broadband access. A WAN gateway can use broadband connection (e.g., satellite) or possibly an IP-based network (e.g., MPLS and DNP3) to provide an access for the utility offices to collect the required data.

New developments in technologies have successively increased transmission rates. In the 1960s, a 110 bit/s (bits per second) line was normal on the edge of the WAN, while core links of 56 kbit/s to 64 kbit/s were considered fast. As of 2014, households are connected to the Internet with Dial-Up, ADSL, Cable, Wimax, 4G or fiber. The speeds

[114] Ancillotti E., Bruno R., Conti M., "*The role of communication systems in smart grids: Architectures, technical solutions and research challenges*", Computer Communications, Volume 36, Issues 17–18, November–December 2013

that people can currently use range from 28.8 kbit/s through a 28K modem over a telephone connection to speeds as high as 100 Gbit/s over an Ethernet 100GBaseY connection.

The following communication and networking technologies have been used to implement WANs.

- Asynchronous transfer mode
- Cable modem
- Dial-up internet
- Digital subscriber line
- Fiber-optic communication
- Frame Relay
- ISDN
- Leased line
- SD-WAN
- Synchronous optical networking
- X.25

Modern WANs have very fast data transmission rates, enabling second-based operation.

Sizes

As mentioned before, WANs are telecommunication network that extend over a large geographical distance/place. Therefore, many could be the WAN devices included into the WANs. Principally the devices involved are hubs, routers, switches, bridges, wireless devices, or other devices. Generally, personal computers, file servers, printers, or other LAN devices are not classified as part of the WAN.

Devices used for transmission of data through WAN are: Optic fibre cables, Microwave link and Satellites.

Broadband provides the connection between a device, home, school or small company and the ISP. Once within the ISP, different WAN technology will be used to transfer the data around the ISP network and between other ISPs.

However, it is becoming increasingly common for even large organizations to connect to the Internet to provide connection between their LANs, as opposed to using more traditional WAN solutions. Thus, they are also using broadband connectivity to provide WAN connectivity.

There are four main types of broadband WAN connectivity available via UK ISPs:

- Digital Subscriber Line (DSL)
- cable
- fibre optic
- wireless

The different options have different advantages depending on site.

For rural areas, point-to-point communication has advantages. A point-to-point connection is a dedicated communication link between two systems or processes using a secure and dedicated WAN connection. The point-to-point protocol (PPP) provides authentication, encryption, compression and transmission in a point-to-point WAN communication. PPP is very important factor in accessing the internet. Internet service providers (ISPs) have also used this technology for the dial-up access of customers to the internet, since IP packets is impossible to transmit over a modem line on their own, without observing the so-called data link protocols.

For urban areas, switched WAN communication has advantages. A switched WAN network is used to connect multiple end nodes through a common WAN network. The end nodes connect to a switched WAN network to either reach other nodes connected to the switched network or to connect to the public Internet.
Switched WAN, named also point-to-multipoint WAN, is used when a virtual circuit in a router is connected to another. Each point-to-point sub interface requires its own subnet. Multipoint is used when the router is the centre of a star-shaped system virtual circuit. The sub interface uses a subnet for all serial interfaces of the router connected to the frame switch. The Switched WAN network consists of multiple protocol specific WAN Switches (like ATM switches or MPLS switches) that basically implement Layer 2 Switching of data frames.

Efficiency and loss
Since WANs cover a large geographical area and it involves increased distance and increased number of servers and terminals, WAN is difficult to design and maintain. Similar to a MAN, the fault tolerance of a WAN is less and there is more congestion in the network. Due to long distance transmission, the noise and error tend to be more in WAN. The communication channels in a WAN are relatively slow. The data transfer rate for WAN generally ranges from 33.6 kbps to 45 kbps, approximately a 10th LAN's speed. Propagation delay is one of the biggest problems faced in a WAN. There are losses and these increase with distance.

Although Virtual Private Networks (VPNs) provide reasonable levels of security for business uses, a public internet connection does not always provide the predictable levels of performance that a dedicated WAN link can. This is the reason why fibre optic cables are sometimes used to facilitate communication between the WAN links.

In MPLS and IP VPN environments, where routers and links are often oversubscribed, packet delivery issues can increase as throughput increases, for example. It is common to see averages of 0.5% packet loss with peaks reaching 1%, 2% or even 5%.

Many businesses started using leased line WANs in the mid-1990s as the web and internet exploded in popularity. T1 and T3 lines are often used to support MPLS or internet VPN communications. Long-distance, point-to-point Ethernet links can also be used to build dedicated wide area networks. While much more expensive than internet VPNs or MPLS solutions, private Ethernet WANs offer very high performance, with links typically rated at 1 Gbps compared to the 45 Mbps of a traditional T1. If a WAN combines two or more connection types like if it uses MPLS circuits as well as T3 lines, it can be considered a hybrid WAN. These are useful if the organization wants to provide a cost-effective method to connect their branches together but also have a faster method of transferring important data if needed.

Considering Digital subscriber line (DSL) communication technology, the bit rate of consumer DSL services typically ranges from 256 kbit/s to over 100 Mbit/s in the direction to the customer (downstream), depending on DSL technology, line conditions, and service-level implementation. Bit rates of 1 Gbit/s have been reached.[115]

Considering fibre optic as communication channel, attenuation over a cable run is significantly increased by the inclusion of connectors and splices. When computing the acceptable attenuation (loss budget) between a transmitter and a receiver one includes:

- dB loss due to the type and length of fibre optic cable,

[115] The Next Generation of DSL Can Pump 1Gbps Through Copper Phone Lines, Gizmodo, 18 December 2013, Andrew Tarantola

- dB loss introduced by connectors, and
- dB loss introduced by splices.

Connectors typically introduce 0.3 dB per connector on well-polished connectors. Splices typically introduce less than 0.3 dB per splice. The total loss for typical 1550 nm single mode fibre is approximately 0.4 dB per kilometre.

Economic parameters

The combination of technological advances and a competitive marketplace have greatly reduced the price that IT organizations pay for most of the major components of IT including processing, memory, data storage, and LAN bandwidth. There is no doubt that the price/performance ratio of wide area networking has improved over the last 25 years. In order to quantify the possible WAN price/performance improvements it is important to identify the current price/performance of WAN services. That task is somewhat difficult because the price that IT organizations pay for WAN services varies based on a number of factors, such as how much revenue the IT organization commits to the WAN service provider and the size of the WAN considered. That being said, it is common for IT organizations in the United States to pay roughly US$1,200/Mbps/month for Frame Relay service and US$800/Mbps/month for MPLS. It is also common to pay $500/Mbps/month for Internet VPNs via a Tier 1 ISP if the IT organization uses a T-1 and not DSL for access.[116]

Therefore, it is difficult quantify the economic parameters of WANs but it is necessary taking into account some criteria to start a good economic evaluation.

<u>WANs include high setup costs</u>:

WANs are complicated and complex and therefore rather expensive to set up, especially the first time. It may involve purchasing routers, switches, and extra security software. Obviously, the bigger the WAN, the costlier it is to set up. One reason that the setup costs are high is the need to connect far-flung remote areas.

<u>Mesh Coverage Extension Reduces Towers Costs</u>:

Mesh backhaul greatly increases the coverage radius of a single capacity injection point, thereby reducing the number of fibre sites required to provide broadband services over a given coverage area. Reducing the number of fibre sites required directly lowers lease costs as well as the number of leased or microwave backhaul connections required for each site.

<u>Integrated Backhaul, Mesh, and Base Station Reduces Capital Costs</u>:

The unique integration of a point-to-point backhaul, a multi-hop mesh relay, and a point-to-multipoint base station leads to a significant reduction in network capital costs. Since these distinct functions are not discrete products, there are no additional costs because they are simply integrated into a single networking system. The ability to reuse the radio for different functions by dynamically switching directional antennas lowers the overall costs of deploying broadband wireless.

<u>Automatic Discovery and Automatic Antenna Pointing Reduces Operating Costs</u>:

The ability to automatically discover all nodes and dynamically and automatically point directional antennas leads to a dramatically decrease in operating expenses. Regardless of whether the links are point-to-point, relay, or point-to-multipoint, WAN that not automatically discovers all nodes and not automatically configures each and every link, it can't reduce the operational cost associated with deploying an advanced broadband wireless network.

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[116] J. Metzler, S. Taylor, "*The high cost of wide area networking. New networking technologies such as cloud computing are targeted at reducing the high cost of wide area networking*", Network World, Sept. 2009

Maintenance Issues:
Maintaining a WAN is a challenge. Devices involved in a Wider Area Network Systems are a lot and they are up and operating 24/7. Managers must be able to detect failures before they occur and reduce communication network downtime as much as possible, regardless of the reasons.

Cuts operative costs:
WANs can help for example a company to cut costs and increase profits in a wide variety of other ways. For example, using WAN infrastructure to send email and make video conference call eliminates or significantly reduces the costs of gathering teams from different offices in one location. Saving on the travel costs alone could make investing in a WAN a viable option.

In case of international WAN, it is much more expensive than home or corporate intranets:
WANs that cross international and other territorial boundaries fall under different legal jurisdictions. Disputes can arise between governments over ownership rights and network usage restrictions. Global WANs require the use of undersea network cables to communicate across continents. Undersea cables are subject to sabotage and unintentional breaks from ships and weather conditions. Compared to underground landlines, undersea cables tend to take much longer and cost much more to repair.

Social acceptance among citizens, planners and politicians
Secure control of cyber-physical systems has been a focus area of systems community and citizens in the last decade. Security goals of each system can be categorized into three parts, which include Confidentiality, Integrity and Availability. Most cyber-attacks typically target one of these security goals. A secure control is one that defends against these cyber-attacks and typically includes one or more defence strategies such as Prevention, Resilience, and Detection. The increasing number of network breaches only emphasizes the critical need for encryption. A variety of supposedly secure connections have been spoofed and hacked. Automatic encryption, no matter what the configuration is, is a key contribution to security.

Software-defined networking in a wide area network (SD-WAN) allows for encryption of traffic while taking advantage of cheaper, widely distributed broadband resources.
Connectivity is often managed via virtual private network (VPN—simply a way to create a safe and encrypted connection over a network of lower security). Therefore, to safely transfer data via an unsecured Internet connection, users make use of VPN solutions.

Therefore, benefits can be gained from WAN approach such as:

- centralized IT infrastructure - Many consider this WAN's top advantage. Setting up a WAN simplifies server management, since you will not have to support, back-up, host, or physically protect several units. In addition, setting up a WAN provides significant economies of scale by providing a central pool of IT resources the whole citizens can tap into.
- boosted privacy - Setting up a WAN allows you to share sensitive data with all your sites without having to send the information over the Internet. Having WAN, encrypt data before sending it, adds an extra layer of protection for any confidential material you may be transferring.
- increased bandwidth - WANs often use leased lines instead of broadband connections to form the backbone of their networks. Using leased lines offers several pluses, including higher upload speeds than your typical broadband connections.

Appropriateness by scale
The communication infrastructure is envisioned as a collection of interconnected networks that will be structured into a hierarchy of at least three main tiers or domains:

- Local area networks for the access grid segment and the end customers,

- Field area networks for the distribution segment, and
- Wide area networks for the utility backbone.

A variety of technologies, network topologies and communication protocols are considered for each of these categories. A WAN is a communications network that spans a large geographic area such as across cities, states, or countries. They can be private to connect parts of a business or they can be more public to connect smaller networks together. No matter what the WAN joins together or how far apart the networks are, the end result is always intended to allow different smaller networks from different locations to communicate with one another. Depending on the type of geographic area evaluated, different types of WANs will be most appropriate.

