Implementing innovative solutions for sustainable energy systems

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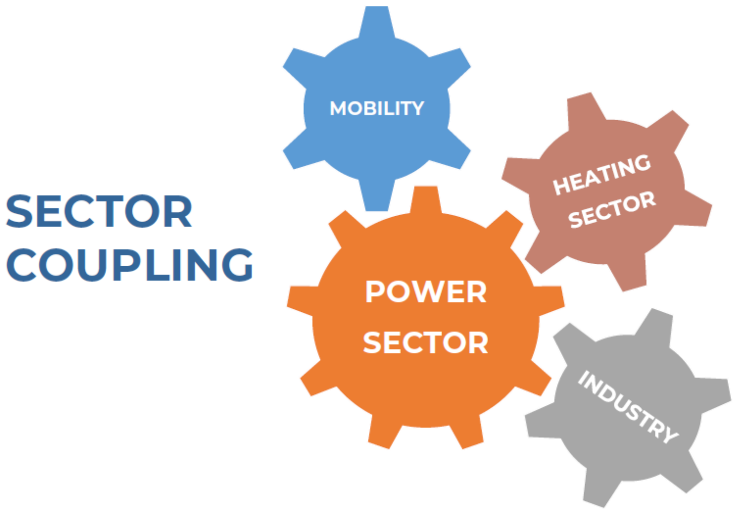
IMPLEMENTING INNOVATIVE SOLUTIONS FOR SUSTAINABLE ENERGY SYSTEMS



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CONTENT

1. INTRODUCTION

This Guideline gives an overview of technologies and applications that can play a key role in the low-carbon transition. The document is aimed to address readers with different levels of expertise and interest. In order to make the themes accessible to users from different backgrounds, the deliverable includes summaries and full documents on each topic, along with lists of references to documents and projects.

Extracts of the deliverable will be published on the IMEAS web Platform, in order to reach a wide audience and stimulate the discussion and sharing within the community. The Platform will give access to easy-to-use and easy-to-understand files, each technology being described in a Summary Document, a Full Document and a List of references table. All this files are downloadable separately on the IMEAS web Platform in the Contents section Technologies. They are collected here to form this Guideline.

The document is intended to be a living document, because it is periodically edited and updated, adding more details about the technologies, including new technologies or extending the tables of references.

The "Summary Document" is a synthesized description focusing on the main features, advantages, potentialities/barriers and potential for application in the Alpine Region territories. The "Full Document" is the extended version and contains more information with higher level of detail, graphs, schemes and examples of existing applications. The "List of references table" is a table containing links to scientific papers, documents, web sites and projects. Some of them have been used as references to write the guideline, the others contain further information.

This document illustrates Sector Coupling, a process that uses excess renewable electricity in another sector with respect to power one. This approach allows integrating different sectors in order to exploit synergies among them; electricity can be used to produce heat (Power-to-Heat) by heat pumps, to produce hydrogen or methane (Power-to-Gas) for vehicles (Power-to-Mobility) or to produce chemical compounds in industrial processes (Power-to-Industry). It is easy to understand that Sector Coupling can help the rise of renewables share and consequently the reduction of carbon emissions in sectors such as heating and mobility that are heavily dependent on fossil fuels. Another important topic described in this work is Energy Storage, which is the operation based on the capture of energy in order to use it when it is needed at a later time. Energy storage is fundamental to enhance the efficiency of the entire energy systems, and it has a key role in improving the penetration of renewable energy sources because it gives flexibility, allowing matching the needs of generation and demand. Another important topic introduced is blockchain, a virtual ledger that allows having infinity of transactions in the energy market, avoiding the centralized and expensive settlement. The potential of blockchain is to enhance the role of prosumers and support the development of microgrid with high-share of renewable energy sources.

It is worth mentioning that Sector Coupling, Energy Storage, Blockchain and demand side management together are considered very important for the future Smart Energy Systems, characterized by an optimized integration among sectors and by a large use of carbon-free energy.

2. SUMMARY DOCUMENTS ABOUT INNOVATIVE TECHNOLOGIES

2.1 SECTOR COUPLING

Sector Coupling is the process related to the conversion of excess renewable electric energy into another energy carrier, which can be used in other sectors. The fundamental principle of Sector Coupling is indeed the integration between different sectors (electric, heating, mobility, etc.), in order to exploit synergies among them and to avoid the wasting of energy.

The energy system is undergoing a rapid change, including the increasing introduction of renewable energy sources (RES) for electricity production. The large increase of intermittent and fluctuant energy sources, such as renewable ones (wind and sun), for electricity production can lead to overloads of the supply. The fluctuation and irregularities of these energy sources make more difficult to regulate, balance and manage the network and to match demand and supply. The system needs an optimization of the operation management and the integration among different sectors in order to guarantee the right stability and flexibility of the service.

Sector Coupling allows using this excess electricity in several other sectors and the processes are usually called Power-to-X where X is what electricity is used for. For example: Power-to-Heat for the production of heat, Power-to-Gas for the production of gaseous fuels such as hydrogen or methane; Power-to-Mobility for the production of liquid fuels/biofuels usable in the transport sector, Power-to-Industry for the production of chemical compounds used for industrial processes and many others.

It is easy to understand that these kinds of solutions for converting excess power from Renewable Energy Sources (RES) are important to pursue the energy transition to a system based on sustainable energy production and use. Obviously, only an optimized operation management of the energy system can guarantee the deep integration of different sectors, hence achieving an efficient Smart Energy System. Currently, the spreading of Sector Coupling is limited because its application requires a high share of RES and because some technologies need processes and infrastructures that still require further development to become competitive in the current energy system. Taken as examples, the Power-to-Heat needs centralized heating systems such as centralized heat pumps or centralized electric boilers and a widespread District Heating infrastructure, while the Power-to-Gas needs storage devices for hydrogen and widespread mobility based on fuel cells, or even sources of CO_2 for generating methane to carry in the gas grid.

Despite the economic and technical issues still open, Sector Coupling is considered an important step to reach a low-carbon society thanks to the electrification of sectors that are still heavily dependent on fossil fuels.

Also in the Alpine Region the rise of electricity from Renewable Energy Sources is introducing irregularities and mismatch of the electricity supply and demand. Thanks to the fact that the Alpine Region is characterized by a production of hydroelectric energy that in some cases exceeds to a large amount the local demand, Sector Coupling could play a key role in providing more flexibility to the system and reducing carbon emissions thanks to the electrification of heating and transport sectors, which are strongly dependent on fossil fuels.

