Position paper on Energy Transition

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Introduction

The necessity of neutralizing the increase of the temperature of the atmosphere by the reduction of greenhouse gas emissions, in particular carbon dioxide (CO_2), as well as replacing fossil fuels, leads to a necessary energy transition that is already happening. This energy transition requires the deployment of renewable energies that will replace gradually the fossil fuels. Furthermore, the renewable energies, such as solar energy, wind energy, hydraulics, biomass, must be able to meet the energy demand that fluctuates not only on a daily basis, but also on a monthly and yearly basis. Thus, a flexibility of production is necessary, which remains rather challenging given the intermittence of certain renewable energies dependent on hourly and seasonal weather conditions. Therefore, the proportion of renewable integrated into the energy sector can vary according to the proposed scenarios and according to the objectives of reduction of CO_2 emissions. At the moment, the "100% renewable" is maybe not, per se, an objective in Europe, nor is it the most direct pathway for a reduction of the global CO_2 emissions.

In this energy context, one of the first questions concerns the possible need for storage and its sizing. With fluctuating electricity production depending on the sun and wind, storage seems inevitable to meet the energy needs of consumers during periods when production is below demand. However, the amount of energy to be stored may not be so important given the large renewable production, even in winter. Therefore, the lack of electricity can either be compensated by releasing previously stored capacity, or by using compensation units operating on fossil fuels, mainly gas. The ideal scenario must minimize the overall cost of the system while respecting the constraint on CO_2 emissions.

If there is a need for storage, questions about the period, size, and power capacity of storage systems are predominant. These elements will determine the type of technology to be selected, among available or under development technologies. On top of addressing these issues, the focus should also be on the nature of the energy carriers produced from renewable sources, considering the networks already in place. Finally, the location of the storage systems must be chosen to make better use of the existing energy facilities. Indeed, one cannot make abstraction of the current energy system that shall nevertheless evolve. In the near future, new electrical installations can be adapted to the scenarios proposed for the optimization of renewable energies.

To develop a realistic energy network, three parameters need to be quantified and optimized: consumer energy demand and flexibility, the amount of energy produced from renewable resources, and available storage. The problem of excessive production of energy during beneficial times ("curtailment") must also be considered, as well as the problem of energy shortage ("black out"). Finally, the energy cost of each production, storage and restitution unit must be defined, as well as the total financial cost of the system.

This document summarizes the discussions held during a workshop on the energy transition, organized by several Belgian academic and industrial experts. All the questions raised above are addressed in a general way, trying to express and justify the different points of view, starting from works published in the literature.

1. Need for electrical storage

One of the first questions to ask when using renewable resources for electricity generation is whether there is a need for storage. This problem is related to the variable but continuous need for electricity while the renewable production is intermittent. To avoid production bottlenecks, tools such as flexibility from non-renewable production, demand management, renewable energy offloading and storage are already being used. Despite the obvious benefits of energy storage, some studies focus on the energy transition without considering this option. Indeed, given the significant additional investment costs of energy storage technologies, an option for the electrical future would be to do without them.

A first study demonstrates, for the United States, the feasibility of minimizing the amount of energy to be stored by using renewable energy and nuclear. Considering existing nuclear as well as hydroelectric, wind, and photovoltaic power plants in 2012, a model was developed by MacDonald et al. (2016). The authors designed a new, optimal power supply system for all contiguous states. This model includes a High Voltage Direct Current (HVDC) transmission network that can transmit electricity over long distances that a High Voltage Alternating Current (HVAC) network cannot achieve. In addition, HVDC is more efficient and less expensive than HVAC. In this work, a scenario was optimized based on the costs of variable electrical power generators using meteorological data with high spatial (13 x 13 km) and temporal (60 min) resolutions. The results show that using wind and solar energy, carbon dioxide emissions from the US electricity sector can be reduced by 80% compared to the 1990 levels, without increasing the price of electricity. Carbon emission reductions are thus possible with current technologies and without electricity storage. This reduction is achieved by switching from a regionally divided electricity sector to a national system connected by HVDC transmission lines. Since meteorological systems at the mid-latitude of the Earth span large geographical areas, the average variability of weather conditions decreases as the size of the system increases. If wind or solar power is not available in a small area, it is more likely to be available somewhere in a larger area. More importantly, an electrical system over a large area allows sites rich in wind and solar resources to provide cheaper electricity to distant markets. The technology best adapted for systems designed for large geographical areas, favored by wind and solar power, is thus composed of a network of HVDC transmission lines. According to the authors, electrical storage could also mitigate the effect of intermittent wind and solar energy, but at a higher cost than HVDC transmission lines.

Other studies by Van Stiphout (2015) and Limpens (2018) concerning the energy transition in Belgium estimate that the storage capacity requirement will be between 8 and 25 GWh when 50% of the energy production comes from renewable sources. This need is justified from both the technical (Limpens, 2018) as well as the economic (Van Stiphout, 2015) point of view. The composition of the Belgian energy mix will have a major impact on the technologies and storage capacities needed. Indeed, the study of Limpens (2018) analyzed the storage needs for different energy scenarios with or without nuclear energy. Nuclear power is assimilated to a form of non-flexible energy, used as a "base load". This base load has little direct impact on storage requirements but influences the amount of renewables to install. When energy production is larger than consumption, since nuclear power is in "base load", the production of renewable energies must be reduced. In the opposite case, where the consumption is larger than the production, with the nuclear "base load", the share of the renewable must increase to meet the energy needs. If this demand is not fully supported by the renewables, storage becomes then necessary to provide energy at these precise times.

Finally, other works also present nuclear power as an important vector in the energy transition. According to the study by McCombie and Jefferson (2016), one of the alternatives to energy storage is the use of nuclear energy together with the integration of renewable energies into the system. If the share of nuclear power is large enough to allow the renewable energy to support the peaks of energy demands, storage can be very limited or negligible.

These various studies demonstrate the importance of renewable energy in the transition and, possibly, of nuclear energy as a source of energy to reduce the amount of energy to be stored. However, according to Limpens (2018), for high shares (> 30-40%) of renewable energy in the mix, energy storage in different forms is still needed.

Finally, to clarify the need for energy storage, a study comparing the societal, technical and financial merits of HDVC and storage should be conducted.