- For Rural areas, a wireless Internet service provider (WISP) is one of the best solutions to adopt. WISPs have a large market share in rural environments where cable and digital subscriber lines are not available; further, with technology available, they can meet or beat speeds of legacy cable and telephone systems.[117] In urban environments, Gigabit Wireless links are common and provide levels of bandwidth previously only available through expensive fibre optic connections.[118] WISP technology may include commonplace Wi-Fi wireless mesh networking, or proprietary equipment designed to operate over open 900 MHz, 2.4 GHz, 4.9, 5, 24, and 60 GHz bands or licensed frequencies in the UHF band (including the MMDS frequency band), LMDS, and other bands from 6Ghz to 80Ghz.
- For urban areas and towns, a wireless wide area network (WWAN) is one of the best solutions to adopt. A WWAN often differs from wireless local area network (WLAN) by using mobile telecommunication cellular network technologies such as LTE, WiMAX (often called a wireless metropolitan area network or WMAN), UMTS, CDMA2000, GSM, cellular digital packet data (CDPD) and Mobitex to transfer data. It can also use Local Multipoint Distribution Service (LMDS) or Wi-Fi to provide Internet access. These technologies are offered regionally, nationwide, or even globally and are provided by a wireless service provider. WWAN connectivity allows a user with a laptop and a WWAN card to surf the web, check email, or connect to a virtual private network (VPN) from anywhere within the regional boundaries of cellular service. Various computers can have integrated WWAN capabilities.[119]

Market readiness and current deployment

To date a number of WANs are already designed, developed and implemented and these are successfully functioning. Some of these WANs were developed to facilitate demand side management (DSM) and smart grids functionality.

There are various options available for the deployment of a WAN network meeting requirements of the smart grid communications, such as all-IP core networks or MPLS-based networks. The fundamental choice that electric utilities are facing is between the deployment of private WANs and the use of public data networks. Several factors are influencing the decision of grid operators and the need of high reliability, security, data privacy, real-time data transmission and low latency are the most important ones, along with the economical affordability. A growing number of utilities are choosing to deploy a private hybrid fibre/wireless network as the backbone for their smart grids.

Another new technology available in the market is the SD-WAN. It simplifies the management and operation of a WAN by decoupling (separating) the networking hardware from its control mechanism. This concept is similar to

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[117] "Meet WiSP", PC World

[118] "Forget Fiber, Monkey Brains Will Bring SF 'Insane' Speeds", MissionLocal. Retrieved 04 March 2016.

[119] Suzhi Bi, Yong Zeng, and Rui Zhang (May 2016) "Wireless powered communication networks: an overview"

how the software-defined networking implements virtualization technology to improve the management and operation.[120] A key application of SD-WAN is to allow users to build higher-performance WANs using lower-cost and commercially available Internet access, enabling users to partially or wholly replace more expensive private WAN connection technologies such as MPLS.

A number of smart grid projects in Europe, such as R2CITIES, SMILE and E-LOBSTER, have developed a cabled or wireless WAN network to facilitate communication between distributed energy resources, the electricity grid and the energy management platforms.

[120] "SD-WAN: What it is and why you'll use it one day". networkworld.com. 2016-02-10. Retrieved 2016-06-27.

19 Power control and conversion – Asset aggregation and virtual power plant (VPP) technology

Leading partner(s) in the technology description: RINA-C

Technical description

The concept of a Virtual Power Plant (VPP) is a robust, centralised, SCADA-linked software tool to assist operation of multiple distributed assets in combination. VPPs comprise an aggregation of distributed energy resources (DERs), which may include conventional generators such as diesel generator sets, dispatchable intermittent generators such as solar PV and wind, demand-side response (DSR) assets such as cold storage and flexible resources such as battery energy storage. The VPP concept is illustrated in the figure to the right[121].

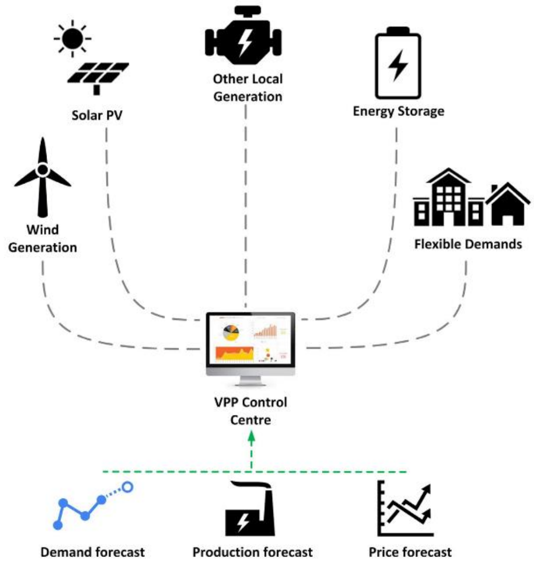

Figure 13: VPP concept.

Common requirements for assets within the portfolio of aggregated assets include flexibility in their net-energy behaviour and remote monitoring and control architecture, to enable response to external signals.

Assets within a VPP generally vary in type, which can be beneficial since limitations in the energy capabilities of one asset type are mitigated by different capabilities of another. For example, grid-interconnected solar PV plants can only provide an infeed of power to the grid when availability of the plant and any behind-the-meter consumption requirements permit. If aggregated with for example demand-side response assets such as cold-loads, the aggregated portfolio's capability to provide a net reduction in load are enhanced. However, a diverse range of asset types within an aggregated portfolio also means that the VPP platform must be able to monitor and collect data from a diverse range of SCADA systems and communication protocols, which differ in architecture and data classification systems. The required technical parameters vary depending on the nature and scale of the assets being aggregated. Key requirements for larger scale VPP assets include the ability to achieve the following points:

- Collect data from all aggregated assets;
    - From a diverse variety of data protocols
    - For each asset, from sources such as;
        - Fiscal meter data
        - SCADA data
        - Online data
        - Standing data
        - Asset forecasts (typically from external sources)
        - Operator accounts/control data
    - With sufficient speed (including processing) to allow short-term forecasting
- Monitor and process data;

[121] G.B. Gharehpetian and S. Mohammad Mousavi Agah: Distributed Generation Systems, Design, Operation and Grid Integration, 2017

- Assess issues such as;
  - Connectivity issues with assets
  - Corrupt data (nonsensical e.g. negative, deviation between SCADA and fiscal meter data (magnitude or time-shift), asset specifications exceeded; some data elements missing etc.)
  - Missing data flagged, and certain missing data is estimated

- Forecast aggregated capabilities of portfolio;
  - Use multiple external forecasts per asset at various intervals, which are generally combined externally to produce combined forecasts per asset
    - Uncertainty statistics calculated, generally presented as visual impact with uncertainty spread around best analytic forecast
  - Create various aggregated forecasts from the combination of external asset capability forecasts and all asset data collected, including;
    - VPP/portfolio-level forecasts
    - Per-balancing area forecasts (if aggregated DERs span multiple balancing zones)
    - Per market forecasts
- Schedule aggregated assets automatically (and manually remotely);
  - Based on merit order of prices, location, asset capabilities
  - Consideration of;
    - Constraints per asset (with constraint categories varying per asset type)
    - External constraints such as network outage and negative pricing
  - Trading
  - Balancing
  - Ancillary services
  - Automatic re-scheduling when required (based on merit order), e.g. for;
    - Unforeseen unavailability
    - Communications outage

Sector integration properties

Depending on their scale, VPPs can be utilised to control and facilitate interactions between asset types including thermal generators, wind power, solar power, hydroelectric, bioenergy, energy storage and demand-side response facilities, to provide diverse services to grid operators and consumers which may not have been possible from individual assets.

Aggregation of multiple assets can allow interactions between entities within networks that would not have otherwise occurred. For example, in the case of aggregated domestic battery energy storage units (or connected EV's), each DER itself comprises a part of an individual home's energy network. When aggregated through a VPP software platform with appropriate back-end communication/control hardware, these DERs can then interact with a wider network, such as the electrical distribution network, in which case the VPP operator would dispatch the VPP on behalf of the distribution network operator (perhaps through an ancillary service agreement with the VPP).

Assets operated as part of VPPs must have contracts between the asset owner and VPP operator. The terms of these bilateral contracts dictate the flexibility that the asset can offer, both to the VPP operator and to the asset owner. For commercial assets intended for the delivery of grid services such as utility-scale battery energy storage assets, it is common for the VPP operator to have the complete flexibility of the asset, with remuneration to asset owners being fixed tariffs based on this fixed flexibility. In such a scenario, the asset owner would assume a passive role of investor and would not be involved in scheduling. This is less applicable to smaller DERs which form part of residential energy systems. Other assets must by their nature offer varying flexibility to the VPP operator, such as cold-storage DSR asset for example. The capabilities that a cold-storage DSR asset can offer a VPP operator depend on a number of factors, such as ambient temperature, chilled stock level and commercial activities. In warm, high stock periods with high commercial activity, a cold-storage asset will have limited flexibility. This division of an asset's flexibility capability between the asset owner and the VPP is critical for integrating DERs with multiple off-takers into VPPs. The topic of contract structures is diverse, with asset utilisation able to be assessed in terms of power and energy utilisation, and utilisation-based remuneration mechanisms being fiscal or energy-based through profit-share or payments between asset owners and VPP operators for example.

VPPs are generally able to be regulated up and down in seconds.

Sizes

There are no technical constraints which impose minimum or maximum sizes for aggregated portfolios of DERs. However, due to the complexities and cost involved, the most widely commercially deployed systems typically aggregated assets of C&I scale and above (i.e. above c. 100 kW). The aggregation of DERs into a controllable VPP is a centralised approach to manage assets. Decentralised management systems such as time-varying tariffs signalled by network operators to residential smart meters can offers an alternative, if less flexible approach to managing smaller scale DERs. However, aggregation platforms which specifically cater for smaller residential systems such as hybrid solar PV-battery energy storage systems are emerging, and a number are already commercially available as discussed below.

Efficiency and loss

Efficiencies of VPP technology itself is difficult to quantify, due to the diverse range of functions and potential variety of assets involved. However, there are a number of potential improvements to wider network efficiencies that can be enabled by aggregation of assets:

- VPPs increase network flexibility, thus deferring and even displacing more costly network management actions and investments. This can translate into consumer savings.
- Beyond providing flexibility, aggregation of assets into VPPs can assist in network operation through simplifying management actions. Even vertically integrated network operators can benefit from VPPs, due to reduced resource requirement for controlling assets integrated in VPPs compared to separate scheduling of many individual assets.
- Strengths of aggregated technologies are combined, and weaknesses can be neutralised.
- VPPs can improve per capacity unit availability and reliability compared to single assets.
- VPPs allow greater market access for smaller assets, providing access to revenue streams which would not otherwise be accessible.

Economic parameters

<u>Capital Investment Costs:</u>

The VPP concept is predominantly a software platform as described above. While additional communications and monitoring hardware is required for assets without pre-existing compatibility, the costs of these will often be included in the service contracts with VPP operators.

<u>Operational costs:</u>

Ongoing operational costs are typically associated with management fees for VPP operators, or platform usage fees for independently operated VPPs. These costs vary greatly depending on the number of aggregated assets, the type of aggregated assets and the required capabilities of the VPP.

<u>Lifetime:</u>

Since VPP technology is a software platform rather than hardware technology, it does not have a finite lifetime.

Social acceptance among citizens

Aggregation of residential DERs presents added complexity when compared to an aggregation of assets which are dedicated to serving the requirements of the VPP operator. Each residential asset's primary purpose of existence is to serve the requirements of the resident, and it is critical that this primary function is not unacceptably compromised by participation in a VPP. Some level of compromise may be acceptable, depending on the incentive mechanism in place to reward the asset owner for granting a portion of the asset's flexibility to the VPP.

Such residential DER's may also form part of home energy management systems (HEMS), which adds a further level of complexity, since participation needs to respect the asset's ability to meet the direct needs of the resident and demands of the HEMS.

Social acceptance among planners and politicians

VPP platforms are a relatively nascent technology, which does not necessarily need additional hardware which would require planning or other consenting processes. There is evidence that the requirement for flexible technologies including virtual power plans is becoming widely recognised. In 2018, the UK and Ireland's Energy Networks Association published a commitment for all distribution network operators (DNOs) to consider demand-side response or flexibility solutions over network reinforcement in all major projects. There has additionally been state foundered projects relating to VPP technology.

In the UK, a 2013 contract award by the UK government's Department of Energy and Climate Change (DECC) to Moixa, which comprised a trial of the Moixa battery system coupled with solar PV across 250 domestic residencies and schools. The Moixa system allows aggregation of the assets to deliver ancillary services, and the project lead to development of their now commercially available GridShare platform; one of the largest domestic VPP resources for residential battery storage systems.

Again, in the UK, the Cornwall Local Energy Marketplace in southwest England has benefited from funding from the European Regional Development Fund under the European Structural and Investment Funds Programme 2014-2020. This project aims to create a virtual marketplace where homes, businesses, renewable energy generators and electricity network owners will be able to buy and sell energy flexibility directly, and includes around 100 residential energy storage systems, 50 businesses and distributed renewable generators. This allows the DSO (Western Power Distribution) to create a bid when a need for market flexibility is forecasted.