2.2 POWER-TO-GAS

The Power-to-Gas (PtG) process chain is related to the conversion of excess renewable electric energy into gaseous fuels, such as hydrogen or methane, which are easily storable and usable thanks to the existing gas infrastructures.

The Power-to-Gas process is composed by four different phases:

1. Electricity is used to extract hydrogen from water;
2. Hydrogen can be stored and used directly in mobility and chemical processes or sent to the further phases;
3. Carbon dioxide is combined with hydrogen to produce methane;
4. Methane is sent to the gas grid for mobility (gas vehicles) or heating.

As described above, the main two products of this process are Hydrogen (H_2) and Methane (CH_4). The former can be used in mobility triggering the spreading of fuel-cell vehicles, or in chemical industry for the steam reforming or the production of methanol and ammonia. The latter is a Synthetic Gas and can be considered a renewable fuel due to the fact that it is produced combining unexploited renewable electricity and CO_2 subtracted from other industrial processes. It is easy to notice that the strength of Power-to-Gas is to integrate the power grid to different sectors (heat, chemical industry, mobility), reducing their carbon emissions. Furthermore, this technology allows utilising the existing natural gas infrastructure as storage medium, which reduces capital investments and facilitates its deployment.

On the other hand, Power-to-Gas is a not yet competitive technology because it involves H_2 infrastructure (electrolysers, storage tanks, etc.), CO_2 sources with capture and storage and several limitations about chemical parameters. In addition, it needs high-share RES system to become commercially competitive. However, it can contribute to solve the problem of excess of electricity caused by the progressive rising of intermittent Renewable Energy Sources (RES) and to provide more flexibility for the future Smart Energy System. Finally, the Power-to-Gas can support the rise of the share of renewables in transport and heating sectors, above all reducing carbon emissions and hence leading to achieve a low-carbon society.

In the Alpine Region, the rise of electricity produced from intermittent Renewable Energy Sources is introducing irregularities and oscillations and mismatch of the electricity supply and demand. It is also worth mentioning that Alpine Region is characterized by large production of hydroelectric energy that in some cases exceeds to a large amount the local demand. Moreover, there are situations in which rural areas are not reached by natural gas grid and so the use of oil derivatives for heating purposes is still very diffused. Furthermore, due to the central location of the Alpine Region in Europe, also road and freight traffic flows must be taken into account. Power-to-Gas gives the possibility to better manage and regulate an energy system characterized by intermittent and fluctuating sources, because it exploits locally the excess of renewable electricity that otherwise would be exported or wasted. It also helps to reduce carbon emissions substituting fossil fuels and using the gas grid as a huge energy storage, thus playing a key role in the low-carbon transition strategies in the Alpine Region.

2.3 POWER-TO-HEAT

Power-to-Heat (PtH) is the set of technologies and processes that use excess renewable electricity, that otherwise would be curtailed, to produce heat.

The Power-to-Heat process involves a good operation management of the energy system composed by the integration of electric network and heating network. Excess electricity from Renewable Energy Sources can be used to produce thermal energy in decentralized heating systems (flat, house, block) and in centralized ones (district heating). The former are usually fed by direct electric heating (fans, radiators), smart electric thermal storage, decentralized heat pumps or electric boilers while the latter can be fed by centralized heat pumps and electric boilers that are coupled with the District Heating Network. In order to improve the flexibility of this system strongly depending on fluctuating and intermittent Renewable Energy Sources, a thermal energy storage (centralized heat storage) is required.

Power-to-Heat has a sufficient technical maturity but economic and regulatory issues are still open to make it competitive with traditional technologies. However, it allows to generate, to store and to use heat for different heat demand sinks, enhancing the efficiency of energy generation processes and leading to a progressive optimization of the operation management of the energy system. The great advantage of this approach is the coupling between power and heat sectors, that is one the important steps to ensure flexibility to the future Smart Energy System. Finally, the Power-to-Heat can support the electrification of the heating sector, which is strongly dependent on fossil fuels, and it can lead both to the integration and rise of renewables and to the achievement of a low-carbon society.

In the Alpine Region, the rise of electricity produced from intermittent Renewable Energy Sources is introducing irregularities and oscillations and mismatch of the electricity supply and demand. It is also worth mentioning that the Alpine Region is characterized by large production of hydroelectric energy that in some cases exceeds to a large amount the local demand. Moreover, there are situations in which rural areas are not reached by natural gas grid and so the use of oil derivatives is still very diffused. Power-to-Heat gives the possibility to better manage and regulate an energy system characterized by intermittent and fluctuating sources, because it exploits locally the excess of renewable electricity that otherwise would be wasted or exported. This technology is fundamental to start electrification of heavily fossil fuel dependent sectors such as heating one. It can help to increase the sustainability of the heating sector, reducing not only carbon emission but also other emissions and pollutants, thus having a key role in the low-carbon transition strategies in the Alpine Region.

2.4 ENERGY STORAGE

Energy Storage is the process based on the capture of energy in order to use it when it is needed at a later time.

The increase of the share of unpredictable and intermittent renewable energy sources (such as wind and solar) introduces instability in the energy system because energy can be produced when not needed or produced in such a quantity that it exceeds the demand. Moreover, a strong and quick variation of RES output may lead to significant ramps that need to be compensated by flexibility solutions including backup power, storage or interconnections with neighbouring grids. Therefore, Energy Storage Systems (ESS) are essential to provide flexibility to the system and to avoid the waste of energy. As a matter of fact, the excess energy, usually heat and electricity, has to be stored in order to improve the efficiency of the energy generation process. The energy vector in which the input energy is converted classifies the several ESS. For what concerns Thermal Storage it can be divided in two categories: Sensible Heat Storage and Latent Heat Storage; the former is based on the temperature of the energy storage medium while the latter exploits the change phase properties of the used material. Referring to Electricity Storage, it can be classified in: Mechanical Energy Storage, Chemical Energy Storage, Electrochemical Energy Storage, Superconducting Magnetic Energy Storage and Cryogenic Energy Storage.