2. Storage Techniques

Different storage techniques are available such as:

- mechanical storage (Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), Flywheels),
- electrical storage (capacitors, Superconducting Magnetic Energy Storage - SMES),
- electrochemical storage (batteries),
- thermal storage (at low and high temperatures),
- chemical storage (hydrogen (H_2), methane (CH_4), ammonia (NH_3), methanol (CH_3OH), ethanol (C_2H_5OH), dimethyl ether (DME), formic acid (HCOOH), etc.).

The chemical storage is often called Power-to-Fuel, PtF, where the "F" represents the production of a gas (for H_2 and CH_4) or a liquid (also called "synthetic fuel", for CH_3OH, DME and NH_3). In some studies, the term PtX is used to mean the production of an end-product, “X”, for the industry, and not necessarily a fuel.

These different storage techniques make it possible to diversify the form of the stored energy (mechanical, electrochemical, chemical) and to restore it to electricity or fuel, depending on the capacity required and the desired storage duration. Numerous articles present these different storage techniques in detail; here is a non-exhaustive list: Ibrahim (2008), Chen (2009), Hadjipaschalis (2009), Koohi-Kamali (2013), Ferreira (2013), Mahlia (2014), Kousksou (2014), Lund (2015), Zakeri (2015), Luo (2015), Kyriakopoulos (2016), Aneke (2016), Gallo (2016).

Recent works classify these different storage techniques, depending the relation between the storage capacity and the electrical power that can be restored, so according to the discharge time (Figure 1). In addition, a comparison according to the CAPEX (CApital Expenditures) and the LCOES (Levelized Cost of Energy Storage) is given in Table 1.

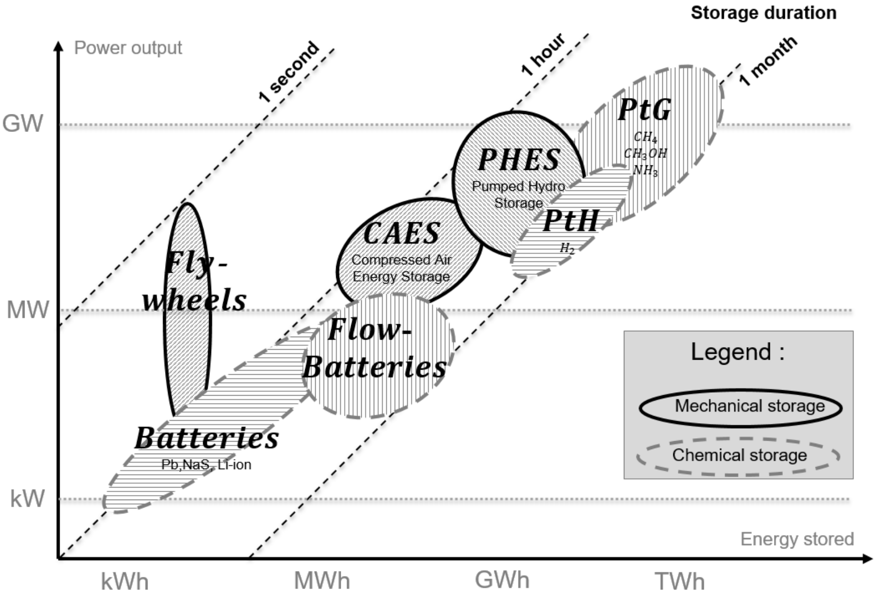

Figure 1: Relation between the restored electrical power and the stored energy capacity for the different storage techniques (Limpens, 2018).

	Pumped Hydro	CAES	Li-ion Batteries	Flow Batteries	Power to Fuel to Power	Power to Ammonia to Power
Storage Capacity price \$/kWh (CAPEX)	5-20[a] 5-100[b]	10-30 [a] 2-50 [b]	300-600 [a] 600-2500 [b]	200-300 [a] 150-1000 [b]	0.3-0.6 [a] 1-10 [b]	
Roundtrip efficiency (%)	76 [a] 65-85 [b]	55* [a] 40-60 [b]	95 [a] 85-95 [b]	80 [a] 60-85 [b]	40 [a] 30-50 [b]	35-40[c]
LCOES (€/kWh)	1.4 [a]	2.4 [a]	-	-	0.5 [a]	0.18-0.25 (with 1-2 \$/kgH2) [c]

Table 1: Comparison of storage techniques according to their overall efficiency, CAPEX and LCOES for 1 cycle usage per year
[a] Jülch (2016) and Hedegaard (2012)
[b] Gallo (2016)
[c] Elishav (2017)

For small amounts of energy (ranging from 1 kWh to 1 MWh) and short periods of discharge (seconds to hours), storage by capacitors, flywheels and batteries appears sufficient. For larger capacities from 10 MWh to 100 GWh, mechanical storage such as CAES and PHES seems more suitable. These techniques make it possible to provide electricity for a country for several hours, or even a week.
For larger amounts of energy (up to 100 TWh) and longer duration (one week and beyond), Power-to-Fuel seems to be the best storage technique. PtF pertinence for long-term, high-capacity storage is explained by the high energy density of the fuels obtained, compared to other storage techniques. Another advantage is the low cost associated with the increase in storage capacity: only the size of the storage tank should be enlarged. These PtX techniques are described in detail in several reference articles: Lehner (2014), Vandewalle (2015), Walker (2015), Götz (2016), Gallo (2016), Connolly (2016), Kötter (2016), Mesfun (2017), Bailera (2017), Etogas (Germany), ITM Power (UK)...

The process consists in using electricity produced directly by wind or solar energy to electrolytically convert water into hydrogen, the useful product, and oxygen, a secondary product. The hydrogen can then react with CO_2 to form methane by methanation; and/or methanol. Finally, the hydrogen produced can also react with the nitrogen (N_2) from the air obtained by an ASU ("Air Separation Unit") to form ammonia. Thanks to Power-to-Fuel, four fuels can be considered as fuels from renewables: H_2, CH_4, CH_3OH and NH_3. These "fuels of interest" are selected according to their ease of production by renewable energies. Ethanol, DME, and heavier compounds are therefore not considered in this study. However, these fuels are not to be excluded in the future, especially for transport applications, and as intermediate products for the industry.