Appropriateness by scale

VPP platforms are equally applicable across cities or nations. However, due to the complexity and associated costs, the widest uptake in capacity has been in the utility-scale sector.

Market readiness and current deployment

Most large-scale deployment in the utility-scale DER space, such as by parties such as Limejump in the UK's case, who have 200 MW of aggregated battery capacity. However, residential systems are also commercially available. The following table provides an overview and comparison of a selection of existing DER aggregators and VPP providers.

Provider	**Objective**	**Approximate DER capacity range (kW)**	**Deployment**
Sonnen (Sonnencommunity)	Energy sharing between members	Residential scale battery storage (sonnenBatterie system only)	Commercially available in Germany, Austria, Switzerland and Italy

Sunverge	To make renewable power reliable, economical and accessible to all.	Residential scale battery storage (Sunverge One system only) and above through Sunverge Energy Platform	C. 1000 residential units deployed in South Australia Deployed in Japan
Moixa (GridShare)	Connect storage devises to grids to enable smart energy management	Residential scale battery storage (Moixa and ITOCHU batteries)	Commercially deployed in Japan and UK State-funded project in UK Project with Northern Powergrid (DSO) in UK
Open Utility (Piclo Flex)	Host DSO auctions for flexible capacity	Residential scale and above: battery storage, DSR.	At trial stages with several UK DSOs: UK Power Networks, Scottish and Southern Energy, Electricity North West, SP Energy Networks, Northern Power Grid and Western Power Distribution
Centrica (Local Energy Market)	Local marketplace for homes and businesses within southwest England	Residential scale storage, energy-flexible businesses	Program with funding from European Regional Development Fund, currently limited to southwest England
SolarEdge	Aggregate photovoltaic systems, battery storage, EV chargers, and loads	Residential scale and above.	Not published – relatively new platform.
Limejump	Route to market for assets including Batteries, Chillers, CHP Engines, LFG Generator, AD Generators	Commercial scale and above	Currently approximately 800MW of aggregated capacity in UK, of which c. 200MW is battery capacity
Next Kraftwerke	To network energy producers, consumers and energy storage	Utility-scale	Deployed in Germany, Austria, Belgium, France, Netherlands, Poland, Switzerland, Italy More than 6,800 assets with combined capacity of >5,900 MW
Energy & Meteo Systems GmbH	Direct marketing, remote control and balancing energy	>=100kW	Deployed commercially in Latin America, USA, Germany and South Africa

20 Power control and conversion – Home energy management system

Leading partner(s) in the technology description: RINA-C

Technical description

Home Energy Management System (HEMS) is a collective term that is intended to describe the intelligent control system to manage the energy needs of homes of the future. The HEMS is primarily a monitoring and controlling application that collects real time demand, generation, and storage data from selected appliances within a home and performs control of those appliances based on command signals received either from consumer locally or from utility remotely, or in a more advanced case autonomously – without control from the grid.

The primary use of HEMS is the energy management within a home. It enables energy savings by optimising the home energy consumption and hence customers can save on their energy bills.

However, the electrification of transport (EVs) and heat sector (heat pumps) is expected to more than double the electricity demand at distribution level. The distribution network operators (DNOs) are seeking more and more demand side response services to avoid expensive grid upgrades. In this context, HEMS is getting recognised as a potential enabler for cost effective residential demand side response.

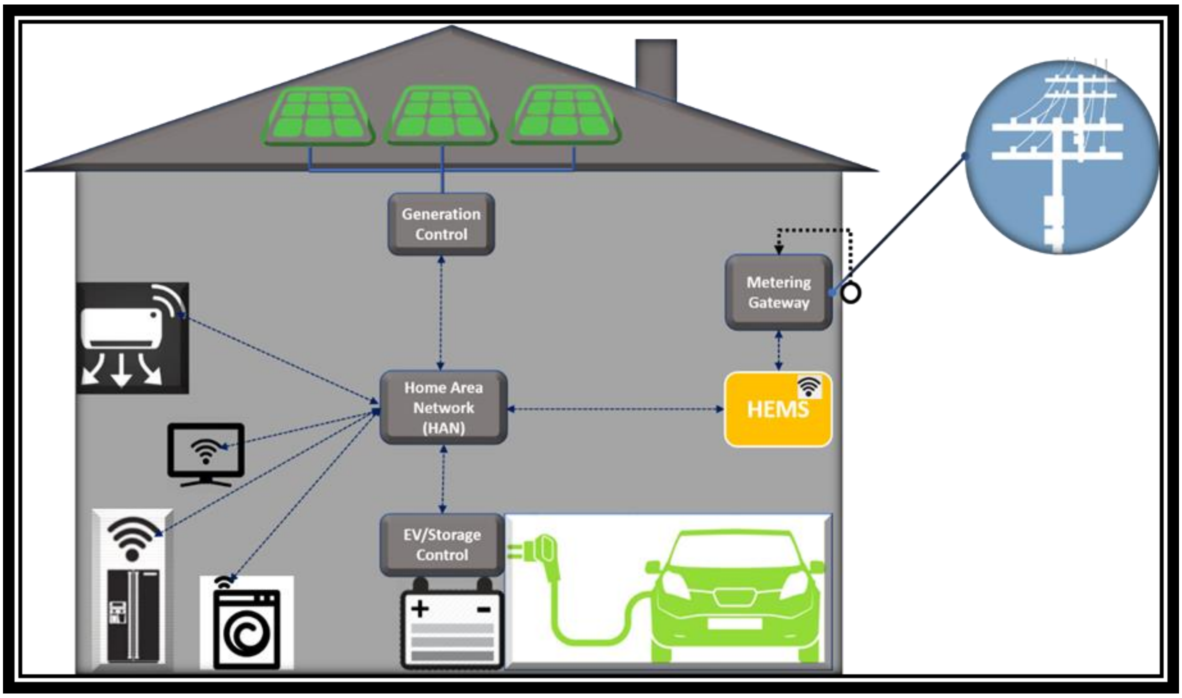

Figure 14: Schematic of a HEMS system and interplay with household energy demands.

Sector integration properties

In the context of a smart grid operation, HEMS enables residential demand side response (DSR). DSR refer to actions taken at a consumer level in response to a signal to change the amount of electricity they take off the grid at a particular time. With more and more consumers becoming prosumers with local generation (such as roof top solar) and storage, the flexibility offered by DSR is improving significantly.

One of the most important smart grid benefits of HEMS is DSR. It is perceived as a critical service which can help reduce grid congestions (or overloads) during peak loads and hence reduce component failure risk and improve supply reliability. HEMS based residential DSR can enable the following smart grid benefits:

Grid constraint management support:
There have been many trials worldwide demonstrating the potential of residential demand side response in managing grid constraints. When grid control detects a potential overload condition developing, it sends a signal to HEMS for DSR support. By either decreasing or time-shifting the demand HEMS supports the grid avoid the overload situation during peak demand conditions. The trials studied in122 have showed how smart appliances, electric vehicles, storage and micro-generation can be combined to manage grid constraints. The study commissioned by DECC investigated many large scale trials across the world and identified that residential DSR based on Time of Use (ToU) achieved a peak demand reduction of as high as 12% and residential DSR based on Critical Peak Pricing (CPP) reduced the 'critical peak' demand by as high as 38%.

Low voltage (LV) grid voltage control support:
With ever increasing penetration levels of roof top solar PV generation LV networks are experiencing large voltage excursions. There is practically no control on the LV grid voltage as the secondary substation transformers typically consist of off-load tap-changers.
The secondary distribution lines are typically of low X/R, this makes active and reactive power less decoupled (unlike in the EHV transmission grid where real and reactive powers are fully decoupled due to the high reactance to resistance ratio of EHV lines). This means the voltage of the low voltage (LV) network can be controlled to a large extent by controlling the active power as well.
It is possible to use HEMS to achieve the voltage control on the LV network by controlling the smart appliances and/or micro generators and/or storage. As demonstrated in trials such as[123], due to large voltage sensitivity factors (0.08-0.16V/kW) for the units at the remote end of LV feeders, where the impact is greater because those networks are more resistive than at high voltages, a headroom of 1% to 2% can be achieved.

Power quality improvement support:
The use of semiconductor-based inverter technology to convert the AC supply to the DC supply required to charge the electric vehicle also creates a number of potential issues. In particular, this conversion can interfere with power quality on the distribution networks due to the creation of harmonic currents generated by high frequency switching. Although currently this problem is not seen to be an issue, with the large-scale penetration of electric vehicles in future it is foreseen that the network harmonic limits on the LV networks may be violated.
HEMS can potentially enable co-ordinated control of EV charging such that network voltage harmonic limits are not violated at any time.

Frequency response service:
It is a well-known fact that with ever increasing levels of intermittent generation the grids across the Europe are experiencing more volatile system frequency. The grid operators are seeking more and more flexible services from generation and demand to manage the minute–to-minute grid energy balancing.
HEMS based residential DSR has the potential of providing cost effective system balancing to counter the influence of intermittent generation.

HEMSs are generally able to be regulated up and down in seconds.

[122] 'Demand Side Response in the domestic sector- a literature review of major trials', by Frontier Economic for DECC, 2012
[123] 'Optimal Solutions for Smarter Network Businesses', Customer-Led Network Revolution Project, http://www.networkrevolution.co.uk/wp-content/uploads/2015/04/OSR-Final.pdf

Sizes
The concept of HEMS is very broad and can cover any number of individual appliances as long as sufficient sensors, controllers and computational power is available. Therefore, at an individual premise HEMS does not pose any size limitations.

Efficiency and loss
Improved home energy efficiency is the basic benefit of HEMS technology. By optimising the energy consumption of home appliances HEMS enables significant energy savings.

In terms of losses, HEMS is a software platform with a limited number of sensors, so energy consumption by itself is very low.

Economic parameters
Basic thermostat control type devices such as NEST can cost around US$250 per device. For more advanced applications, such as DSR and micro-generation/storage control, tailoring of existing HEMS platforms will be necessary and hence costs can vary from application to application.

Social acceptance among citizens
HEMS is basically a software platform that communicates with home appliances, energy supplier and grid operator. In its basic version, HEMS is like an advanced smart meter that informs the customer about their energy usage in real time and also enables some level of control over smart appliances to optimise the energy use to save on bills. This level of HEMS technology is already being in use in many parts of the world.

In its more advanced version HEMS enables control of home appliances, storage and micro generation to support the grid. An incentive mechanism will be in place where the customer gets additional revenues when the HEMS provides a service to support the grid. Many trials have taken place to demonstrate the HEMS based DSR and the general perception is that customers are highly engaged in the process. Concerns regarding the privacy infringements (because of utility interaction) have already been addressed in the case of smart meters and HEMS is no different in that perspective.

Social acceptance among planners and politicians
Being a software platform HEMS is not expected to require planning permission for its implementation. As far as politicians is concerned, again HEMS falls in the category of smart meters and there is already a significant push from most governments all over the Europe.

Appropriateness by scale
HEMSs are primarily appropriate and intended for residential households, however similar control mechanisms can be deployed in industrial or large-scale settings.

The simple thermostat controller type HEMS devices are relatively easy to install and use. For more advanced applications, such as demand side response and micro-generation/storage control some level of bespoke modification of commercially available HEMS platforms would be necessary. HEMS also involves advanced sensors and controllers, and if a household has unusual appliances, finding suitable sensors and controllers can be challenging, if not impractical.

If HEMS requires to support stable running of local LV network, monitoring of secondary substations, owned by the electricity utility company, and communications to HEMS is a basic requirement.

A limitation of current HEMS technology is that they cannot support islanded operation of home energy system that is an autonomous energy system at individual premises. This means, under the scenario of loss of mains due to a fault on the grid, HEMS cannot on its own run the household appliances in islanded mode. Advanced micro grid controllers (like small scale virtual power plants, discussed above) may be required to achieve islanded operation of home energy systems.

Market readiness and current deployment

HEMS is an emerging technology that is being adapted at various levels[124]. For example, in the UK most of the HEMS technologies currently in use are thermal energy controls (such as NEST, HIVE). However, large scale trials are being conducted to test residential DSR through HEMS. In US, platforms such as Tendril are already available commercially that enables HEMS based DSR. Below is a list of most referred HEMS technology providers in the market:

- Tendril[125]: Appliance control, communicates with grid.
- Itron[126]: Appliance control. Communicates with grid.
- Oracle[127]: Appliance control. Communicates with grid.
- NEST[128]: Thermostat control.
- HIVE[129]: Thermostat control.
- Genius Hub[130]: Heating control.