The great advantage of ESS is their support in improving the efficiency and so reducing the environmental impact of energy generation. In addition, they can enhance grid stability and increase the penetration of renewable energy sources. As mentioned before, energy storage provides a good flexibility to several energy systems: for example, Pumped Hydroelectric Energy Storage (PHES) covers daily peak of electricity demand, and Thermal Energy Storage (TES) works analogously in District Heating Networks. This potential highlights that energy storage will have a key role in the future Smart Energy System approach, because it allows integrating high-share of RES and optimizing their exploitation.

With regard to the applied technologies, it is important to define that some systems such as Pumped Hydroelectric Energy Storage (PHES) and Compressed Air Energy Storage (CAES) were used for decades. On the other hand, innovative and more efficient technologies, such as thermochemical or superconducting ones, are in demonstration and research stage. This suggests a strong policy support from the Government in order to make them competitive in the energy market and to enhance the large introduction of ESS especially for grid applications.

The coupling of energy storage systems to the energy grid in different sectors (power, heating, mobility) is fundamental to improve the spread of renewable energy sources and consequently to reduce the usage of fossil fuels and the carbon emissions.

In the Alpine Region, the rise of electricity produced from intermittent Renewable Energy Sources is introducing irregularities and oscillations and mismatch of the electricity supply and demand. The Alpine energy system needs to gain stability and flexibility, and Energy Storage Systems can guarantee them. These territories are characterized by large production of hydroelectric energy and Pumped Hydroelectric Energy Storage (PHES) has been used for decades and helps balancing the systems. However, the hydro storage is almost saturated and new energy storage technologies are needed to store both electricity and heat. The altitude variations of Alpine Region can be a driving force for the introduction of innovative Gravity Energy Storage (GES) based on the same principle of PHES but eliminating geological constraints and using solid materials (bucket of grave, boxcars) instead of water. The excess electricity produced by RES can be used for Chemical Energy Storage (CES) in order to produce chemical compounds such as hydrogen, biofuel, biodiesel, which can be used in space heating or mobility, helping the integration of different sectors and exploiting their synergies (Sector Coupling). Finally, Alpine Region energy policies could promote the diffusion of 4th generation district heating network integrating several innovative thermal energy storage systems. These technologies and approaches would enhance the integration of RES and the achievement of the European energy and climate targets for the development of a low-carbon society.

2.5 BLOCKCHAIN

Blockchain is a technology that can be considered a "virtual ledger" because it is collocated in the cloud and allows to register and store an infinite number of transactions, called blocks.

The large introduction of Renewable Energy Sources (RES) and the diffusion of distributed systems are changing completely the energy system. It is easy to foresee that in a not so distant future a large number of consumers will decide to opt out of the central power grid to join smaller micro-grids with their neighbours (not completely "off the grid") and to become active consumers (or "prosumers"), who both produces and consumes power.

Blockchain is a technology that can support and drive this important change. As known, blockchain sits behind Bitcoin, the cryptocurrency introduced in 2008. Bitcoin facilitates the transfer of money without the involvement of traditional intermediate institutions such as banks or credit card companies. What is unique is that the database, or digital ledger, is completely decentralized, where every Bitcoin transaction is recorded on the network in a virtual block with a unique time stamp, verified across a network of peers. As all blocks are connected, it creates a complete transactional history that has occurred in a particular network. Unlike a conventional database, which is held on a central server, the network is visible to all participants and is tamper-proof – making the network very secure, completely transparent and permanent. These principle are valid for several sectors, included the energy one.

The energy sector is characterized by decentralization of energy generation, new peer-to-peer trading and the request for more flexibility. These trends align well to the attributes of blockchain technology. Potential solutions from the technology include:

- Tracking and tracing energy production and consumption, enabling differential pricing for renewables;
- Automated network balancing with pre-agreed legal forms, to allow zero-trust peer-to-peer exchange of energy/currency;
- Verifiable identification of consumers and operational technology, to drive out non-technical losses and speed settlement;
- Energy trading using the distributed ledger, to eliminate the need for centralised (and expensive) settlement.

Blockchain or distributed ledger technologies can clearly benefit energy system operations, markets and consumers. It has the possibility to empower prosumers and small renewable generators to play a more active role in the energy market. However, blockchains are still in research and development stage, therefore further experiences on this emergent technology are required in order to improve understanding and realise their potential.

The Alpine Region energy system is rapidly changing. The spread of decentralized energy generators, the use of RES and the evolution from producer-consumer approach to a prosumer-prosumer approach will enhance the creation of microgrids. In such a future, blockchain helps reduce the cost of energy tradings because centralised and expensive settlements are avoided and the prosumers can sell their energy surplus directly to their neighbours. In addition, blockchain could be used also for management of the distribution grid and so the energy produced by prosumers can add more flexibility to a system with high-share of intermittent sources. Blockchain needs deeper research and study, but it has the potentiality to make the energy trading easier, simpler and democratic leading to an innovative concept of Smart Energy System characterized by carbon-free energy production.

3. FULL DOCUMENTS ABOUT INNOVATIVE TECHNOLOGIES

3.1 POWER-TO-GAS

3.1.1 DESCRIPTION OF THE TECHNOLOGY/APPLICATION

The rise of electricity production from *Renewable Energy Sources* (RES) leads to the introduction of irregularities and fluctuation in the energy system. There are several situations in which the power supply exceeds the demand. This suggests that future energy systems need an optimized operation and side management, but actually, when it is not enough, grid overloads can be avoided only by the shutdown of renewable power plant (i.e. wind farm) and consequently economic damage is inevitable. In order to prevent the waste of excess renewable electricity and the waste of money, the solution is to find a way to efficiently store and reuse this energy. The solution can be given by the so-called *Sector Coupling*, a process related to the conversion of excess renewable electric energy into another energy carrier, which can be used when needed in other sectors. The fundamental principle of *Sector Coupling* is the integration between different sectors, in order to exploit synergies among them and to avoid wasting of energy.
One of the procedures whereby *Sector Coupling* realizes itself is the *Power-to-Gas* (PtG) which is based on the conversion of excess renewable electricity into a gaseous fuel, such as hydrogen or methane.
The *Power-to-Gas* process is composed by four different phases:

1. Electricity is used to extract hydrogen from water;
2. Hydrogen can be stored and used directly in mobility and chemical processes or sent to the further phases;
3. Carbon dioxide is combined with hydrogen to produce methane;
4. Methane is sent to the gas grid for mobility (gas vehicles) or heating.