The different chemical properties of these four fuels allow them to be used for different purposes. Hydrogen has a low energy density (10 kJ/l). To increase and facilitate storage, various techniques exist such as compression (usually up to 700 bar), liquefaction, immersion in fluids (Wang, 2016) or absorption to produce metal hydrides (Aslam, 2015). The process of producing hydrogen is less expensive than the formation of CH_4 or liquid fuels, but its expensive storage is a drawback (Pochet, 2016). For some applications, the use of hydrogen is justifiable, mainly for direct use without storage. Note that the producted hydrogen can be injected direclty into the natural gas network, with a current

European limit of 2% of the energy content (Altfeld, 2013), which circumvents the problem of its long-term storage cost (Qadrdan, 2015).

Concerning the production of the different fuels, the energy efficiency of hydrogen production through electrolysis remains high compared to the production of the other fuels: 72.4% for H_2 (Connolly, 2015), against 63.7% for methane (Connolly, 2016), 60.5% for methanol (Connolly, 2015) and 55% for ammonia (Fuhrmann, 2013) or over 62% for electrolysers of the "Solid Oxide Electrolysers" type coupled by thermal recovery to the Haber-Bosch process (Cinti, 2017). However, next to the production cost, the costs of storage and transport, that differ for each fuel, are crucial parameters that should be considered when choosing the fuel to produce.

The efficiency of the different energy storage techniques can be schematized on a diagram presented in the work of Aneke (2016) (Figure 2). We note that the chemical storage has a lower yield (30-45%) than batteries, "flywheels" or supercapacitors (80-100%). However, the discharge time is much longer which allows the chemical storage to remain one of the best solutions for the long term. In addition, the very low cost associated with large storage capacity benefits this technique. The efficiency of the system should therefore not be the unique criterion for estimating the total efficiency of the process. This figure also presents the most reactive storage systems (in time) for a specific power. From Fig. 2, it is clear that electric energy storage technologies using batteries and super capacitors are the most reactive storage systems. Additionally, they combine this high reactivity with an excellent efficiency (85-100%).

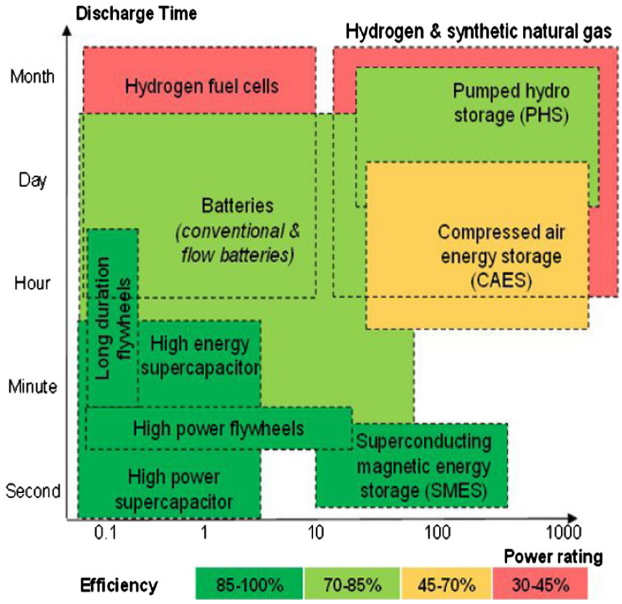

Figure 2: Energy efficiencies of different storage techniques (Aneke, 2016)

3. Power-to-Fuel: a solution for the future?

In the context of the energy transition, Power-to-Fuel, which is a technological integration of hydrogen production from water, appears as a promising option in combination with batteries.
Indeed, some studies claim that long-term storage (PtF type) will be unavoidable to reach 70-80% renewable energy integrations in the electricity grid (Limpens (2018), Connolly et al. (2016), Mathiesen et al. (2015), Jentsch et al. (2014)). However, it is the need for renewable energy in the

future electricity production mix for emission reduction that will fix these integration rates in the energy systems. For example, for some countries, such as France and Belgium, the role of nuclear power in the energy transition will have a great influence on the nature of the storage techniques needed, their capacity and the time for their development. PtF could not only be used as an energy storage technique, returning the energy in its electrical form using classical production, but also as a producer of fuels for long distance transport. In addition, this long-term storage could act as a stabilizer for the electricity network (German Environment Agency, 2016). A recent study of Lazkano (2017) shows that without considering nuclear power and considering the requirement that electricity supply must match demand at all times to balance the grid, intermittent renewables can not fully support the electrical need of the network without storage. In the absence of storage, excessive overcapacity of renewable energies would be necessary to ensure the balance of the network, which is economically and physically not feasible.

The PtF process provides a combined time and location balancing solution for a time when renewable energy will provide the bulk of electrical demand. Until recently, the recognition of Power-to-Fuel as an efficient storage technology has been weak. However, thanks to the existing power grid infrastructure, Power-to-Fuel offers significant benefits that would allow smart distribution, as presented in the study of Walker (2015):

- Highly efficient transport with gas losses of only 0.05% per 1000 km;
- Flexibility to simultaneously provide energy storage and ancillary services;
- Energy density significantly higher than competing energy storage technologies (except for H_2).

Indeed, Power-to-Fuel has a significantly reduced cost compared to other long-term energy storage technologies. It gains in benefits when comparison is made based on criteria such as energy portability, seasonal storage, and potential use as a fuel for mobility or heating. In addition, unlike other energy storage systems, particularly batteries, there is less requirement for the coupling between the power and the size of the storage. Power-to-Fuel offers additional development of natural gas infrastructure and operational flexibility. Based on these criteria, Power-to-Fuel is preferred for many applications, such as power distribution, network or independent power storage, and fuel storage.

Several studies highlight the importance of coupling two storage systems, one for short and one for long term, like batteries and Power-to-Fuel. The study of Gahleitner (2013) shows that in PtF connected to the grid, on average, only two out of ten plants would use a battery. On the contrary, in projects in which the renewable energy generator is connected directly to the electrolyser, 53% of the plants would use a battery. The batteries are suitable for short-term energy storage and maximize the life of the electrolyser. In addition, they can handle transient loads and peaks of power, and thus ensure the stability of the network and reduce the installed power of renewable energy.

Next to the high potential for energy storage, Power-to-Fuel allows also the production of renewable fuels: Power-to-Fuel technologies allow the integration of renewable energies into the transport sector. Excess energy produced by an increased proportion of renewables in the electricity generation can be stored as alternative liquid fuels. There is also the possibility of stabilizing the fluctuation of electricity production by means of chemical storage so that industrial processes can operate continuously and therefore with a significantly greater efficiency. The maturity of these different fuel production and storage techniques is presented in the work of Schemme et al. (2017).