124 https://www.navigantresearch.com/reports/navigant-research-leaderboard-home-energy-managementetwork
125 https://www.tendrilinc.com/solutions/solutions-for-utilities-and-retailers/orchestrated-energy
126 https://www.itron.com/lam/industries/electricity/distributed-energy-management/demand-response
127 https://www.oracle.com/industries/utilities/products/opower-energy-efficiency-cloud-service/
128 https://nest.com/thermostats/
129 https://www.hivehome.com/
130 https://www.geniushub.co.uk/

21 Storage - Communal heat/cold storage

Leading partner(s) in the technology description: GALU and UNIVPM

Technical description

Thermal energy storage is the process of collecting thermal energy from various production technologies for later use, thereby detaching production and demand of thermal energy in time. Traditionally thermal energy storage has stored heat, however cold energy storage technologies are also increasingly being deployed in energy systems.

Thermal storage technologies can be classified under two broad different groups according to the physical medium used to store the thermal energy. Sensible heat storages change the temperature of a medium without phase change, with the medium usually being water in most applications; latent heat storages on the other hand also use the liquefaction/solidification of the medium. The most common type on thermal energy storage uses the sensible heat of water. In its essence, this technology is simply a body of water contained in a tank or other container fitted with inlet and outlet pipes. Utilising water as a storage medium has a number of advantages including a low-price, well-known and accessible, and the possibility to connect directly to heat or cold distribution systems without auxiliary equipment such as temperature-loss inducing heat exchangers.

Latent heat or phase change storage on the other hand use the physical transformation of substances in order to store heat or cold, which can be both inorganic and organic: such as paraffins, salt hydrates and in the case of cold storage also water. While in ice storage there is direct contact between the frozen water and the rest which is still in the liquid phase, this is not the case for other types of substances. In these cases, the phase change material (PCM) is contained in a physical medium (such as capsules of various sizes) for a series of reasons, such as the avoidance of chemical interactions with the surroundings and the increasing of the heat transfer surface.

Thermal storages can be used for a wide range of applications; for storing excess production for later use in combination with different conversion technologies (waste heat, renewable surplus etc.) thus increasing self-consumption capabilities and the share of renewables. Also, it is possible to increase the operational flexibility when coupled with fluctuating user demand, such as for example within district heating/cooling networks. Storage can be performed with different time horizons in mind, typically ranging from a few days to storage for several months (seasonal storage). Short-term storage enables the possibility of shifting production independently of demand for a few days, for example storing excess production on a weekend where the demand usually is lower. Long-term (seasonal) storage makes it possible to exploit seasonal variances in renewable energy production, for example storing excess heat produced by solar thermal collectors during the summer.

Sector integration properties

Thermal energy storages both allow an increase in self-consumption of variable energy sources and also increase the operational flexibility on the production side. Heat/cold storages are a common solution in large district heating/cooling systems for the two reasons just described, allowing both traditional thermal powered plants and renewables to be coupled with unsteady user demands. In most existing systems, the typical applications include seasonal thermal energy storage for solar district heating, CHP optimization, integration of power-to-heat technologies, storage of industrial waste heat, or CCHP applications.

As noted in the literature, thermal storage is orders of magnitude cheaper than electricity storage[131], thus sector

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[131] Energy Storage and Smart Energy Systems - https://doi.org/10.5278/ijsepm.2016.11.2

integration and use of thermal energy storage is of high priority in developing renewable energy-based energy systems where load-following capability becomes an issue.

Response time of heat/cold storage is low and can typically be regulated within few seconds since it is merely a matter of changing the flow direction.

Sizes
Heat storage as a technology covers a wide range of power and storage capacities. Considering only sensible heat thermal storages, the range starts from the needs of single residential households achieved by means of small water tanks (300 litres); to systems in on a scale of several MWh, coupled with district cooling systems or large production plants with capacities of more than 100,000 m^3.

Efficiency and loss
The efficiency of an energy storage system is expressed by referring the combination of the charge and the discharge phase, with a single parameter usually referred to as round-trip efficiency. Considering the three groups of technologies defined earlier in this chapter, the round-trip efficiency can be considered within 50-90% for sensible heat systems and 75-90% for latent heat systems.
Thermal losses incurred while the heat is being stored must also be considered, the degree of which depends on both the insulation of the storage medium itself and the outside temperature. With modern materials like advanced Polyurethane or even vacuum systems the thermal losses can be significantly limited.

Economic parameters
The same storage medium can be used for different systems configuration, with great impact on the costs and the technological solutions to be used. Sensible heat storages can be designed both as insulated steel tanks (more suitable for short term) starting from very small sizes and as underground pits/boreholes (seasonal storages) with much lower specific costs. The costs are also highly influenced by the temperature level of the system; however, the following table presents some general economic figures for different heat storage solutions.

	Sensible Heat[132] [133]		**Latent Heat**	
	Low Temperature	High Temperature	Low temperature	High temperature
Size [MWh]	0 – 15k	350 – 1000	0.01 – 2.5	0.01 -10
Investment [€/kWh]	0.1 – 10	15 - 70	0.4 – 10	20 - 70
O&M [€/kWh/y][134]	0.01 - 1	0.5 - 2	0.01 – 0.3	0.6 - 2
Lifetime [years][135] [136]	20 - 40	30	10-50	30

Social acceptance among citizens
Including heat/cold storage within domestic systems has traditionally not been a high priority, perhaps due to a lack of knowledge on the benefits of storage among the general community. Those who would like to integrate it into their own renewable system may be restricted due the size, and thus investment cost, of storages required for

[132] EASE-EERA, European Energy Storage Technology Development Roadmap 2017
[133] Energinet, Danish Energy Agency. Technology data for Energy Storage. 2018-2019
[134] ETSAP-IRENA, Thermal Energy Storage, 2013
[135] EERA, High Temperature Latent Heat Storage Fact Sheet, 2018
[136] EERA, Low Temperature Latent Heat Storage Fact Sheet, 2018

optimal benefits. When it comes to larger scale systems there is little negative feedback regarding the integration of large thermal stores.

Social acceptance among planners and politicians

Land use and environment aesthetics are known issues and sources of disputes among planners and politicians. This is perhaps to some extent problematized due to a lack of long-term considerations with regards to the advantages of thermal storage in energy system, where politics often focus on short-term benefits.

Appropriateness by scale

As mentioned previously, thermal storage systems can be adapted to any scale, thus in the context of urban multi energy systems they could be deployed from the single unit/building scale to large scale to serve entire neighbourhoods in district heating/cooling networks.

Market readiness and current deployment

The stage of development is not uniform among heat and cold storages. For sensible heat storages, low temperature technologies are already widely available, and a commercial solution used for decades in small systems (home solar thermal applications) throughout Europe, and in small underground systems in northern Europe. High temperature storage is a little behind, with the only technology fully commercially available being storage by means of molten salts coupled with solar thermal plants.

The same trend is observed for latent heat storages, with low temperature systems being already commercially deployed (ice storage for district cooling) while high temperature systems are mostly still at the pilot plant development phase. Still efforts are being made in improving the effectiveness of such technologies by means of control and prediction software.

22 Storage - Communal electricity storage

Leading partner(s) in the technology description: UNIVPM

Technical description

Storage of electricity can be achieved by means of a broad set of technologies, differing in the medium used to store the energy which can be chemical, mechanical, thermal, or magnetic. The range of applications is also broad: electricity storage can provide support in increasing self-consumption of intermittent renewables but also a series of ancillary services such as frequency regulation on different timescales. A general classification can be done by considering electricity storage systems by the power range they can provide and the amount of time this power would be available, meaning the capacity. Power intensive technologies will be more suited to provide balancing services to grids while energy intensive ones will be used mainly to store bulk amounts of energy to perform load levelling or reduce congestion in networks, and finally to back start grids after blackouts in order to improve resiliency.

- Pumped hydro (PHS): Water is pumped to a high reservoir when there is a production surplus or off-peak demand hours, and then retrieve by means of a turbine when needed.
- Compressed air (CAES): Energy is stored as high-pressure compressed air in tanks or underground caves and then retrieved by means of an expander which is a gas turbine. In the expansion phase (discharge) the retrieved air must be warmed up in combustion chambers before being expanded, resulting in CO_2 emissions and contributing to lower the electricity-to-electricity efficiency of the system.
- Flywheel (FES): Energy is stored by accelerating a flywheel powered by an electric motor, stored as kinetic energy of the flywheel and retrieved by means of the same motor acting as a generator.
- Hydrogen (or other power-to-X): More on this in Chapter 12 on electrofuels.
- Lithium Batteries: Lithium-ion batteries are based on electrochemical cells, which are composed of two electrodes (anode and cathode) separated by a porous membrane. Lithium ions migrate through the porous membrane from anode to cathode while discharging (cell attached to a load) and vice versa while charging (cell attached to a power supply).
- Flow batteries: A flow battery system (of which the most common is based on Vanadium, VRF for short) is still based on an electrochemical cell, with the difference in the storing of the two electrolytes, which are stored in tanks. The fluids in the tanks are then pumped in the two sides of the cell, achieving charge or discharge depending on the voltage applied to the electrodes. Differently from Lithium-ion batteries the capacity (size of the tanks) is completely decoupled from power (size of the cell stack), making flow batteries much more adaptable to specific application needs.

Sector integration properties

Electricity storage technologies have no sector integration capabilities by themselves, but they have already shown the capability to help welcome intermittent renewable sources systems on a wide range of system sizes, balancing production and demand. Thus, given that such share of renewable is likely to increase given the decarbonization goals that many countries are pursuing, electricity storage will surely have a key role in upcoming energy systems.

Electricity storage technologies generally have very fast response times and can regulate within seconds.

Sizes

Depending on the technology under consideration storage of electricity can happen at any system scale, both if power and capacity are the goal of the application under consideration. Small battery systems can suit the needs of single residential units (few kWh), but the same technology is expandable to suit the needs of much larger units.

Large capacity systems such as pumped hydro (which is currently the most common electricity storage medium by deployed capacity) can serve the needs of users at a town/regional scale.

	Mechanical storage			**Electrochemical storage**	
	Pumped Hydro	**Compressed Air**	**Flywheel**	**Li-ion batteries**	**Flow Batteries**
Power [MW]	50 - 1000	100 - 300	0 – 1	0.001 - 10	0.1 – 15
Capacity [MWh]	1000+	10 - 1000+	0 – 0.1	0.01 – 500+	1 – 60

Efficiency and loss

The efficiency of an electric energy storage can be defined by its round-trip efficiency: meaning a single parameter taking into account the losses due to both the charging and discharging phases.
It varies among the technologies described, with some of them reaching very high (85-98%) values for the ones with the fastest responses (ancillary services and frequency regulation). Values are lower for bulk storage (CAES and PHS) with values in the 50-85% range, and very low for power-to-X technologies with values in the range 30-45%.

Then the losses which incur during the standby of the system, with the energy already stored. These kinds of losses can be significant, limiting the application range of certain electricity storage technologies to a few days' maximum. This is the case for battery systems (both Lithium and flow) which other than showing a self-discharge due to the non-controlled chemical reactions and the need to sustain the operation of a series of auxiliary systems.

Economic parameters

The following table provides a comparison of costs for different electricity storage technologies.

All data are for 2016/2017 [137] [138]	**Mechanical storage**			**Electrochemical storage**	
	(PHS)*	**(CAES)**	**(FES)**	**Li-ion batteries**	**Flow Batteries**
Capital Cost [€/kWh]	10-10000[1]	650	350	500-1000	600
O&M – Fixed [€/MW/y]	6000-12000	2.20	750	500	2**
Lifetime [years]	30-50	40	20-25	5 - 20	20

*for PHS costs are expressed in relation to the power of the system, not the capacity ([€/MW])
**yearly O&M cost expressed as a fraction of the total investment

[137] I. R. E. Agency, Electricity Storage and Renewables: costs and markets to 2030, Technical Report, 2017.
[138] Energinet, Danish Energy Agency. Technology data for Energy Storage. 2018-2019

Social acceptance among citizens

Many companies have already started to propose electricity storage solutions for individual users, to be sold eventually in combination with a PV system. For example, in Germany a survey[139] showed that the majority of domestic PV system owners are willing to invest in adding a storage system. But in a more general way to date the amount of data and studies regarding the citizens acceptance towards energy storage technologies is still scarce[140]. This results in a feedback gap between policymakers and the public opinion regarding these technologies, which could potentially turn in a barrier towards a wide scale deployment.