The first phase is fundamental because electrolysis produces hydrogen that is the first output of the process and it is based on the usage of excess electricity from renewable energy sources. The electrolysis technologies of interest for PtG process chain are different, they are well-described by Gotz et al. [1] and the main peculiarity of electrolysers is that they must work in a large operation window (also in overload) in order to adapt themselves to fluctuating and intermittent power supply.
In consequence, fluctuating power supply and intermittent operation of electrolysers require a temporary storage of hydrogen. The two best options for this technology are high-pressure gas tank (350-700 bar) which are currently used or innovative metallic hydride tanks that are more effective but expensive.[1]
The conversion efficiency of *Renewable Energy Sources* into hydrogen is in the range 54-77% depending on the used technology. An overview about commercial electrolysis systems (AEL – alkaline electrolyisis, PEM – polymer electrolyte membranes, SOEC – solid oxide electrolysis) has been made by Buttler et al.[2]. Hydrogen can be used to produce electricity again in fuel cells to feed H_2 vehicles or as a raw material in chemical industry (methanol production, ammonia production, steam reforming). In these two cases, the Power-to-Gas gives the possibility to integrate power sector with transport and industrial sectors and the

[1] M. Gotz, J. Lefebvre, F. Mors, A. McDaniel Koch, F. Graf, S. Bajohr, R. Reimert, T. Kolb, Renewable Power-to-Gas: A technological and economic review, Renew Energy, 2016, 85: 1371-1390
[2] A. Buttler, H. Spliethoff, Corrent Status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review, Renew Sustain Energy Rev, 2018, 82: 2440-2454

two processes are usually called *Power-to-Mobility* and *Power-to-Chemicals*.
An alternative to the direct utilisation of H_2 is the methanation, that is the production of methane CH_4 (the so called Synthetic or Substitute Natural Gas, SNG), through the hydrogenation of carbon oxides (CO or CO_2). A detailed description of the different methods for the methanation is given by Gotz et al. [1], and they can be divided into catalytic and biological ones.
In order to apply the methanation process a carbon source such as CO or CO_2 is required. The Carbon Capture and Sequestration (CCS) can solve this problem but it needs large stationary point sources of CO_2 such as power plants and refineries. Other several industries (e.g. iron, steel, cement) cannot be taken into account because they produce also other components like sulphur that is a poison for the methanation. In consequence, the removal of CO_2 from these gases reduces the energy efficiency and increases the costs. In contrast, Power-to-Gas requires much smaller carbon sources and as a result, even a biogas plant can be sufficient. The main advantages of biogas are the cheaper cleaning gas costs and the possibility to use the heat from methanation and the O_2 from electrolysis.
The process chain of *Power-to-Gas* is shown in the **Figure 1** and it is easy to notice that this technology allows to integrate different sectors using excess renewable power and CO_2 emissions to produce gas for transport, heating or industrial processes.

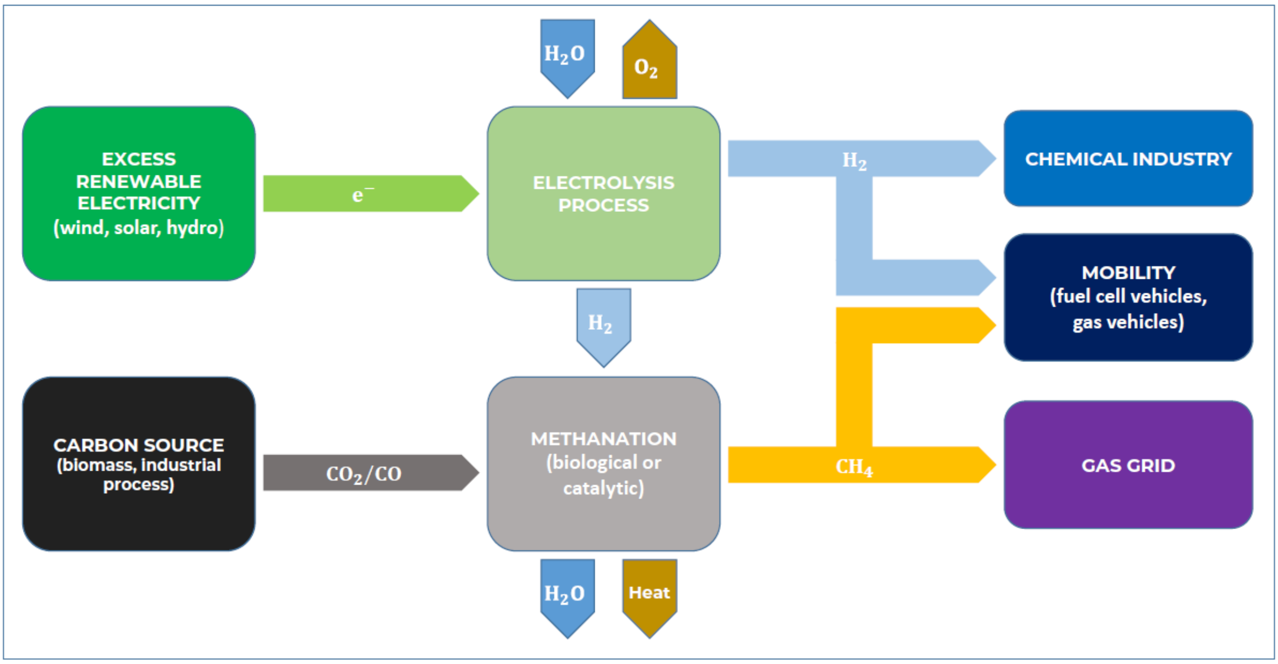

Figure 1: Exemplary Power-to-Gas process chain

Sankey Diagram in **Figure 2** shows the *Power-to-Gas* process efficiency. The steps are described by Shaaf et al.[3] and current available electrolysis technologies delivering H_2 at 25 bar with an electrical efficiency of about 80% are considered. The methanation reactor operates at 20 bar with an efficiency of 80% (maximum chemical efficiency). CO_2 is already compressed to 20 bar for the methanation reaction (otherwise 2% efficiency loss). Finally, methane can be compressed to 80 bar with a whole process efficiency of 63.6%. At this stage, Synthetic Natural Gas can be sent to the existing natural gas grid in order

[3] T. Schaaf, J. Grünig, M.R. Schuster, T. Rothenfluh, A. Orth, Methanation of CO_2 - storage of renewable energy in a gas distribution system, Energ Sustain Soc, 2014, 4:1-14

to be used where needed thanks to the gas distribution system (individual heating, CHP plants, refueling of gas vehicles, etc.).