Electric mobility is expected to play a key role for passenger cars, light commercial vehicles, buses and short-haul road freight. But even though the most energy-efficient option for the use of renewable electricity in the transport sector is its direct use in electric vehicles, electrification is difficult for some applications. Indeed, to reach long distances, electric vehicles need an additional liquid or gaseous fuel (as in hybrid vehicles) from a renewable source. Given this need and the limited availability of residual biomass, PtF becomes necessary to ensure a fully renewable energy supply for transportation. In addition, PtF can provide the renewable liquid fuels needed for aviation and provide a renewable energy supply without greenhouse gases for shipping.

For the short- and medium-term reduction of greenhouse gas emissions from fuels, particularly during their production, the potential of current technologies in combination with PtF needs to be considered. The storage of electricity by these technologies generates products that can be used to replace analog fossil fuels (natural gas and petroleum products) at least partially, which is very important if we consider the analysis of emissions of greenhouse gases. At present, more than two-thirds of anthropogenic greenhouse gas emissions are associated with the energy sector, of which about 40% is related to electricity and heat production and 20% to transports (Gallo, 2016). In addition, synthetic fuels produced from PtF have a purity significantly higher than that of conventional crude oil fuels, which can reduce the cost of conventional exhaust gas treatment systems (catalytic converters, particulate traps) (German Environment Agency, 2016). Indeed, the purity of the hydrogen produced by PtF is estimated at 99.999% (Matzen, 2015), between 90% and 92% for methane (Er-rbib 2014, ENEA 2016, E&E 2014, Götz 2016) and close to 100% for methanol and ammonia (Matzen, 2015). The use of these purer fuels, of better quality, with a higher calorific value, makes it possible to increase the efficiency of the combustion in all the existing systems.
A study by Lund (2015) shows that combined cycle gas turbines (CCGT) coupled with PtF are an attractive option for increasing the flexibility of the energy supply. A CCGT typically has a power ramp from 10 MW to 50 MW per minute, depending on the used gas or steam turbine, and the investment cost remains low with high electrical efficiency, up to 60%. In addition, existing gas turbine plants can be reused and coupled with PtF. In addition, CO_2 emissions are half of those of coal-fired plants. A major disadvantage for CCGT remains the relatively low price of electricity, which can reduce the attractiveness of CCGT as balancing power and marginalize its use in the electricity markets. However, the combination of a renewable energy gas and fuel system could be quite attractive as such, to offset the energy fluctuations of the renewable.

Finally, in a holistic view of the energy sector, Gallo et al. (2016) consider that technologies such as PtF can be generalized to PtX, where X can also be H, for Power-to-Heat, in cases where electricity is stored for heating or cooling purposes. A comprehensive report on Power-to-Heat is presented by the United Nations Environment Program (UNEP) in 2015.

4. Integration of renewable energies in the network

There are several technical barriers to the integration of renewables into the electricity grid:

- Lack of adequate infrastructure (transmission and distribution);
- Generation and demand are not flexible;
- Connection and operating conditions.

Indeed, an insufficient network infrastructure represents a significant obstacle for an efficient use of the available production from renewable. A lack of transmission or distribution capacity reduces the availability of electricity and may, in the case of insufficient transmission, require additional storage capacity. In addition, the capacity of the power system to integrate this energy can also be limited by insufficient flexibility in generation or demand.

According to a report from NERA (2014), the integration of a large fraction of renewable electricity into the current grid would require the adaptation of important infrastructures, including transmission and distribution networks. However, this adaptation could be minimized by the use of decentralized storage. Compared with the use of more centralized sources of renewable energy that are directly connected to the transmission network, this decentralized storage would thus require an extension of the distribution networks.

As a result of the reduction in renewable electricity costs, the cost of extending the grid becomes an increasingly important factor. However, the need for network extensions and additional storage capacities could be reduced by a balanced geographical distribution of renewable energy production, considering not only the availability of the resources but also the proximity of consumption.

As mentioned above, it is technically possible to integrate more intermittent renewable resources into the power system, even without additional infrastructure, provided that it is possible to reduce power generation punctually to avoid grid saturation. As a result, the ability of European energy systems to integrate increasing volumes of renewable energy is mainly linked to economic and political factors.

Demand-Side Management (DSM) is potentially one of the promising low-cost instruments that offers a source of short-term alternative flexibility and brings benefits to the integration of renewable electricity.
Demand management includes a wide range of means to modulate final electricity consumption and relieve the transmission and distribution networks. It can be used to reduce, increase or reschedule the energy demand. An optimum DSM could potentially match all fluctuations in production.
In practice, the technical potential of DSM is determined by the availability of flexible power capacities, the potential power demand restrictions, the duration of the requirements, and the effective energy storage capacity available in the facilities. Positive (i.e. decreasing charge) and negative (i.e. increasing charge) power capabilities are often different. Costs associated with DSM are divided into investments, variable costs and fixed costs. In addition to technical and economic issues, the DSM is also linked to the behavioral and policy-making aspects that affect the achievable potential of DSM when connected to renewable energy systems.
According to Lund (2015), DSM studies in the renewable energy sector show on average a 20% reduction in costs and a 10 to 20% increase in the use of renewables, for cases combined with energy storage. Lund (2015) also demonstrated the viability and benefits of DSM stabilization of effective frequency and voltage.

As highlighted in the review of Lund (2015), in recent years, several studies have put forward another technique for optimizing the electricity grid by integrating renewable energies: "Smart Grids" and "Micro-Grids". The concept of Smart Grids has generated a lot of attention and is seen as a key technology for an optimal integration of renewable electricity. Basically, it is an electricity grid where all the stakeholders (energy producers, consumers and network companies) are intelligently connected to each other. This "smart grid" includes the integration of distributed power generation and storage technologies, robust bi-directional information communication and a high degree of automation. This vision combines very well with the DSM, storage and especially the use of decentralized PtF. An important logic of a Smart Grid is to increase the reliability of the power supply and reduce the ecological impacts by integrating, regardless of size, all energy producers and consumers in the optimization of the network that could lead to significant savings and reductions in carbon emissions. In addition to technological innovations, the development of the Smart Grids can also include changing the structure of the electricity market. Accurate weather forecasts, load and markets (short-term) and the future development of energy demand (long-term) are also becoming important in this context. Storage could be a flagship technology for future Smart Grids (Lund, 2015).