Social acceptance among planners and politicians

At a European level the key role that electricity storage will have is recognised, specifically for electricity due to both the increased demand and the switch to electric loads. Still the regulatory framework did not yet change enough to properly welcome these technologies[141]. The highlighted limitations are diverse, ranging from barriers to the deployment of demonstration projects to a lack of appropriate description of what electricity storage technologies are and how they can operate within the already existing infrastructures.

Appropriateness by scale

Depending on the technology considered, electricity can be stored on any scale of capacity, available power and response time. The type of the better suited electricity storage technology depends on such factors but as shown previously there is a type/size of electric storage for any particular application.

Market readiness and current deployment

Market readiness vary among the mentioned technologies: some have been mature for decades while others only recently became commercially available with large penetration. For mechanical electricity storage systems PHS has been used since the early 1900s in southern Europe, while CAES has some successful applications (not only in Europe) but only at the pilot plant stage. Flywheel storage systems are also commercially available but with costs that are still to lower in order to be competitive with other technologies with the same application characteristics (batteries).

The market of electricity storage systems appears to be particularly favourable for Lithium-ion batteries, which are undergoing significant technological development also thanks to the push from the automotive industry, with prices per kWh of stored electricity projected to drop as low as US $100[142]. Forecasts indicate also a huge deployment of battery capacity worldwide.

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[139] Gährs S, Mehler K, Bost M, Hirschl B. Acceptance of ancillary services and willingness to invest in PV-storage-systems. Energy Procedia 2015;73:29–36. doi:10.1016/j.egypro.2015.07.554.

[140] Devine-Wright P, Batel S, Aas O, Sovacool B, LaBelle MC, Ruud A. A conceptual framework for understanding the social acceptance of energy infrastructure: Insights from energy storage. Energy Policy 2017;107:27–31. doi:10.1016/j.enpol.2017.04.020.

[141] EASE-EERA, European Energy Storage Technology Development Roadmap 2017

[142] BNEF, Lithium-ion Batter Costs and Market, 2017

23 Storage - Gas storage

Leading partner(s) in the technology description: ASTEA

Technical description

Storage of natural gas is usually achieved at very high scales (regional/national level), in the order of several millions of cubic meters. This is done in pressurized cavities, such as depleted gas reservoirs, aquifers and salt caverns. These kinds of storage are mostly used in combination with the main high-pressure gas distribution networks, in order to behave as a buffer between a steady gas inflow and a non-regular withdrawal from the smaller networks that ultimately deliver to the final users. Thus, the usage is mostly for seasonal use and backup supply in case of emergencies.

The pressure level of the storage is in the range 90-150 bar, and to some extent a degree of pressurization has to be maintained to assure the proper functioning of the reservoir. This implies that part of the stored gas cannot be used (cushion or base gas), with its value depending on the type of reservoir being used, ranging from 30% for salty caverns to 50% for depleted gas fields.

Sector integration properties

These kind of storage technologies only allow for the storage of methane which comes from deposit sites. Given the compliance with strict quality requirements it is possible to inject methane produced by other processes, such as anaerobic digestion, but this is usually done within the lower pressure distribution networks.

Gas storages are able to respond to load changes within seconds.

Sizes

In Europe there used to be a kind of communal urban gas storages, commonly known as gasometers, which were mostly used to store a mixture of gases to be used for public lighting and as short-term gas reservoirs for peak requests. This kind of storage has been mostly abandoned since the widespread diffusion of the natural gas infrastructure; therefore, today natural gas is now mostly stored only in very high volumes with the technologies described above.

Efficiency and loss

Underground storage of natural gas can be considered without significant storage loss, supposing the storage site has been properly investigated from a geological standpoint. Losses are to be taken into account in the depressurization phase, with part of the gas that is to be burned in order to cope with the resulting cooling, and in the compression phase. Thus, this is to be accounted to in the network infrastructure.

Economic parameters

The costs for large scale gas storage systems vary depending on the technology and on the particular scenario under consideration, one example being re-use of depleted reservoirs, but further depends on geological characteristics of the site, and whether it is onshore or offshore etc.

A more precise cost estimate can be done for salty cavern storage, still by considering from a small number of projects. The costs shown in the table refer to a cavern of 100 million Nm3 of storage capacity, with an injection and withdrawal rate of 200 thousand Nm3/hour and 600 thousand Nm3/hour respectively and with a yearly working gas volume of approximately 500 million of Nm3[143].

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[143] Energinet, Danish Energy Agency. Technology data for Energy Storage. 2018-2019

	Salty cavern storage
Investment – cavern establishment [M€]	36
Investment – process equipment [M€]	63
O&M [M€/y]	6.5

Social acceptance among citizens

As explained underground gas storage is mostly tied to the infrastructure related to the bulk of transportation of natural gas, which is achieved with the biggest branches of the gas transmission network. For these reasons average citizens do not have a proper knowledge of where and how natural gas is stored.

Social acceptance among planners and politicians

Large-scale natural gas storage has been a technological solution for decades, thus the efforts in policymaking regarding the natural gas industry are now focusing not on the technology itself, but in how to increase the knowledge and awareness towards its benefits[144].

Appropriateness by scale

Gas storage systems have a scale which is mostly relevant at a national/regional level, but if needed is possible to deploy small tanks for individual residential units, as for example in rural settings.

Market readiness and current deployment

Natural gas storage is an established technological solution, which is well-integrated within the European natural gas infrastructure. Considering both the reservoirs which are already operational and the ones which are still at the planning/construction phase the European gas storage capacity is around 2000 TWh of working gas, with a withdrawal capacity of 30 TWh per day[145].

[144] GIE, The value of gas storage – question and answers, 2015

[145] GIE, Storage Database, 2018

24 Storage - Smart electric thermal storage (SETS)

Leading partner(s) in the technology description: GDHVI

Technical description

Smart electric thermal storage (SETS) is based on the existing technology of traditional night storage heaters, designed to reduce the large differences in peak and off-peak electricity demand. Traditional night storage heaters have an insulated thermal core that stores heated during the night (to avail of more abundant low-cost energy), and then releases it during the day (when demand and prices are higher). The SETS system is more flexible in that it allows the core to be charged at any time, to suit electricity grid conditions, as well as offering end-users more control over the release of this heat and potential costs savings with efficiency gains compared to traditional night storage heaters.

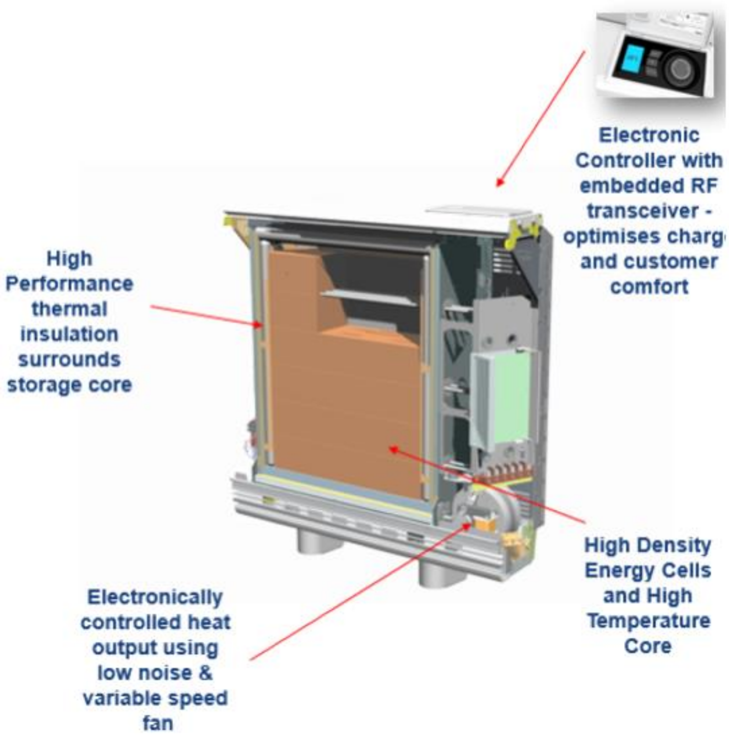

Figure 15: SETS concept illustration.

As apparent from the previous illustration, the key components of SETS systems are high performance insulation material, a high temperature core, and smart electronic control systems, enabling efficient charging and discharging.

The primary benefit of SETS solutions is the potential for adjusting according to changing heat demands throughout the day or adjust based on time-of-use electricity tariffs or fluctuating electricity prices to lower operation costs. This principle is illustrated in the following figure.

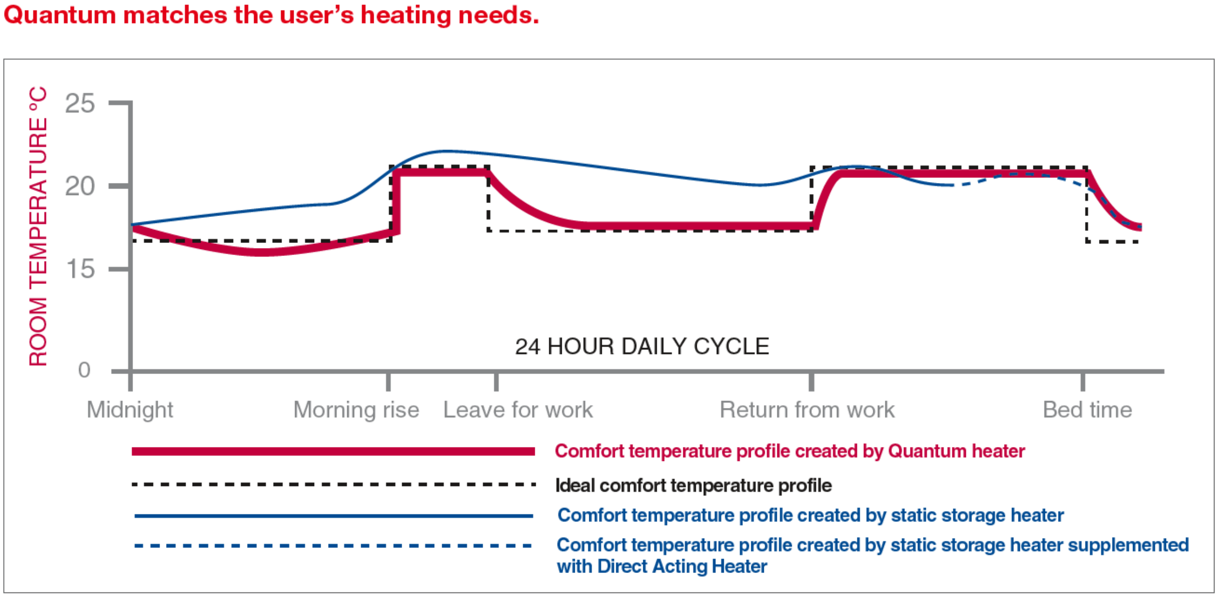

Figure 16: SETS heating cycles to adjust temperature level.

SETS solutions allow for flexible operation and thus energy savings, e.g. by lowering heat consumption during the day when residents leave the house for work, and by lowering heat consumption during the night, when lower temperatures typically are acceptable.

Sector integration properties

Smart Electric Thermal Storage (SETS) are space heating and hot water systems, designed for smart grid integration, that offer the following to the end user and system operator:

- Lower cost
- Increased comfort
- System control
- Reduced carbon emissions

In addition to these benefits to the owner, SETS could prove to be a valuable from a system perspective in the integration of variable renewable energy because of the ability to charge during hours with lower electricity prices. Low electricity prices are often a result of high production from renewable energy sources such as solar and wind and having flexible storage options such as SETS assist in balancing the energy system. Furthermore, SETS provide an opportunity for coupling the electricity and heating sector.

The following figure illustrates the role of SETS as a source of heat based on renewable fluctuating electricity supply.