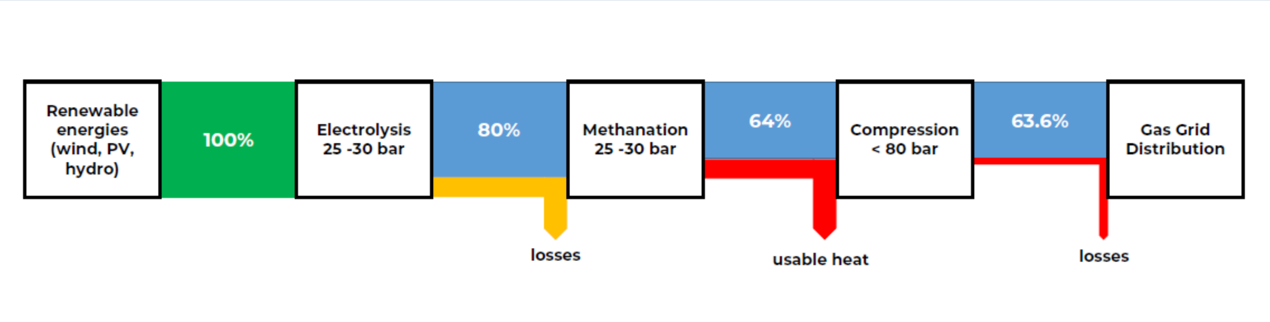

Figure 2: Sankey diagram of the Power-to-Gas process efficiency

Power-to-Gas can play an important role in the future Smart energy system, because it adds flexibility by linking power to gas fuels that can be used in other sectors. Moreover PtG provide the opportunity to recycle large volumes of captured CO_2 avoiding its emission in the environment. The Synthetic Gas produced by PtG can be considered a renewable fuel due to the fact that it is produced combining unexploited renewable electricity and CO_2 subtracted from other industrial processes. Furthermore, this technology allows utilising the existing natural gas infrastructure as storage medium, which reduces capital investments and facilitates its deployment.

However, in order to become commercially competitive (successful), technical and economic barriers have to be faced. Concerning with the process chain, the cost are strongly influenced by hydrogen production and storage. The essential CO_2 source could be biogas or biomass gasification because Carbon Capture and Sequestration (CCS) is not completely developed so far. In addition, methanation produces heat and its utilisation is important to increase the whole process efficiency.

Actually, the requirements to introduce such a solution in the energy system are the following:

- A good experience and specific infrastructure to storage and manipulate H_2;
- The *Power-to-Gas* plant must be next to a CO_2 source (e.g. biogas plant);
- High Renewable Energy Sources share in order to have excess power of almost 2 MW per electrolyser.

In conclusion, *Power-to-Gas* is a not yet a competitive technology. The costs for H_2 infrastructure (electrolysers, storage tanks, etc.), CO_2 sources with capture and storage and to guarantee the required chemical parameters are currently too high. However, thanks to a more favourable economic and incentive framework, PtG could effectively contribute to better manage the problem of excess of electricity caused by the progressive rising of Renewable Energy Sources (RES). The strength of *Power-to-Gas* is to connect the power grid to different sectors (heat, chemical industry, mobility) and to provide more flexibility in an energy system with a significant share of Renewables.

This innovative process can support the rise of the share renewables in transport and heating, above all reducing carbon emissions and hence leading to achieve a low-carbon society[4].

[4] H. Blanco, A. Faaij, A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage, Renew Sustain Energy Rev 2018, 81: 1049-1086

3.1.2 POTENTIAL FOR APPLICATION IN THE ALPINE REGION TERRITORIES

In the Alpine Region, the rise of electricity produced from intermittent Renewable Energy Sources is introducing irregularities and oscillations and mismatch of the electricity supply and demand. It is also worth mentioning that Alpine Region is characterized by large production of hydroelectric energy that in some cases exceeds to a large amount the local demand. Moreover, there are situations in which rural areas are not reached by natural gas grid and so the use of oil derivatives for heating purposes is still very diffused. Furthermore, due to the central location of the Alpine Region in Europe, also road and freight traffic flows must be taken into account. Power-to-Gas gives the possibility to better manage and regulate an energy system characterized by intermittent and fluctuating sources, because it exploits locally the excess of renewable electricity that otherwise would be exported or wasted. This process is an important step to use the excess electricity from Hydro Power Plant in order to produce hydrogen for sustainable mobility in the Alpine Region, and to produce Synthetic Gas substituting natural gas or other fossil fuels for space heating. In such a way it helps to reduce carbon emissions in transport and heating sectors and using the gas grid as a huge energy storage, thus playing a key role in the low-carbon transition strategies in the Alpine Region.

3.1.3 EXAMPLES OF EXISTING APPLICATIONS

Audi e-gas plant in Wertle, Germany

The Audi e-gas plant in Wertle (Germany) is the biggest Power-to-Gas plant worldwide. Hydrogen is produced from three alkaline electrolysers with a total electrical power of 6 MW powered by an offshore wind park in the North Sea and stored in a tank at approximately 10 bar before it is fed into the methanation reactor [5]. The CO_2 is provided by a biogas plant using amine absorption and fixed-bed methanation reactors are used to produce synthetic gas combining H_2 and CO_2. The heat released from the methanation reactor is used to regenerate the amine absorbent in order to increase the total efficiency of the plant. Performance data of the Audi e-gas plant is shown in the **Table 1**. Other information about this Power-to-Gas plant are available on Audi web-site. [6]

Table 1 - Performance data of the Audi e-gas plant in Wertle

Data	Value
Specific energy of SNG on average	13.85 kWh
Annual electricity consumption (prognosis)	26 – 29 GWh/y
Power to SNG efficiency (without using heat)	54 %
Maximum H_2 output from electrolyzers	1300 Nm^3/h
Maximum H_2 storage time	60 min
Maximum SNG output from plant	325 Nm^3/h
Annual operation time (prognosis)	4000 h/y
Annual SNG production (prognosis)	1000 t/y

[5] K. Ghaib, F. Ben-Fares, Power-to-Methane: A state-of-art review, Renew Sustain Energy Rev, 2018, 81:433-446

[6] Audi e-gas plant web-site: https://www.audi-technology-portal.de/en/mobility-for-the-future/audi-future-lab-mobility_en/audi-future-energies_en/audi-e-gas_en

Power-to-Gas demonstration plant in Rozenburg, The Netherlands

Due to the innovative technological nature of Power-to-Gas, Stedin, DNV GL, TKI Gas, Community of Rotterdam and Ressort Wonen carried out a demonstration project that investigated the use and applicability of Power-to-Gas technology. Sustainable electricity that is generated with solar panels is converted into synthetic gas of natural gas quality, via hydrogen and methane and is applied in a gas-fired boiler of nearby flat buildings. The conversion of electricity into hydrogen and oxygen is performed with an energetic efficiency of 47%. The energetic efficiency of this methanation process is set at 73%. The energy balance of the complete Power-to-Gas system demonstrated an energetic efficiency of 35%. This study has demonstrated that Power-to-Gas, with adequate security of supply, can be used for energy storage in the gas grid.