About Micro-Grids, they have been proposed as a solution to integrate renewable energy into the power system and balance the supply-demand mismatch. Micro-Grids are local networks that provide electricity to local consumers. A Micro-Grids energy system can include local power generation (micro-CHP, small scale renewable energy), storage systems, controllable loads, and power system. In a wider power distribution system, Micro-Grids could function as a component of the larger network system to balance voltage fluctuations. During disturbances, they can be isolated from a larger system to secure the power supply in their own area (Lund, 2015).

The studies on DSM and Smart Grids show that the integration of renewable energy storage will have the advantage of improving the quality and stability of the network. Indeed, the quality of the power supply depends on voltage peaks, momentary failures and harmonics. To overcome these weaknesses, storage devices are often used to protect sensitive equipment. Power supply systems can also experience frequency and voltage oscillations. Unless damped, these disturbances can limit the network's ability to transmit energy and can affect the stability and reliability of the entire system. Knowing that the stability of the system requires response times of less than one second, it can be satisfied by a variety of devices, including fast response energy storage systems.

In conclusion, future infrastructure requirements and the overall costs of electricity supply are strongly influenced by the choice and geographical distribution of the different types of renewable energy as well as the overall design and planning of electricity supply system. To facilitate the integration of renewables, technical and regulatory measures, as well as broader efforts in the areas of research and development, should aim at the following objectives:

- Facilitate the use of on-demand management, respecting the law on the protection of privacy;
- Encourage in parallel the expansion of renewables and network infrastructures, which aim at a geographical distribution balance;
- Promote a balanced distribution of decentralized sites across different network levels and between different types of distribution networks (for example, on low and medium voltage networks in urban and rural areas);
- Support technological upgrades of large-scale, centralized renewable fleets on high voltage networks, resulting in increased capacity factors and decreasing variability;
- Stimulate the use of innovative transmission and "smart grid" technologies to relieve the network during high demand peaks.

5. Storage: centralized or decentralized?

As described in the previous section, to optimize an energy network with renewable energy, several parameters are involved, including the location of the production units, the storage units and the electricity consumption.

Electricity was originally produced by small thermal power plants in urban areas. As demand for electricity increased, it was cheaper to produce electricity more centrally in remote areas while investing in transmission and distribution systems to provide electricity to communities, households and consumers despite the energy losses associated with processing and transmission. However, the maintenance and construction of the network has become increasingly expensive. Today, transportation and distribution represent a significant fraction of the price of electricity.

Nowadays, the concept of decentralized energy is more interesting for individual households that produce their own electricity. While large networks sometimes become too cumbersome to manage, decentralized energy and smaller networks seem to be a more flexible and less expensive alternative. In fact, electricity produced from small, decentralized companies is much more profitable, especially when residual heat is used. Cogeneration facilities, which produce both electricity and heat, can recover about 90% of the input energy or more by using the heat generated during the electricity production. This is a well-known process, a large initial investment in heat networks and political support to become a more widespread electricity generation technique.
While massive power plants produce electricity continuously on the grid for most of their lifetime, decentralized power generators can be used in a more flexible way and provide electricity when and

where it is needed. Their adaptability is one of their main advantages in terms of overall network resilience, especially in case of disturbances and failures.
A combined, interconnected micro, mini and medium size smart grid architecture allows the coexistence of many different power generation systems. In the future, this decentralized system will enable consumers to become electricity producers (or "prosumers"). However, this evolution of the complexity of the network generates a much more difficult management of demand and consumption.

According to the literature, centralized and decentralized network systems have each their advantages and disadvantages, particularly in connection with storage.
For the centralized system, the cost of transport must be minimized. The most suitable storage method is chemical storage, thanks to Power-to-Fuel. In this case, the production of methane and easily storable fuels in liquid form (methanol and ammonia) is favorable. These fuels are stable and with a energy density, allowing storage on the short and long term at the production location. In addition, their transport costs are minimal, even negligible, which makes it possible to supply several sites with fuel to be transformed locally into electricity. Indeed, different networks for the transport of these fuels already exist. The natural gas network in Europe can be used to transport the methane produced by PtF. This network, already existing and highly developed, offers a large storage capacity for methane. Since methanol and ammonia are two stable liquid fuels, they can be easily transported in containers by road or rail. Regarding ammonia, several railway lines are intended solely for the transport of this compound, in particular in the Netherlands. In addition, in the United States, liquid ammonia pipelines already exist and serve the center of the country.
For the decentralized system, the most advantageous storage technique remains PHES and batteries for the short and medium term. For the long-term, PtF can directly produce hydrogen from the electrolysis of water. If the subsequent consumption of the stored energy is located on the site itself and no transport is necessary, hydrogen becomes an energy-efficient fuel. Then methane, methanol and ammonia can be produced for long-term storage or transportation.

To summarize, a decentralized energy system (local production and storage) has the advantage of being accessible to all by minimizing transmission and transport losses, unlike the centralized system where transportation can be expensive for lonely energy needs. However, having a large number of small power generation units can become more expensive than a single large centralized generation.
According to Bouffard (2008), a mix between these two production and storage methods is probably the best solution: to produce fuel in a larger centralized unit to reduce equipment costs, store at the same production site large quantities of these fuels and finally use these fuels in a decentralized network to be closer to the users. This decentralization of fuel usage will also help to develop local heat networks. Given the negligible cost to transport these fuels, this mix between centralization/decentralization is a promising solution but limited by the capacity of the grid. This alternative of decentralization of the use of fuels allows a better management of the network by reducing its load, a larger local flexibility and an optimal yield for the production of electricity and heat.

6. How to manage the excess of renewable energy?

One of the complex problems to deal with is the surplus of electricity during certain periods and the choice to be made, beyond the DSM, between storage in all its forms and the curtailment (cap on the injection of electricity into the network to avoid an overload or a drop in the electricity price).

According to Lund (2015), a simple way to regulate large amounts of renewable energy power in energy systems would be curtailment. It is used mainly in four situations: a saturated storage capacity, a limited transmission, an excessive share of generators with a non-flexible production and a price of electricity too low on the market. Curtailment is also used to cushion rapid changes in production and it can provide a power reserve capability. The curtailment always generates a loss of electricity, which could be avoided if the overall flexibility of the power system was increased.