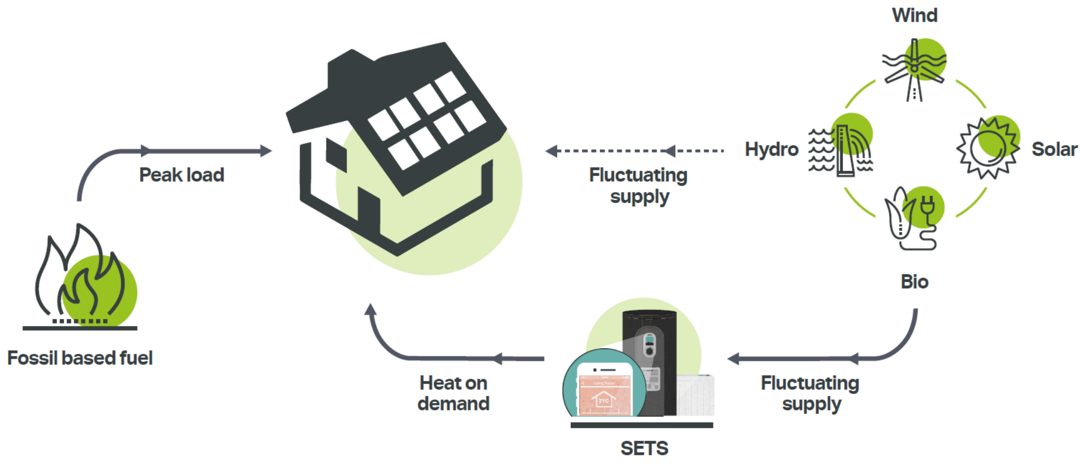

Figure 17: Schematic of SETS as a potential for integration of fluctuating renewable electricity.

Integrating fluctuating renewable energy is an important challenge for future renewable and smart energy systems, and thus the ability of SETS to couple the heat and electricity sector could prove to be very important.
SETS technologies can regulate their output within seconds.

Sizes

Charging inputs range from 1.1 to 3.3 kW and output from 0.5 to 1.5, with maximum storage capacities ranging from 8 kWh to 23 kWh. Volumes for water heating cylinders range from 125 L to 300 L.

Efficiency and loss

The efficiency and loss of SETS heating systems depends heavily on the insulation and energy efficiency of the household in which it is installed within. Based on UK governmental assessment standards and assumptions, space heating in three different property types with a Quantum SETS heating system was compared to traditional direct acting heaters such as electric radiators. The assessment found that on average, the SETS heating solution was able to reduce running costs by 44-47% due to exploitation of reduced tariff rates during night time [146]. Space heating requirements were based on average weather conditions for Northern Ireland.

Economic parameters

Investment costs for Quantum 8-23 kWh SETS systems range from 800-1150 €[147].

Social acceptance among citizens

SETS is a fairly unobtrusive and uncontroversial technology in many regards and will thus likely face complicated issues with regards to social acceptance among citizens. Some of the strengths of SETS solutions from the perspective of end-users are listed below:

- Uses low-cost, low-carbon, future-proofed technology.
- Completely automatic once set up.
- Economical to run, helping to alleviate the increasing problem of fuel poverty.

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[146] https://www.dimplex.co.uk/sites/default/files/assets//Quantum_Consumer_Brochure.pdf
[147] https://www.dimplex.co.uk/product/quantum-heater-qm150

- Offers improved comfort levels, heating only when required.
- Low maintenance.
- Accurate room temperature control with a thermostat accurate to +/-0.3°C.
- Responsive to changes in external temperature.

The three-year Horizon 2020 RealValue project which ran from June 2015 to May 2018 involved physical demonstrations of Smart Electric Thermal Storage (SETS) space and water heating systems in around 750 properties (domestic and non-domestic) across trial sites in Ireland, Germany and Latvia. Using these physical demonstrations, combined with advanced ICT and innovative modelling techniques, RealValue has been able to prove that an aggregated population of SETS can bring benefits to all market participants.[148]

RealValue carried out extensive consumer engagement studies in order to develop an overall picture of acceptance to SETS, and in particular when used as part of a connected smart system for DSM purposes. The central themes of this study were cost, comfort, and control. The findings are detailed in the Consumer Impact Study entitled 'Getting the balance right: Can smart electric thermal storage work for both customers and grids?' [149]. See also the 'Customer Testimonial Video'[150] which features first-hand feedback from end-users involved in the demonstration.

Social acceptance among planners and politicians
Alike the direct electric heating technology described in Chapter 11, SETS relies on direct conversion of electricity to heating and as such the reservations with regards to efficiency are also relevant to SETS.

Appropriateness by scale
The SETS is currently applied in home systems.

Market readiness and current deployment
The SETS is market-ready and available. In countries with high shares of electricity for heating SETS will be more relevant compared to countries with low shares of electricity for heating. However, existing prevalence of storages also influence expected adoption of SETS solutions, since households with existing storage capacity have less incentive to invest in SETS.[151]

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[148] Role of SETS in evolving European energy system - http://www.realvalueproject.com/images/uploads/documents/Role_of_SETS_in_Evolving_European_Energy_System.pdf
[149] Getting the balance right: Can smart electric thermal storage work for both customers and grids? - http://www.realvalueproject.com/images/uploads/documents/D5.3_RealValue_Consumer_Impact_Report_-_FINAL_%28Compressed_spread%29_.pdf
[150] Real people - real perspective - https://www.youtube.com/watch?v=d2G882wONO0&t=9s
[151] Role of SETS in evolving European energy system - http://www.realvalueproject.com/images/uploads/documents/Role_of_SETS_in_Evolving_European_Energy_System.pdf

25 Grids - Electricity

Leading partner(s) in the technology description: ASTEA

Technical Description

Electricity grids consist of the infrastructure delivering electricity from the producers to the final users. Distribution is achieved under different ranges of voltage on the connection cables, with the distribution at a local level achieved in Medium Voltage (10 – 60 kV) and Low Voltage (400 V). Connection between different voltage levels is done by means of transformer cabins. The transmission of electricity is achieved in AC, with DC transmission having applications only for very long distances (over 600 km).

The electricity distribution grids can be separated into two broad categories: overhead and underground lines. Key differences in the two solutions include costs, visual impact, and reliability. Typically, underground lines will be preferred, however local context can make underground lines infeasible, and often it is also more expensive.

Sector integration properties

Electricity grids have a crucial role in renewable and smart energy systems due to the need to link different technologies that might be spatially dislocated. As for example transferring electricity produced in both renewables and fossil fired systems to electric vehicle charging stations, thus effectively contributing in achieving multi energy sector integration.

Electricity grids are able to respond to load changes within a second.

Sizes

Electricity grids can be used to transmit electricity with power ranges of several MW, depending on the size of the conducing cable used.

Efficiency and Loss

Long distance transportation of electricity by means of electrical cables can occur with efficiencies around 97-98%. This can be even higher for distribution at a local level.

Economic Parameters

	Overhead Lines	**Underground Lines**
Efficiency [%]	98	98
Investment costs [€/m][a]	35 - 50	65 - 120
O&M costs [€/m/y][152]	1.5 – 3	1.5 - 3
Technical lifetime (years)	40-60	40-60

[a] Investment costs consider both the costs for the material and the installation.

The costs for the system can be mainly distinguished in overhead and underground lines. Costs vary due to different technical parameters for the grid-line, such as the cable number and diameter and the number/type of cabins needed.

For underground lines also the costs vary in consideration of the environment where the line is to be deployed, which implies a different complexity for the needed works: from rural environments to cities. The O&M costs are mostly related to occasional malfunctions then a regular maintenance practice, and for the same reason the lifetime of system varies widely depending on the particular application under consideration.

[152] Energinet, Danish Energy Agency. Technology data for energy transport. 2017

Social acceptance among citizens
Electricity grids are the main medium for electricity distribution in developed countries and are thus widely accepted. While overhead lines are a very common solution for high voltage transmission over very long distances in the countryside this might not be a viable solution for urban areas, thus forcing the choice on underground cables. Social acceptance is generally higher for underground high voltage power lines compared to overhead lines, as indicated in a study from Switzerland[153]. It was also found that thorough information on the differences between the two technologies and possible drawbacks were able to decrease the perceived differences.

Social acceptance among planners and politicians
The technology forms the backbone of the current electricity distribution system, thus widely accepted by planners and politicians, with a preference towards distribution by means of underground lines in urban contexts for increased reliability reasons.
This kind of systems will still go major changes in the upcoming future, due to the embracing of the smart grid paradigm. The efforts in policymaking will then be focused on facilitating demand response programs and energy storage deployment, thus not directly aimed at the distribution infrastructure itself.

Appropriateness by scale
Transmission and distribution of electricity by means of grids is already in place on every developed country worldwide. The used technology is basically the same both for withdrawing power from the main producers and for delivering it to the final users.

Market readiness and current deployment
The distribution of electricity by grids is already a well-established technological solution, with little marginal improvements to be made regarding the actual systems (cables, transformers etc.) in costs and performance.

[153] Public acceptance of high-voltage power lines: The influence of information provision on undergrounding - https://doi.org/10.1016/j.enpol.2017.10.025

26 Grids - Gas

Leading partner(s) in the technology description: ASTEA

Technical description

Technically, the distribution structure consists of the set of delivery points (regulation and measurement stations) and/or connection points, the network itself, and the utility distribution plants to the end customer supply points. In gas networks the pipelines connect the point of extraction or storage of natural gas, to the final users: both residential, industrial and electricity generation plants. The distribution system is similar to the electricity one, with the national transmission of natural gas in high pressure, and regional/local distribution in medium and low pressure. Particularly, national transmission lines link the extraction point with the regional distribution, located in the areas with a relevant natural gas demand. Similarly, regional distribution networks guarantee the natural gas transport in a widespread manner throughout various region and are linked to the national transmission. The interconnections between the regional distribution and local distribution is realized through the reduction and measurements cabins, where the gas is recognized and odorized (natural gas would be odourless otherwise), and the gas pressure is reduced from 50-60 bar (transmission in high pressure) to 12 bar (distribution in medium pressure). Then passes through another cabin, where the gas pressure is reduced from 12 bar (medium) to 0.5 bar (low) before being delivered to the final users, the gas pressure is furtherly reduced to 0.02 bar[154].

In addition, biogas can be injected in the distribution line, only after being treated to reach a level of purity which is regulated by agreed standards. Thus, distribution network has continued to expand to provide natural gas service to new commercial facilities and housing developments.

The following table shows the Italian classification classes of the networks for the transport and distribution of gas, based on the operating pressure.

Category 1	Pe > 24 bar	High pressure
Category 2	12 bar < Pe < 24 bar	
Category 3	5 bar < Pe < 12 bar	
Category 4	1,5 bar < Pe < 5 bar	Medium pressure
Category 5	0,5 bar < Pe < 1.5 bar	
Category 6	0,04 bar < Pe < 0.5 bar	
Category 7	Pe < 0.04 bar	Low pressure

Sector integration properties

Natural gas network transport natural gas from the storage sites to ultimately the final users, but as explained they also allow for the injection of other gases: such as gas derived from biogas and to some extent also hydrogen[155]. The sector integration properties then lie in the possibility of integrating a mostly already existing infrastructure with a series of novel technologies, which are supposed to be of great importance in the upcoming future being mostly green and distributed technologies.

To this has also to be added the fact that given the urgent decarbonization targets the bulk of the fossil-based electricity production will probably migrate to natural gas-powered solutions while carbon is phased out in the near future.

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[154] ACEA, Il gas Metano, 2012

[155] NREL, Blending hydrogen into natural gas pipeline networks: a review of key issues, 2013

Gas grids are able to respond to load changes in seconds.

Sizes
The size of the pipes depends on their function: the main transmission lines have a diameter that can be from 16 to 36 inches or more (most of the interstate lines are between 24 and 36 inches); lateral pipelines, which deliver natural gas to or from the mainline, are typically between 6 and 16 inches in diameter.
Transmission lines can deliver power up to more than a thousand MW, while smaller distribution networks deliverable powers are usually in the order of hundreds of MW. Finally, the smaller branches which connect directly to the smallest final users are in the order of on hundred kW.

Efficiency and loss
Natural gas transmission and distribution pipeline is a proven and efficient technology. Various systems for network monitoring have already been developed, and they are able to guarantee their safety and efficiency. During the construction and maintenance operation, losses occurs in terms of efficiency and environmental impacts are rare gas leakage and CO_2 emission for preheating at the decompression stations, where part of the natural gas has to be burned in order to compensate for the temperature decrease.