The completed process releases several product flows that are not used usefully as yet. Future study could focus on expanding the system with other technologies to obtain cycles for those product flows (process water, heat and oxygen).

From a sustainability point of view, it is recommended to perform further studies into the options to recover water and carbon dioxide from the flue gases of the gas-fired systems in order to close the carbon cycle.

Other information about this Power-to-Gas plant are available on the EuropeanPowertoGas site[7]

Power-to-Gas plant in Rostock, Germany

Exytron Company, together with the Leibniz Institute for Catalysis (LIKAT) and the University of Rostock have developed a revolutionary concept of storing renewable energy. The EXYTRON Smart Energy Technology, which is shown in **Figure 3**. This system enables the use of an innovative and global power supply system for a decentralised and autonomous energy supply without any CO_2 emissions.

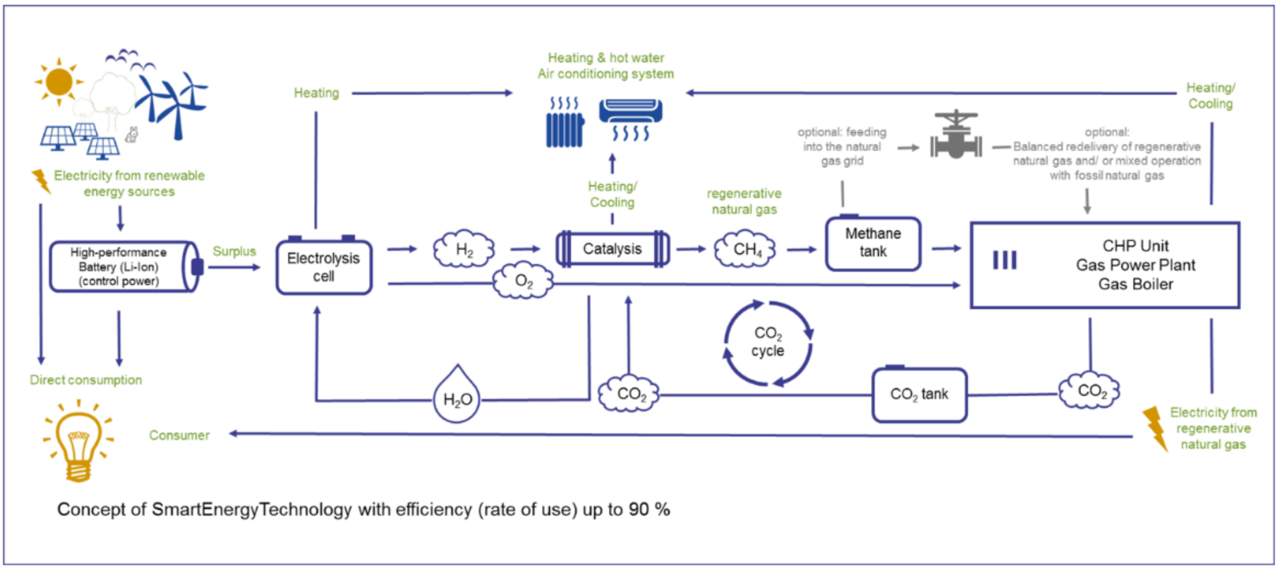

Figure 3: Power-to-Gas process of EXYTRON Smart Energy Technology, https://exytron.online/en/the-principle-of-smart-energy-technology-zero-emission-technologys/

[7] Technical assumptions, technology demonstration and results P2G Project, DNV-GL, 2015, http://europeanpowertogas.com/wp-content/uploads/2018/05/qFKAp2AF.pdf

The main features of this system are the following:

- the use of oxygen, rather than air, in the methane combustion, so that the only products of the reaction are reusable Water and CO_2
- Water is condensed and used for future electrolysis
- The CO_2 is recirculated and used for the methane manufacture. The surplus heat generated in the process of methane generation, and then combustion, is used for water and space heating.

More information are available on the EXYTRON Web site[8]

Power-to-Gas in Europe

Several Power-to-gas applications are available on Europeanpowertogas website[9]. An interactive map gives the possibility to localize lot of projects around Europe.

[8] Exytron web-site: https://exytron.online/en/the-principle-of-smart-energy-technology-zero-emission-technologys/

[9] European Power-to-Gas Platform: http://europeanpowertogas.com/projects-in-europe/

3.1.4 LIST OF REFERENCES

The “List of references” is a table containing links to scientific papers, documents, web sites and projects. Some of them have been used as references to write the guideline, the others contain further information about the described technology. **Table 2** shows references about Power-to-Gas.