Rather than reducing the renewable production by curtailment, the study of Simonis (2017) demonstrates that PtF provides a mean to transfer excess electricity from the grid to the gas grid or to a process consuming gas. Thanks to the existing gas network, PtF systems can help balancing the electricity grid and facilitate the use of renewable energies regardless of location and origin.
Any excess production of electricity can be used to produce gas and/or liquid if the system appears profitable. In real energy systems, an interruption of the PtF process can also occur due to operational constraints. Technically, it is not always possible to build PtF plants that functionally follows the peaks of the excess energy profile. However, according to Mesfun (2017), electrochemical processes have less technical limitations than thermal conversion processes, such as minimum operating times, minimum loads and power requirements. The curtailment can thus be minimized by coupling the PtF with batteries, to manage peak power periods.

Taking PtF plants into account in view of the increase renewable production, policymakers will have to ensure that there are adequate conditions to absorb the surplus of renewable electricity rather than waste it and to set chronological targets (e.g. stipulating the percentage of excess renewable electricity that must be absorbed by the grid in 2030, 2040, etc.). In this respect, it is interesting to note that the "Winter Package" of the European Commission stated that "the reduction (curtailment) of renewable energies should be carried out last". This directive motivates the PtF energy storage solution presented in the work of Simonis (2017): these conversion systems can be designed to absorb the large amounts of excess energy as a result of the increase of renewable energy production.
However, the PtF has limitations regarding the valuation of excess renewable energy. According to a recent study by Limpens (2018), PtF facilities have a certain cost and it is sometimes cheaper to opt for some curtailment, rather than adding a PtF facility with a low load factor. In this case, the investment costs are too high to make this excess energy profitable. The inevitable fraction of curtailment is estimated at 4-5%, which represents a reasonably low amount of energy. Beyond this value, PtF would start to become profitable to value this excess of energy.

A recent study of Vandewalle (2015) showed the impact of integrating PtF in the Belgian electricity grid, on the short and the long term. Regarding the distribution of electricity over a day, part of the excess electricity generated by wind and solar is converted into CH_4 by PtF, for direct storage. The rest of this excess electricity is not valued. This curtailment is done on wind and/or solar also depending on costs and technical constraints. During the night, wind power is not enough to cover the demand for electricity and gas-fired power plants produce electricity from the stored CH_4.

Figure 3, taken from a paper by Vandewalle (2015), shows a distribution between gas-fired power plants, PtF, renewable energies and curtailment in Belgium.

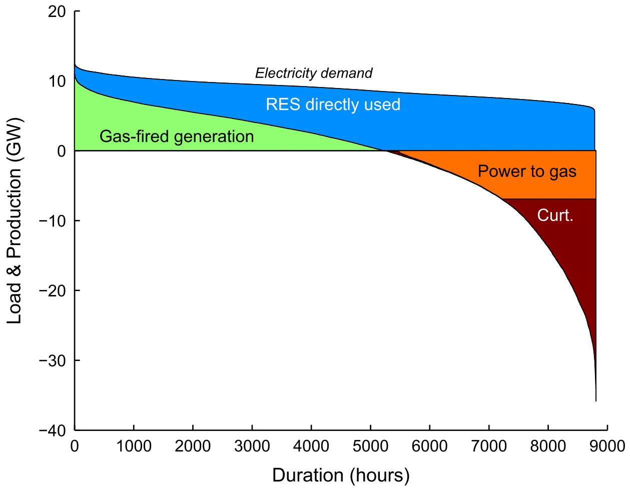

Figure 3: Demand curves and annual electricity generation distributed between gas-fired plants, renewable energies, PtF and curtailment in Belgium (Vandewalle, 2015).

Although renewable energy accounts for 100% of electricity demand, production and demand are not synchronous, resulting in relatively high residual load coverage (31%) by gas-fired power plants. Of the excess renewable energy, about 55% can be used by PtF to be injected into the gas network. Even though curtailment is decreasing thanks to PtF, 45% of the excess renewable energy is still lost. This energy could be valuably converted to fuels for transports through PtF. A market for these fuels produced from PtF during excess energy could be developed.

7. Cost of storage

The financial elements to be considered in an economic model, concerning the cost of renewable energies and storage, are very numerous. Different studies present these costs considering investment costs, energy production costs, maintenance, storage, transport, returns...

The LCOES (Levelized Cost of Energy Storage) is used to evaluate the costs of the various storage systems, for the short and long terms. The LCOES method is derived from the LCOE method: capital expenditure (CAPEX) is added to the annualized cost of the storage system over its lifetime. This sum is divided by the sum of the annual energy productions, which is also updated. This criterion is used to compare several currently relevant types of electricity storage techniques based on the installation configuration and the number of operation hours per year.

In a recent study by Jülch (2016), the LCOES was compared for four storage techniques: Pumped Hydro Energy Storage (PHES), Compressed Air Energy Storage (CAES), PtF and batteries. In this work, the storage techniques are dimensioned for a discharge power of 100 MW over a short time (4h), and over a long time (700h). The results of the LCOES analysis confirm that PHES and CAES are cost-effective technologies for short-term energy storage, while PtF technologies are more suitable for long-term storage (see Table 1 in Section 2). PHES, CAES and lead batteries are mature technologies that have been on the market for a long time. Most other technologies are still in a development or pilot phase, so cost reduction is expected in the near future, mainly for the Li-ion battery and PtF. The results of this study demonstrate that the design of the storage facility (for charging and discharging) has a high impact on the resulting LCOES, with the exception of the battery. In particular, PtF technologies should be carefully designed to provide low cost stored electricity. Overall, the results show that PtF systems will be the most economical option for long-term energy storage. Note that the LCOES of H_2 storage systems is slightly lower than the LCOES of CH_4 storage systems (Jülch, 2016).