Economic parameters
Costs differ depending on the scope of the particular branch of the network and on other aspects such as the need to be underground or not. Typically, transmission lines are realized by strong carbon steel material. All the pipes are tested to ensure that they meet the pressure and strength standards for transporting natural gas. Larger diameter steel pipes are produced by folding sheets of metal, ends welded together to form a pipe section and the smaller diameter pipes can be produced seamlessly. Some distribution pipes are made by highly advanced plastic, in order to meet the need of flexibility, versatility and the ease of replacement.
Also, plastic materials such as polyethylene can be used, with the latter only used for distribution networks.

Carbon steel	**Transport pipeline**	**Distribution pipeline**	**User connections**
Size [inch]	12”- 36”	<10”	<6”
Investment cost [€/m]	84 - 325	15.6 - 70	7 - 38
O&M cost [€/year]*	30%	30%	30%
Lifetime [years]	50	50	50

**O&M cost, they are estimate on the cross-check of some transport and distribution utility data, and they are referred (in percentage) to the total cost of service. These are dependent on the following parameters: maintenance (cost of electricity, electric or otherwise, for the operation of pumping and heating systems), emergency response, management, network planning and both control and operational switching, quality and standard functions, network monitoring systems and other variable costs.*

Polyethylene	**Distribution pipeline [**	**User connections**
Size [inch]	<10”	<6”
Investment cost [€/m]	4 - 80	2 - 45
O&M cost [€/year]*	30%	30%
Lifetime [years]	50	50

Social acceptance among citizens
Natural gas has been used by European citizens for more than a century for space heating, hot sanitary water and cooking, and thus it’s supposed to be widely accepted as a resource. The existing infrastructure is usually well integrated within the already existing urban scenery, so it can be stated that natural gas distribution infrastructures are widely accepted among citizens.
Still some protests have been raised regarding large projects, as for example in Italy regarding the construction of a new large pipeline in the south, which has encountered protest from local authorities mostly supported by citizens. The concerns regarded the safety of the environment due to the construction process and on the economics of the project, protests which ultimately led to a review of the project by the central government.

Social acceptance among planners and politicians

Given the advantages of being a clean, abundant, flexible, and cost-effective fuel, and which is expected to overtake coal as the second leading source of energy by 2040, natural gas is widely recognized by policymakers as a key element in the upcoming energy transition phase. Natural gas consumption has already been increasing steadily in the past years, reaching a 3.7% increment in 2017.

The priorities in policymaking are diverse depending on the geographical areas under consideration. For Europe these have been indicated as ensuring a cost competitiveness versus coal and renewables from an economic standpoint, while diversifying the portfolio of suppliers in order to be resilient from a geopolitical point of view and the facilitation of the deployment of low carbon applications.

It is due to cost competitiveness, security of supply and environmental sustainability. Cost competitiveness is regulated by policies via price regulation, taxation and upstream access; supply security is directly affected by governments on how and where gas infrastructure will be developed; the last one, environmental sustainability, policies guide the future emissions trajectories and the role that gas can play to reduce them.

Planning and realising grid development projects is often difficult and time consuming due to local opposition, complex permitting procedures and the challenges of minimising impacts on nature and communities. Still, national governments lack the political will of pushing for a step which would spell the end for their residual control of national energy markets. In a fully integrated European gas market with a consistent grid, planners have no legal nor physical boundaries, national regulation and state ownership in energy companies, so they are eventually deprived of their original rationale. However, a successful scale-up of renewable gas production requires policy support, such as the introduction of a 10% target for renewable gas by 2030.

Appropriateness by scale

Gas distribution network can adapt to different scales depending on the pressure level in the duct and its diameter. High pressure lines can deliver directly to large consumers such as industries or electricity generation plants, while smaller parts of the network can branch directly to residential buildings such as individual units.

Market readiness and current deployment

As mentioned, a widespread natural gas infrastructure is already in place throughout Europe, it's composed of well-established technologies which are not supposed to undergo major technological advancements in the near future. Still the network is expanding, also to embrace the upcoming phase out of coal as a fuel of electricity generation, with many new projects being realized[156]. As an example, recently one of the bigger projects was Europe's Nordstream pipeline[157], which added 55 bcm (billion cubic meters) of transmission capacity from Russia to Europe via Germany.

[156] GIE, Investments in Infrastructure in Europe

[157] SNAM-ICU-BCG, Global Gas Report 2018

27 Grids - Heating/cooling networks

Leading partner(s) in the technology description: ASTEA

Technical description

District heating/cooling networks allow the distribution of centrally produced heat or cold over long distances, up to several km by means of insulated pipes usually filled with water. The pipes of the main network (transmission) get the heat or cold to substations, where heat exchangers transfer the commodity to a second smaller network (distribution) or directly to single buildings, to be integrated with already existing climatization systems or in the case of heating also for the production of hot sanitary water.

The benefits of both the two technologies lie in the increased efficiency of production, which is done in large centralized plants instead of small individual units, leading to significant savings in CO_2 emissions. There is also flexibility regarding the primary source of the commodity being produced. In the case of heating the source could be waste heat from industrial processes or electricity generation (CHP), which can be powered by different types of fuel (including biomass for example) or also in large centralized boilers or electric compression heat pumps. Also, in the case of cooling different technologies can be used, again compression heat pumps or also absorption heat pumps using waste heat (CCHP).

Sector integration properties

As for electric grids, district heating and cooling distribution are not apparently linking any energy sector, but their existence allows for the coupling of different heating/cooling generation sources with the thermal demands of final users which otherwise would not be within reach.

Heating/cooling networks can respond to load changes in seconds.

Sizes

District heating networks can deliver thermal power from plants up to hundreds of MW. The distribution grid, delivering heat to the end users can have branches for small amounts of power down to a few kW for a single user.

Efficiency and loss

While as explained the centralized production of heating/cooling generally allows for better conversion efficiencies the distribution of heat implies thermal losses. These losses can range widely due to several parameters: the water pipes and external ground temperatures, the length of the network, and the conditions/technology of the pipes themselves. Losses can range from 5% to 50% for very poorly maintained networks for district heating[158].

Economic parameters

Costs vary with distance and power to be delivered, meaning the diameter of the actual pipes, and on the type of the conditions of the soil the pipes have to be buried in, as for example rural area and already urbanized area. The costs can be distinguished among the end uses, transmission or distribution networks (for urban areas)[159].

	Transmission network			**Distribution Network**
Power Range [MW]	0 - 50	50 - 250	250 - 500	0 – 0.35

[158] Energinet, Danish Energy Agency. Technology data for energy transport. 2017

[159] Energinet, Danish Energy Agency. Technology data for energy plants for electricity and district heating generation. 2016-2019

Technical lifetime [years]	40	40	40	40
Investment costs [€/MW/m]	25	11	6	400
O&M costs [€/year]	NA	NA	NA	NA

Social acceptance among citizens
Reception among citizens has mixed traits even given the efforts among local authorities to increase the public awareness of economic and environmental benefits of district networks. Still in some cases these are perceived as old and obsolete technologies as for example when heat production is involved, due to the production of such heat still being based on fuels being burned[160]. As an example, for cooling buildings, owners/managers rarely have awareness regarding the electricity consumption due to the sole climatization, which usually comes included within the electricity bill. In these kinds of situations, the economic benefits of using district cooling is often not fully understood[161].

Social acceptance among planners and politicians
District heating and cooling networks are widely accepted given their ability to both lower overall emissions due to the increased efficiency (also enabled by the exploitation of CHP/CCHP technologies), and also move them away from urbanized areas and concentrate them in specific sites, which can be more efficiently managed and controlled[162]. But it has shown that so far, the adoption of district networks has been driven mostly by local dynamics, with local authorities acting driven pursuing economic and environmental benefits without being supported by a proper policy scheme.
The high-level policymaking cannot aim at regulating the district heating and cooling market directly as done for gas and electricity supply, but still potential policy improvements are achievable. The adoption would be still mostly driven by local initiatives, but these could be provided of benchmarks and best practices in order to facilitate the adoption. It is also showed that the adoption of district heating and cooling systems are tightly connected to the adoption of CHP/CCHP on large scales, therefore the policy efforts should also be focused in facilitating the diffusion of such technologies[160].

Appropriateness by scale
This technology can be adapted to a variety of different scales, as mentioned regarding the range of power than can be generated in the centralized heating or cooling production plants. A district heating/cooling system can be deployed to serve a district of the size of a few buildings, to large urban districts of several thousands of inhabitants.

Market readiness and current deployment
While both district heating and district cooling are mature and commercially available technologies, the latter is less widely diffused in Europe, principally due to a later development (also of the generating technologies) and due to a smaller demand by final users compared to heating.

They are both mature technologies with several applications mainly concentrated in Europe, with a high degree of adoption especially for satisfying the heating demand in Nordic countries. Also, district cooling networks are being

[160] Galindo Fernández, M., Roger-Lacan, C., Gährs, U., Aumaitre, V., Efficient district heating and cooling systems in the EU - Case studies analysis, replicable key success factors and potential policy implications, EUR 28418 EN, doi: 10.2760/371045
[161] RESCUE Project, Cool Conclusions – how to implement district cooling in Europe, 2015
[162] Werner, S. (2017). International review of district heating and cooling. Energy, 1–15. https://doi.org/10.1016/j.energy.2017.04.045

adopted especially in the southern countries, mostly for user demands of the tertiary sector (hospitals, universities etc.) and large-scale consumers in general.

An example of a district network serving only heating is in Gram (Denmark), a relatively small system meeting the heating needs of approximately 2,500 people. The network is heated up by a series of different systems: such as solar thermal panels (44,000 m^2, supplying the majority of the demand), a 10 MW electric boiler fed by grid electricity, waste heat from two CHP gas engines, a 5.5 MW natural gas boiler, a 900 kW heat pump and 2 MW of waste heat recovered from industrial usage. To optimize the production from the solar plant a sensible water heat storage of 8,500 MWh is used. The system allows to meet a demand of 20 GWh of heat per year totally. Another example, with both a network for district heating and cooling, is situated in Brescia (Italy). The district heating network serves the needs of more than 20,000 buildings, mostly residential, while the district cooling network is used to meet the demand for a hospital and a university.

Some research is still going on regarding the range of temperature levels for the network, as for example Low Temperature District Heating (LTDH) and Ultra Low Temperature District Heating. This in order to extend the span of possible heat generation technologies to produce the heat.

28 Designing multi-energy grids

Leading partner(s) in the designing multi grids guide: RINA-C

Multi-energy systems operating within a defined boundary have the opportunity of advantages in efficiency, flexibility and reduced environmental impact. Multi-energy grids can enable a wide range of energy sources including renewable and non-renewable types, as well as interactions between energy demands, and the availability of complimentary energy sources and technologies can provide improvements in energy security, reliability, efficiency, economy and sustainability.

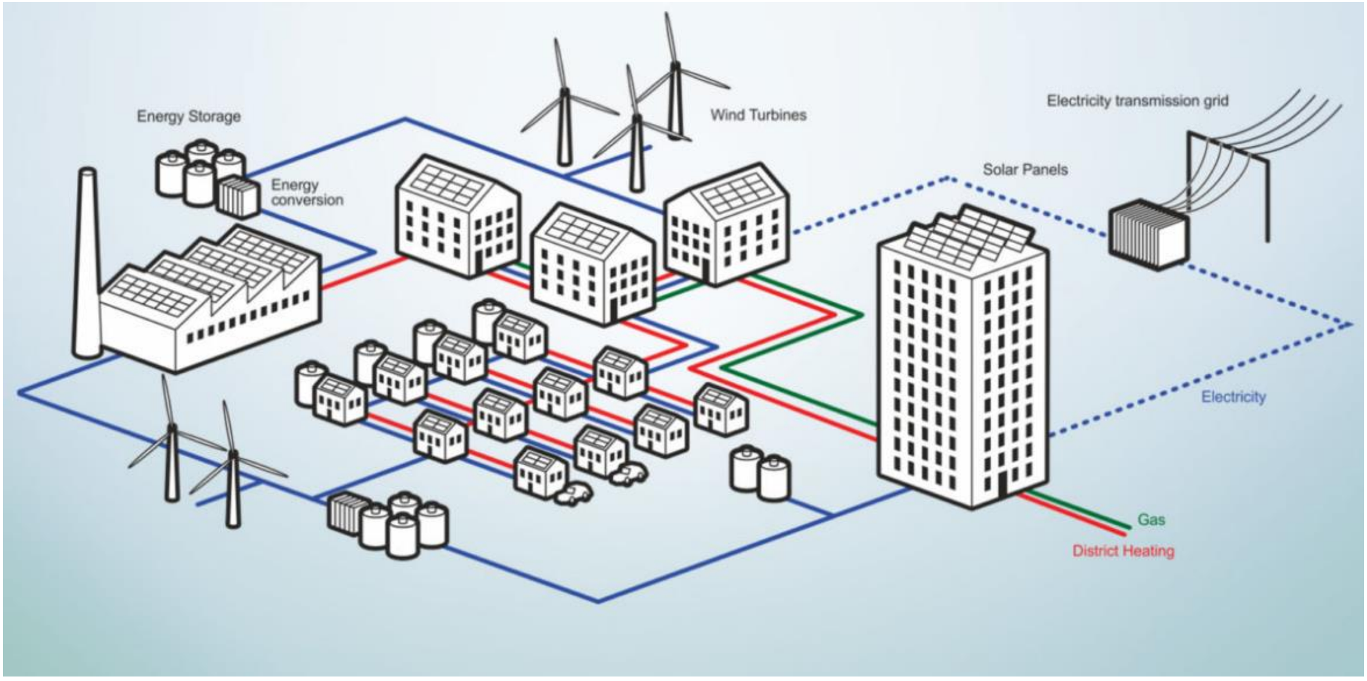


Figure 18: Typical elements of multi grid energy systems.