Table 2 - List of references about Power-to-Gas

Topic	n.	Type	Title	Authors	Year	Link to web page
PtG	PtG.01	scientific paper	Renewable Power-to-Gas: A technological and economic review	M. Gotz, J. Lefebvre, F. Mors, A. McDaniel Koch, F. Graf, S. Bajohr, R. Reimert, T. Kolb	2016	https://doi.org/10.1016/j.renene.2015.07.066
PtG	PtG.02	scientific paper	Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review	A. Buttler, H. Spliethoff	2018	https://doi.org/10.1016/j.rser.2017.09.003
PtG	PtG.03	scientific paper	Methanation of CO_2 - storage of renewable energy in a gas distribution system	T. Schaaf, J. Grünig, M.R. Schuster, T. Rothenfluh, A.Orth	2014	http://dx.doi.org/10.1186/s13705-014-0029-1
PtG	PtG.04	scientific paper	A review at the role of storage in energy systems with a focus on Power to Gas and long-term storage	H. Blanco, A. Faaij	2018	http://dx.doi.org/10.1016/j.rser.2017.07.062
PtG	PtG.05	scientific paper	Power-to-Methane: A state-of-art review	K. Ghaib, F. Ben-Fares	2018	https://doi.org/10.1016/j.rser.2017.08.004
PtG	PtG.06	web-site, platform	Audi e-gas plant in Wertle, Germany	Audi	2014	https://www.audi-technology-portal.de/en/mobility-for-the-future/audi-future-lab-mobility_en/audi-future-energies_en/audi-e-gas_en

Topic	n.	Type	Title	Authors	Year	Link to web page
PtG	PtG.07	document	Technical assumptions, technology demonstration and results P2G Project	DNV-GL	2015	http://europeanpowertogas.com/wp-content/uploads/2018/05/qFKAp2AF.pdf
PtG	PtG.08	web-site, platform	Power-to-Gas plant in Rostock, Germany	EXYTRON		https://exytron.online/en/the-principle-of-smart-energy-technology-zero-emission-technologys/
PtG	PtG.09	web-site, platform	European Power-to-Gas Platform	EUROPEAN POWERTOGAS		http://europeanpowertogas.com/projects-in-europe/

3.2 POWER-TO-HEAT

3.2.1 DESCRIPTION OF THE TECHNOLOGY/APPLICATION

The heating sector accounts for the majority (79%[10]) of final energy consumption in the European Union and therefore it could play a central role in achieving EU's climate and energy goals[11]. Although the heating sector is moving to clean low carbon energy, 75% of the fuel it uses still comes from fossil fuels (nearly half from gas)[10].

The future electricity grid will integrate more renewable energy, especially wind and solar including decentralised supplies. The elevated introduction of intermittent and fluctuating energy sources lead to situations in which electricity is produced when not needed and excess electricity should be stored in order to use it in a later time. The new electricity system must guarantee the flexibility among supply and demand, through wider use of demand reduction, demand response mechanisms and energy storage. Linking heating with electricity networks is expected also to reduce the cost of the energy system – to the benefit of consumers. In addition, the electrification of the heating sector may be an appropriate pathway for the decarbonisation of this sector, while at the same time providing additional flexibility to an electricity system characterized by fluctuating and intermittent sources[12]. In order to prevent the waste of excess renewable electricity and the waste of money, the solution is to find a way to efficiently store and reuse this energy. The solution can be given by the so-called *Sector Coupling*, a process related to the conversion of excess renewable electric energy into another energy carrier, which can be used when needed in other sectors. The fundamental principle of *Sector Coupling* is the integration between different sectors, in order to exploit synergies among them and to avoid wasting of energy.

In this case, the appropriate sector coupling is the so-called Power-to-Heat (PtH) that is the process related to the use of excess electricity from renewable energy sources to generate heat.

The essential condition to exploit Power-to-Heat potential is a large diffusion of systems that use electricity to produce heat (electric boilers, heat pumps, etc.). As a result, Power-to-Heat gives the possibility to interconnect the electricity network and the heating network. The integration of these two sectors allows to exploit synergies between these two energy field, providing an optimized operation management of the system and allowing to send excess electricity both to decentralized heating systems (flat, house, block) and to centralized ones (district heating). In the former, the heat can be produced by direct electric heating (fans, radiators), smart electric thermal storage, decentralized heat pumps or electric boilers. In the latter, the heat can be generated by centralized heat pumps and electric boilers that feed the district heating system. It is worth noting that such a process, using excess renewable electricity to produce heat, has the possibility to provide the necessary flexibility to a high-share RES system, and further flexibility can be improved by adding to the system thermal energy storage (centralized heat storage)[13].

These processes are well synthesized in the **Figure 4**.

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[10] European Commission, https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling

[11] European Commission, 2030 Climate and Energy framework, https://ec.europa.eu/clima/policies/strategies/2030_en

[12] Yilmaz et al., Analysis of the potential for Power-to-Heat/Cool applications to increase flexibility in the European electricity system until 2030, INSIGHT_E Policy Report, February 2017, https://www.bib.irb.hr/889378/download/889378.PtH_C_final_version_final.pdf

[13] Bloess et al., Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials, Applied Energy 212, 2018, pp. 1611-1626, https://doi.org/10.1016/j.apenergy.2017.12.073