According to the study by Götz (2016), even if the microeconomic evaluation shows that the price of synthetic natural gas (SNG) produced by PtF is not competitive with natural gas or even biomethane, to study the economic feasibility of this process, it is necessary to combine different parameters such as mobility, services and CO_2 taxes to obtain a better estimate of the total cost. Regarding a macroeconomic consideration, that PtF can help minimize the expansion of electricity infrastructure and increase the share of renewable energy in the transport and heating sectors, must be considered. Therefore, PtF can play a major role in assessing an ambitious transition of the energy system.
One of the important parameters in the development and adaptation of PtF to produce CH_4 or CH_3OH as chemical storage will be the carbon tax (price of CO_2) which will make it competitive or not compared to the production of NH_3. In the work of Trop (2016), comparisons were made in terms of technological efficiency and economic viability for five different chemical storage scenarios: NH_3, CH_3OH, CH_3OH produced from biomass, SNG from biomass, LNG (liquefied natural gas). The economic comparisons are based on IRR (Internal Return Rate) calculations, while the sensitivity analysis covers different independent variables such as carbon tax, electricity price and investment costs. SNG and LNG production have been shown to be economically uncompetitive with respect to ammonia and methanol production due to high equipment costs and low product prices. Ammonia production is the best choice for a carbon tax set between 0 and 83 €/t of CO_2. For a CO_2 tax higher than 83 €/t, the production of methanol would be the cheapest option. This study shows that the carbon tax could be the main motivator for the development and investment in technologies that use renewable energy sources combined with non-renewable CO_2 emissions to produce chemicals.

Finally, according to Gallo (2016), there are two main financial barriers to the deployment of energy storage: the first concerns the economic feasibility of integrating energy storage and the second concerns environmental regulation. The economic equation is complex to solve since energy storage technologies require significant capital expenditures and it is necessary to bundle several applications to achieve sufficient return. In addition, many applications are difficult to quantify and monetize, and require regulatory changes.

8. Case of Belgium

An essential element in the development of a single electricity market in the European Union has been the physical link between the different markets, which are typically national, with cross-border interconnections and market coupling agreements to ensure efficient European capacity. This market integration is also expected to increase price convergence over time.

According to a report of the IEA (2016), the Belgian electricity market was linked for the first time with France and the Netherlands in 2006 (trilateral coupling of markets). The entire western European region (CWE, Central Western Europe), including Germany and Luxembourg, was linked in November 2010. The CWE region was associated with the northwest region in February 2014 and the Iberian Peninsula in May 2014. This zone was extended to Italy and Slovenia in February 2015. It covers about 85% of the electricity demand in the European Union. In May 2015, the CWE region adopted a flow-based market coupling model where capacity is allocated by algorithms that optimize the total economic surplus of the order books of the different markets while respecting the physical limits of the network.

Belgium is therefore an interconnected country and electricity imports can be considerable. The Belgian high voltage power grid is owned and operated by Elia, the Transmission System Operator (TSO). In 2015, the transmission system had a total length of 3,655 km, including 891 km at 380 kV, 302 km at 220 kV and 2,462 km at 150 kV. The CREG (Commission for the Regulation of Electricity and Gas) has certified S.A. Elia System Operator (Elia) as the Belgian TSO for electricity. Investments planned by Elia for voltage levels above 70 kV are defined in the 2015-2025 Federal Development Plan. Investments for a voltage of 70 kV or less are defined in the regional investment plans. Elia estimates that its investment needs will total more than 2 billion euros for the next decade. Investments focus on interconnections with neighboring countries and network upgrades that are needed to connect distributed and renewable generations. Finally, significant replacement investments must also be made to address the aging of the network (IEA, 2016 Review).

However, in Belgium, the potential for renewable energy is relatively modest. The country is rather flat, densely populated and not particularly sunny. The use of hydroelectric solutions is already working at full capacity. On-shore wind power and, to a lesser extent, solar power are facing challenges in regional planning and public support. In the context of current technologies and social constraints, foreign biomass and off-shore wind have the largest potential.

In 2014, according to the IEA report, renewable energies made it possible to supply 18.8% of the Belgian electricity grid: mainly by bio-fuels and waste (7.9%), wind energy (6.5%), solar (4%) and hydro and geothermal (0.4%).

Regarding available storage, Belgium has a natural gas storage facility, an aquifer, located in Loenhout (Flanders). Its working capacity is 7.73 TWh, with a maximum output capacity of 6.44 GW. Under normal winter conditions, the Loenhout facility can (theoretically) send gas for 45 days at maximum flow rates. In addition, Belgium has another technique of storing electricity: the PHES of Coo-Trois-Ponts, with a total capacity of 5.0 GWh. The Coo power plant is able to operate at a full power of 1164 MW for 5 hours with a startup time of less than 2 minutes. This plant plays a new role in the management of the intermittency of wind and solar energy (http://corporate.engie-electrabel.be/fr/producer-local/hydroelectricte/).

Turbines/pumps can be quickly started to compensate for a sudden decrease in electricity production or to absorb some of the excess electricity.

A recent study of Limpens (2018) estimates storage needs based on the amount of integration of renewable resources in Belgium. Up to 30% renewable energy, short-term storage is favored considering the variation of solar production between day and night, and excess wind. This storage is dictated mainly by solar production during the summer. When 50% of renewable energy is reached, Belgium needs 15-25 GWh of storage. With more than 70% renewable energy, long-term storage becomes essential for off-peak periods without sufficient wind or sun. During the summer, the PtF units operate at full load during the day thanks to solar energy and at night thanks to the energy stored in batteries. Even though the electrical efficiency of PtF-to-Power is about 33% only, this technology is less expensive than installing more solar and wind, combined with curtailment. The balance of curtailment with storage amounts to about 3-6% of the production of renewable energy (see Section 6). It is a balance between the peaks of renewable energy production and the storage installed to absorb them.

In 2016, a study by PwC Enterprise Advisory revealed that nuclear energy should be considered in the Belgian energy mix, with the renewables, in order to reduce CO_2 emissions sufficiently. Nuclear and renewables are two complementary sources to meet the country's needs and they ensure energy reliability, being financially affordable and sustainable. If Belgium phases out nuclear power as planned by the federal government in 2025, CO_2 emissions will increase by 31% by 2030, and by 17% by 2050. The country will therefore not reach its objective regarding the reduction of CO_2 emissions. Moreover, without nuclear energy, Belgian energy production will not cover the national demand. Only a mix of a nuclear power production capacity of 6 GW combined with renewables of up to 67.4% of the total volume of electricity consumed, would cover the country's electricity needs in 2050. In this scenario, the presence of nuclear energy would ensure the conservation of relatively low electricity prices, compared to a purely renewable generation. In addition, an overload of the electricity network would be avoided, even in a situation of overproduction and low consumption. Finally, the control of the electricity network would remain secure by the presence of nuclear power that does not depend on climatic fluctuations. According to the PwC study, energy storage, renewable energies and nuclear power present the energy mix of the future in Belgium.