The planning and implementation of multi-energy grids to serve discrete areas of population requires a wide range of variables to be considered at the planning and design stage. The following lists some examples.

- Heating, cooling and electricity load profiles (sub-hourly, daily, seasonal, annual) – current and future, including from buildings, supporting urban infrastructure and transport systems.
- Heating and cooling end user temperature requirements.
- Layout and architectural details of existing buildings and their surroundings.
- Opportunities for flexibility of end user energy demands, to provide balancing resources.
- Plans for future development of the built environment and surroundings.
- Land area potentially available for energy infrastructure within and surrounding the built environment.
- The extent, capacities and limitations of existing energy networks (electricity, gas, heat, cooling).
- Opportunities for reductions in the demand for energy through energy efficiency measures and behavioural change.

- Availability of renewable energy resources and opportunities for the development of local renewable and low carbon energy systems.
- Opportunities for the development and integration of energy storage systems to maximise efficiency of capital and the percentage energy supply from renewable energy sources.
- Availability of conventional energy sources.
- Opportunities for energy grid interactions and synergies.

A suitable design considering the optimal operation of the system is key to delivering stable, economical and efficiently operating multi-energy system. For a given set of circumstances and constraints, multi energy grid solutions are likely to include a range of possible alternatives, which may or may not include some or even all of the non-electricity network types (gas, heat, cooling), and only a comprehensive analysis of the variables and optimisation of potential solutions will determine the most advantageous system to emerge. This was touched upon in Chapter 2, in which the role of smart energy systems was discussed in the context of renewable energy transitions.

In order to assess the extent of the design task at hand, a comprehensive understanding of the various energy services, or end user demands and their respective individual details is required, and this will provide a baseline from which alternative strategies enabling the introduction of multi energy grids can be explored. An example table which includes examples of different types of end user energy demands is shown below.

	Existing			Future (developing over time)		
	Peak load	Annual demand	Demand profile	Peak load	Annual demand	Demand profile
Energy service demands	(MW)	(MWh/yr)	(daily & seasonal)	(MW)	(MWh/yr)	(daily & seasonal)
Heat:						
Very low temperature how water and air (<50°C) - Space heating						
Very low temperature how water and air (<50°C) - Hot water						
Low temperature hot water (50°C-100°C) - Space heating						
Low temperature hot water (50°C-100°C) - Hot water						
Medium and high temperature hot water (>100°C) - Process						
Steam - Process						
Cooling:						
Medium temperature (>10°C)						
Low temperature (0°C-10°C)						
Very low temperature (<0°C)						
Electricity:						
Small power						
Large power						
Lighting						
Heating						
Cooling						
Gas:						
Heat						
Cooling						
Cooking						
Process						

It is noted that a number of the existing energy demands may overlap, for example heat demands delivered by gas-based heating systems, and cooling demands delivered by electricity based cooling systems. Energy demand profile information should include sufficient detail in order to be able to model hourly data profiles as a minimum.

Following on from the energy demand analysis, the availability of energy resources which may be deployed locally and their suitability to provide for the various energy demands is assessed, including renewable and non-renewable types. An example table which includes examples of different energy resources is shown below.

	Existing			Future (developing over time)		
	Peak load	Annual demand	Demand profile	Peak load	Annual demand	Demand profile
Energy resources	(MW)	(MWh/yr)	(daily & seasonal)	(MW)	(MWh/yr)	(daily & seasonal)
Suitable to provide heat demand:						
Solar thermal						
Biomass						
Hybrid PV-T						
Solar PV						
Wind turbines						
Gas						
Suitable to provide cooling demand:						
Solar thermal						
Biomass						
Hybrid PV-T						
Solar PV						
Wind turbines						
Gas						
Suitable to provide power demand:						
Biomass						
Hybrid PV-T						
Solar PV						
Wind turbines						
Gas						
Suitable to provide cooking demand:						
Hybrid PV-T						
Solar PV						
Wind turbines						
Gas						

Furthermore, Chapter 27 on heating/cooling networks outline the capability of each energy resource to provide for each of the various temperature requirements associated with the energy demands.

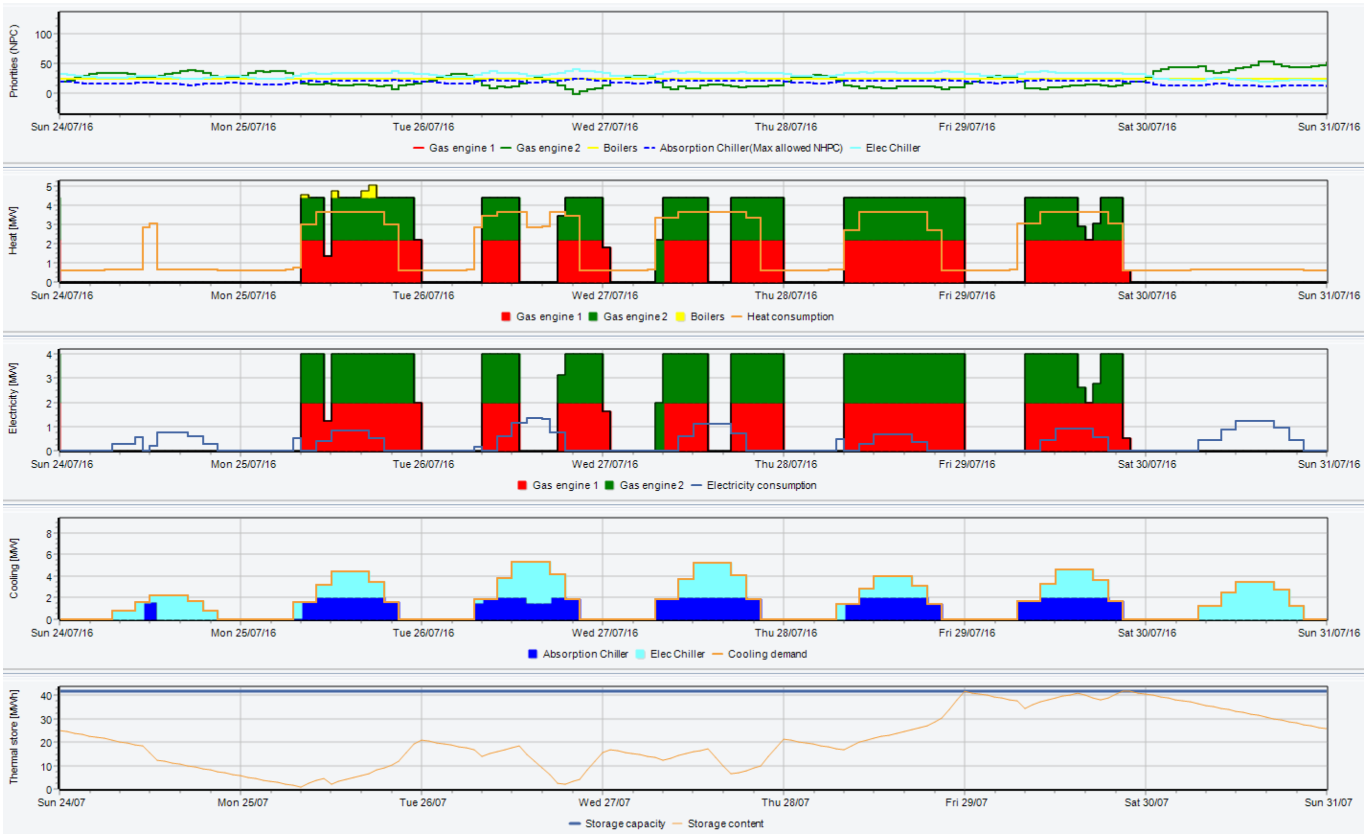
In addition, and combined with the assessment of energy resources above, consideration will be given to the range of energy conversion technologies available, giving due regard to efficiency of generation of heat, cooling and electricity. An example table which includes examples of different energy conversion technologies is shown below.

	Existing		Future (developing over time)	
	Output capacity	Annual generation	Output capacity	Annual demand
Energy conversion technologies	(MW_{th}, MW_e)	MWh_{th}, MWh_e/yr	(MW_{th}, Mw_e)	(MWh_{th}, MWh_e/yr)
Suitable to provide heat demand:				
Heat pumps - ground, water, air source				
Boilers - biomass				

Boilers - gas				
CHP - Biomass				
CHP - gas				
Direct electric heating				
Suitable to provide cooling demand:				
Heat pumps - ground, water, air source				
Absorption chillers				
CHP (tri-generation) - biomass				
CHP (tri-generation) - gas				

With an overall understanding of existing and future energy demands, the extent of energy resources available and the suitability of energy conversion technologies to supply demand it is possible to consider a range of alternative scenarios of matching energy demand with supply. Along with consideration of suitable energy storage technologies and capacities, and an analysis of energy flows, it will be possible to maximise energy supply from renewable resources in the most energy efficient manner, and at the lowest lifecycle cost. The results of this analysis will then form the basis of the designs for each energy grid, both individually and as a single interactive system.

Examples of model results of district energy system simulations are shown below. These are modelled in EnergyPRO[163].



Gas CHP (tri-generation)

[163] EMD International - https://www.emd.dk/energypro/

Gas CHP & heat pump

29 Closing

The transition to renewable energy systems will require an array of technologies and with that extensive knowledge of both technical and societal aspects. The deployment of technologies is, as indicated in this catalogue, related to a range of challenges; including not only installation and operation, but also integration of technologies in both the existing energy system and the social structures and practices of individuals, planners, and politicians.

This technology assessment has described both well-established and emerging technologies with the intention of outlining their role in future renewable and smart energy systems. From this, it is clear that the technologies necessary to transition to renewable energy systems are, with a few exceptions, already readily available - even at commercial scales. But, while the technologies might be available, planning for and developing such integrated renewable energy systems remains a challenge on both local, national, and international scale. This validates the continued need for spreading knowledge and awareness on technologies enabling grid and energy system interactions.

Balancing variable renewable energy production in future renewable energy systems calls for all sources of flexibility. This technology assessment has described how most technologies provide considerable potential for sector integration, flexibility and system optimisation. One of the central benefits of Smart Energy Systems is, as discussed in Chapter 2, the holistic and integrated approach to energy systems in which flexibility is obtained through a diverse technology mix. The complexity of such energy systems does however increase, calling for more information interchange in addition to more advanced communication- and control mechanisms.

All of the technologies described in this technology assessment are relevant for smart energy systems - the pivotal challenge is determining where and the extent of which they are relevant. Solving this requires extensive energy planning efforts combined with technology- and energy system knowledge.

To put matters into perspective of the MUSE GRID project and the demonstration projects included here, in Osimo there will be installed stratified thermal storage by GALU, SETS by GDHVI, controller by CAR, EV by SCAME and DUFERCO (the EV will be used as programmable load, V2H and V2G, both AC and DC charging station will be implemented). In Oud-Heverlee, a neighbourhood battery by ABB will be installed together with SETS (by GDHVI) and EV as well as the controller by CAR. In addition, comes hybrid heat pumps. Heat pumps from GDVHI could possibly replace SETS. For EVs V2G charging poles will be installed, and ABB control systems are considering for overall control.