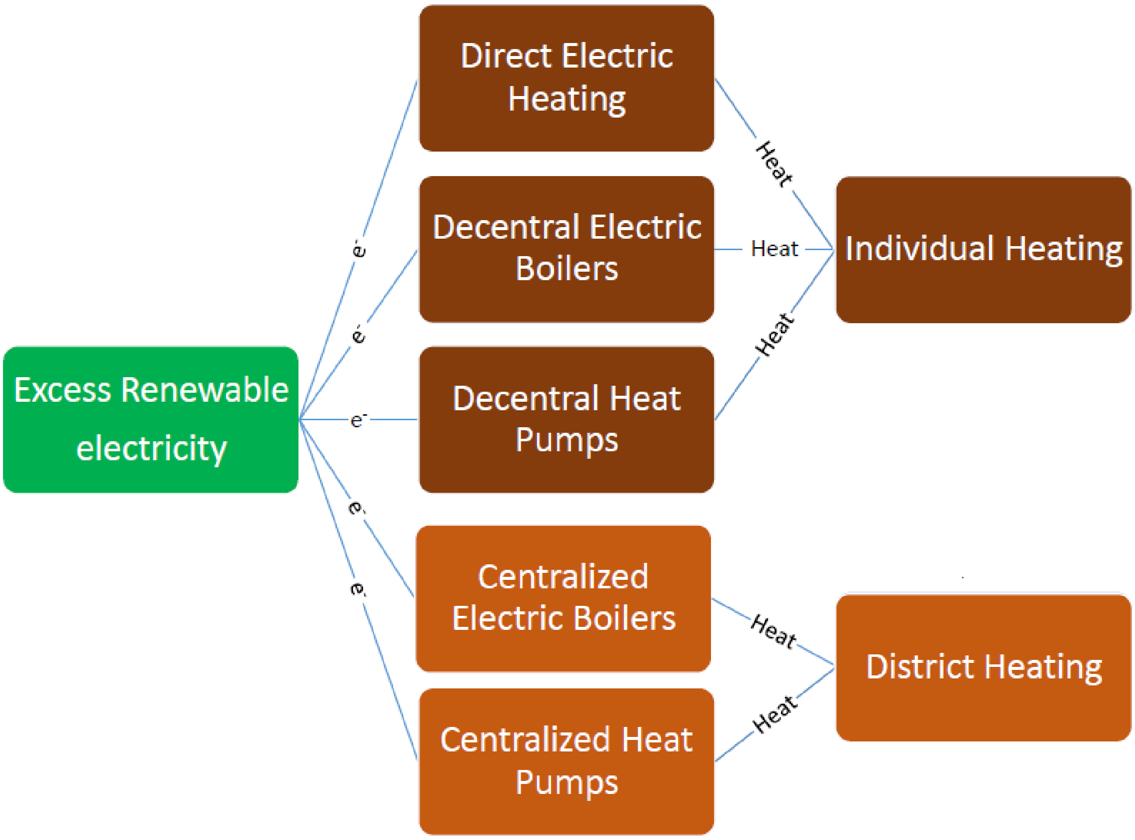

Figure 4 - Interconnections of power-to-heat options with electricity and district heating networks

In this evolution of the heating sector, heat pumps have a central role. Unfortunately heat pumps and other power-to-heat technologies hardly manage to penetrate the energy market due to elevated nominal investment. This kind of applications seem to have the sufficient technical maturity and potential to play a key role in future European energy markets but their use is limited by unfavourable electricity fees and tariffs. Hence, they need tighter regulation and direct support measures.

Power-to-Heat allows to achieve: reduced need for peak load and power storage technologies, more efficient operation of thermal plants, synergies of using existing district heating infrastructures, reduced renewables curtailment. Consequently, a better integration and a higher utilization of renewable energy sources is promoted and this situation leads to a low-carbon energy transition.

In conclusion, Power-to-Heat has a sufficient technical maturity but electricity fees and tariffs influence a lot the competitiveness of this application and therefore its development. PtH allows to generate, to store and to use heat for different heat demand sinks, enhancing the efficiency of energy generation processes and leading to a progressive optimization of the operation management of the energy system. Finally, the electrification of the heating sector is a positive process both for the integration of renewables and for the gradual reduction of fossil fuels in this sector.

3.2.2 POTENTIAL FOR APPLICATION IN THE ALPINE SPACE TERRITORIES

In the Alpine Region, the rise of electricity produced from intermittent Renewable Energy Sources is introducing irregularities and oscillations and mismatch of the electricity supply and demand. It is also worth mentioning that the Alpine Region is characterized by large production of hydroelectric energy that in some cases exceeds to a large amount the local demand. Moreover, there are situations in which rural areas are not reached by natural gas grid and so the use of oil derivatives is still very diffused. Power-to-Heat gives the possibility to better manage and regulate an energy system characterized by intermittent and fluctuating sources, because it exploits locally the excess of renewable electricity that otherwise would be wasted or exported. This technology is fundamental to start electrification of heavily fossil fuel dependent sectors such as heating one, and the Alpine rural areas can have the possibility to substitute oil boilers with innovative heat pumps avoiding the large investment to expand the gas grid. In such a way, Power-to-heat helps to increase the sustainability of the heating sector, reducing not only carbon emission but also other emissions and pollutants, thus having a key role in the low-carbon transition strategies in the Alpine Region.

3.2.3 EXAMPLES OF EXISTING APPLICATIONS

For what concerns the applicability of these technologies and processes there are not big technological constraints, and there are several applications. Among the others, two examples are listed below:

1) The "Sunstore 4" project[14] is a district heating plant located in Marstal (Denmark) that was developed to demonstrate the production of 100% renewable-based district heating and flexible management of different intermittent energy sources with the assistant of thermal storage. The plant combines solar thermal energy, a biomass boiler coupled with an Organic Rankine Cycle (ORC), a compressing heat pump (1.5 MW) and thermal storage.
2) THE "FHP" project[15] has received funding from the European Union's Horizon 2020. The title means Flexible Heat and Power, connecting heat and power networks by harnessing the complexity in distributed thermal flexibility. The main objectives is "To secure mitigation of RES curtailment in the electric distribution grid by dynamic coalitions of power-to-heat resources". FHP is developing operational strategies based on power-to-heat solutions. Electric flexibility provided by DER (Distributed Energy Resources) will combine with thermal inertia to shift electric load to those moments when RES are producing more electricity than needed, specifically those related to heating.

[14] Final Report of "Sunstore 4" project: https://www.euroheat.org/wp-content/uploads/2016/04/SUNSTORE4_Report.pdf
[15] FHP Project web-site: http://fhp-h2020.eu/

3.2.4 LIST OF REFERENCES TABLE

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Table 3 – List of references about Power-to-Heat

Topic	n.	Type	Title	Authors	Year	Link to web page
PtH	PtH.01	web-site, platform	EU strategy for heating and cooling	European Commission	2016	https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling
PtH	PtH.02	web-site, platform	2030 Climate and Energy framework	European Commission	2018	https://ec.europa.eu/clima/policies/strategies/2030_en
PtH	PtH.03	document	Analysis of the potential for Power-to-Heat/Cool applications to increase flexibility in the European electricity system until 2030	H. Ü. Yilmaz, R. Hartel, D. Keles, R. McKenna, W. Fichtner	2017	https://www.bib.irb.hr/889378/download/889378.PtH_C_final_version_final.pdf
PtH	PtH.04	scientific paper	Power-to-heat for renewable energy integration: A review of technologies, modelling approaches, and flexibility potentials	A. Bloess, W. Schill, A. Zerrahn	2018	https://doi.org/10.1016/j.apenergy.2017.12.073
PtH	PtH.05	scientific paper	Final Report of "Sunstore 4" project	Consortium: Marstal Fjernvarme, Advansor, Ambiente Italia, Bios Bioenergisysteme, AF-CityPlan, Energy Management, Euroheat&Power, Euro Therm A/S, PlanEnergi, Solites	2014	https://www.euroheat.org/wp-content/uploads/2016/04/SUNSTORE4_Report.pdf

Topic	n.	Type	Title	Authors	Year	Link to web page
PtH	PtH.06	web-site, platform	FHP Project web-site	FHP Project	2016	http://fhp-h2020.eu/

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https://doi.org/10.12910/DOC2020-013