In August 2017, Elia published data for the energy mix of that month. Electricity generation came from the following energy sources: nuclear 69%, gas 17%, solar 5%, wind 3%, hydro 1%, and biomass 5%. With this energy mix, Belgium could easily achieve its European climate objectives.
However, in this report on the energy transition in Belgium, the cost of decommissioning a nuclear power plant is not discussed, neither the public opinion concerning this energy. Indeed, after Chernobyl and Fukushima, the Belgian population is not in favor of the construction of new plants. Belgian nuclear power plants are aging and should be renewed. In addition, the issue of nuclear waste is not considered in these scenarios, which skews the profitability of this energy.

The competition between nuclear and renewable is often raised. Nevertheless, the more nuclear power there is, the smaller the gaps between production and consumption.
The study of Limpens (2018) also shows that the use of PtF is inevitable for a 70% integration of renewable energy (without nuclear power). However, the share of PtF will be reduced to 35% considering 50% nuclear. In this case, dependence on renewable energies is estimated at 15%, compared to 35% in the case without nuclear power. This result comes from the "base load" behavior of nuclear power and to a consumption profile that varies little.

Finally, several questions arise concerning the Belgian energy future: with or without nuclear energy, would the integration of 80-90% of renewable energy be feasible? Will energy imports be inevitable? What is the potential of DSM in Belgium? Is a decentralized/centralized architecture feasible? To answer these questions, several research projects are ongoing in Belgium and may offer different scenarios to policy makers to optimize the Belgian energy transition.

9. Synthesis and Perspectives

As the work of Aneke (2016) demonstrates, in the traditional electricity grid, energy storage has not been considered as an active element. This observation can be explained partially by the electricity generation that was based, in the past, on reliable and flexible fossil fuels (a form of storage) and on nuclear power. Previously, the lack of interest in conserving energy and reducing greenhouse gas emissions has contributed to the low investment in renewable energy and in the storage of electricity. Nowadays, because of the increase in the amount of renewable energy resources, the need to conserve fossil fuel resources, the reduction of greenhouse gas emissions and the need to keep a secure electricity supply, energy storage is considered an integral part of the modern electricity grid.

In fact, storage has many advantages such as better energy management, a reduction of energy waste and an optimization of the energy restored in the system. Secondary energy storage such as heat and electricity helps reducing primary energy consumption (fossil fuels). It thus reduces CO_2 emissions and other greenhouse gas emissions associated with global warming. It can also play a crucial role in increasing the penetration of clean but intermittent renewable energy resources such as wind, solar and hydro in the power grid.
Energy storage also contributes to power grid planning, operation and frequency regulation. It helps maintaining the stability of the energy networks, improve power quality in micro-grid systems, and match demand with supply (Aneke, 2016).

According to the activity report of EASE (2014), energy storage offers thus added value to the entire energy system and can therefore not be clearly placed under one of the 3 segments – Generation, Transmission, and Distribution and Consumption – but it is involved in each of these categories.

Storage is often considered as the 4th element of the energy system, capable of being an element of generation, transmission and distribution or consumption.
Intermittent power generation can benefit from energy storage, including:
- Improve the reliability of production planning and production forecasts;
- Optimize the integration of wind and solar generators in the medium voltage network at their connection point;
- Mitigate network disturbances in areas of strong wind or sun penetration, and when production stops abruptly;
- Store wind and solar energy in times of excess production, avoiding curtailment.

It is obviously important to keep in mind that most energy storage devices offer several services in the energy system.

Indeed, energy storage has been recognized as a technology with high potential for the flexibility of the energy system, but its role in the market is somewhat complex since it includes both a demand and a supply function and therefore, does not fully correspond to existing regulations. This gap could discourage investment in energy storage. In addition, price distortions, royalties and lack of price transparency can have a negative impact on the costs of energy storage. The IEA suggests that policy makers should allow compensation for the multitude of services offered by energy supply, for example, value-based payment for reliability, energy quality, energy security and efficiency gains. According to Lund (2015), future models will have to take into account real-time prices, prices per service, and taxation on end products.

In the study by Gallo (2016), for a Power-to-Power (PtP) application with hydrogen including an electrolyser, a storage device and a fuel cell or a gasoline/turbine engine, the total efficiency is low (30-50%), which is a disadvantage as a source of power. In addition, the capital costs of this process are high, but the CAPEX for this storage size remains low. However, a PtF is a very promising technology because it can perform long-term energy storage, with a very low self-discharge rate and it can evolve to very large storage capacity sizes. This long-term storage will be more attractive in an energy transition scenario where renewable energies reach high proportions in the energy grid.
Methane, another energy vector produced by PtF, requires a conversion process, called methanation, and CO_2 input. Methane is three to four times more energy dense than hydrogen, but these additional manufacturing steps make PtF more complex, expensive and less effective in the end in the case of PtP (25-35%). The compatibility of methane with natural gas allows the use of all already installed infrastructures. As a result, it can replace the use of fossil-based methane while retaining existing structures (such as pipelines) and be used directly in existing user devices (such as boilers). Anaerobic digestion produces carbon dioxide, which allows PtF to be integrated into biogas, biomass, bioethanol and other industrial plants with CO_2-rich exhaust (Gallo, 2016).
In addition, the Power-to-Fuel which produces hydrogen, is then used in a Fischer-Tropsch synthesis, to form a liquid fuel. As with methane synthesis, the addition of new transformation processes increases the overall costs and reduces the overall efficiency. The main motivation for the development of PtF is to replace fossil fuels, in this case petroleum products, taking advantage of existing structures (such as the distribution infrastructure) and being directly used in current systems (internal combustion engines…) or energy systems that cannot run on electricity (aircraft, maritime transport...). Several different products can be obtained during the synthesis process such as methanol, ethanol, ammonia, dimethyl ether, diesel, etc.

As presented in the introduction, this document addresses the topics discussed during a meeting between Belgian energy experts and allows to report the various positive and negative points concerning the energy transition, and, especially, power-to-fuel.
More in-depth studies will have to be carried out to answer more precisely the various topics discussed, in particular on investments:

- What storage techniques and capacities will be needed based on a certain share of renewable energy integration?
- How to improve the electricity grid and adapt it to the needs of the future?
- How much energy can the demand side management handle?
- Will the CO_2 tax help reduce emissions and encourage societies to migrate to other energy sources?
- How should the criterion of curtailment be defined?
- etc

The answers to these questions, that are not exhaustive, will help to clarify the different ways to optimize the energy transition.

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