Renewables Grid Initiative

Background Paper for the RGI Workshop on:

Storage Needs, Options and Challenges Today and Tomorrow

Summary

Today it is broadly accepted that the share of renewable energy sources in the European power grid is going to increase substantially and will reach very high percentages in the future production mix. Expansion of storage technologies is often considered pivotal to allow for this renewables European power grid. This background paper discusses the role of storage and provides an overview of technologies within the context of a European power supply penetrated by high shares of electricity generation from renewable energy sources. The paper is written as support to the RGI Storage workshop and aims at contributing to the workshop a broad but general overview on storage technologies.

The operating characteristics of storage technologies have been attractive to grid operators as they provide them with resources that can adapt quickly to supply and/or demand changes. This feature has positioned them as a candidate for mitigating the variability of renewable generation. The fundamental operation of a storage technology is to convert and store electricity in another form and re-convert back to electricity at times when it is most valuable. Electricity can be stored through mechanical, thermal, electrical and chemical storage. A number of technologies that have emerged from these options including pumped hydroelectric, compressed air, flywheel, batteries and hydrogen.

According to its operational characteristics, each technology can respond to certain needs of the system. Hence, as the technical challenges that immature technologies face are being dealt with, identifying the applicability of each technology will become less of a demanding task. However, the current cost of most storage technologies in combination with the lack of a coherent business model and favourable market conditions have proved to be insurmountable obstacles for investors. Nevertheless, the expected large renewables market will require a significant amount of flexible generation assets. This will essentially keep storage in the forefront and push all relevant stakeholders to overcome any technological, operational and/or policy challenges.

From grid expansion to storage

The first RGI workshop looked upon transmission technologies for the much needed expansion of the HV transmission grid. This expansion is required both between and within regions and serves two purposes.
Firstly, it allows the growing capacity of renewables to be connected to the HV transmission grid and transferred nationally. Secondly, it can accommodate for seasonal and medium-term[1] variable generation from renewables (mainly wind and photovoltaics) by transferring power from one region to the other. In

[1] Throughout this document the variable generation of renewables is classified as intra-day, day/night, medium-term (day-ahead) and seasonal

About the Renewables-Grid-Initiative
The mission of the Renewables-Grid-Initiative (RGI) is to promote effective integration of 100% electricity produced from renewable energy sources. RGI was launched in July 2009 by a coalition of Transmission System Operators (TSO's) and Non-Governmental Organizations (NGO's). RGI's members originate from a variety of European countries, as it consists of TSO's from Belgium (Elia), France (RTE), Germany (50Hertz Transmission), Netherlands (TenneT), Switzerland (Swissgrid), UK (National Grid), and NGO's such as WWF International, Germanwatch, RSPB (UK) and Natuur Milieu (NL). RGI advocates national and EU authorities to strive for an efficient, sustainable, clean and socially accepted development of the European network infrastructure for both decentralised and large-scale renewable energies.

this way, a region that experiences low renewable generation and high demand can import electricity from another region with low demand and high renewable generation. This implies that the region's renewable generation and demand profiles are complementary, which is often the case for wind and PV in northern and southern Europe. Improved medium-term forecast errors and EU-wide coordination could allow for the efficient utilization of these complementary profiles.

However, grid expansion has its weaknesses. Transmission within or between countries cannot accommodate for all types of variable generation from renewables. In extreme weather conditions, seasonal or day/night variations could result to insufficient EU-wide renewable generation.
Furthermore, Member States' growing renewables capacities and any resulting overcapacities could have a significant effect on the demand of excess electricity. This would reduce the effectiveness of the transmission grid's expansion between regions. This result would rather be an outcome of ineffective EU-wide coordination and energy vision as opposed to a shortcoming of grid expansion. However, it does remain a possibility that could potentially become reality for the future EU power sector.
An additional hurdle towards expanding the transmission grid is public acceptance and lengthy permitting procedures.

The above weaknesses do not imply that grid expansion is not required but it is rather certain that it will play a vital role towards the effective integration of large shares of renewables. What these limitations do signify is the necessity of complementary means of mitigating the variability and uncertainty of renewables that could contribute towards these limitations of grid expansion. Such an option could be electricity storage.

Electricity storage

Electricity, as with other forms of energy, is the result of the conversion of a primary energy source. In the case of wind and PV, the primary energy source is the kinetic energy of wind speed and photonic energy for PV. The variability and unpredictability of large shares of renewable generation creates additional problems towards the constant balancing of generation and demand. This in effect has brought storage technologies to the forefront. In principle, electricity cannot be stored in its form. Hence, electricity storage refers to the result of converting electricity to another form of energy. The purpose of storage is to re-convert it back to electricity when it is most required. Electricity can be stored through mechanical, thermal, electrical and chemical conversion.

Storage can play a fundamental role in a power grid penetrated by high shares of renewables as it can avoid curtailment of renewable generation and capture any excess electricity, which can be used in periods of low renewable generation. This offers a fundamental characteristic of storage as it can accommodate for both troughs and peaks of variable renewable generation. Furthermore, an important feature of storage is that it increases the self-sufficiency of a region. On the transmission side, it can alleviate constraints on the grid posed by increasing shares of renewables.

Nevertheless, storage comes with a few disadvantages and uncertainties. Firstly, most technologies are immature and/or lack operational experience for large-scale applications. Secondly, storage technologies are, to different extents, inefficient. Lastly, the lack of a market framework for storage along with economical factors like uncertain electricity and technology costs, in effect make storage technologies less attractive for investments.

Storage characteristics

The three characteristics of a storage technology that to a large extent determine its range of applications are its rating, response and efficiency. These characteristics are broad enough to categorize each storage technology and define its suitability for various applications.

Rating
The rating of a storage technology refers to its power and energy rating. The power rating is the rate at which the technology can supply electricity, while the energy rating is the amount of electricity that can be generated. In some technologies the power and energy rating can be designed independently while in others it is not possible. In principle, the power and energy rating define the discharge duration as the time needed for the energy stored to be discharged at its rated power, without any re-charging. Similarly, the charge rate signifies how soon the storage technology would be available and fully re-charged.
Storage technologies can be identified by classifying them between those of higher energy/lower power rating and discharge time, and those of lower energy/higher power rating and discharge time. In practical terms, the first category refers to those technologies capable of delivering large amounts of electricity for a long period of time (minutes to hours), and the second to those capable of delivering limited amount of electricity at a high discharge rate for a short period of time (seconds to minutes). Due to their very high discharge rate for short periods of time, some technologies are termed to have an 'emergency' power capability[2] as they can accommodate for urgent needs that occur frequently or infrequently and demand high power for a short period of time.

Response
What is termed here as response, is a set of characteristics that are time-focused and define how quickly a storage technology can respond to changes. Response has two characteristics that define how quickly the storage technology can start operating (start-up time), and the time required to operate from 0 to its full discharge rate (deployment time[3]). Because most types of conventional generation have start-up and deployment times of several minutes to hours, storage technologies need to be able to respond to within a few seconds or minutes to be in a better position towards generation and/or demand changes.

Efficiency
As with any conversion process, storage has losses and its efficiency plays a crucial role towards developing a business case for a technology. According to the type of technology, efficiency varies from around 50% to up to 90%. An additional source of losses, that can overall reduce the conversion efficiency of a storage technology, is losses incurred while the technology is not in use. Each storage technology has a specific amount of time that it can retain its energy stored and levels of self-discharge. This characteristic is vital for storage technologies that are not used frequently.

Other characteristics of storage technologies include:
- energy and power density[4]
- charging costs[5]
- operating costs[6]
- lifetime
- reliability
- power conditioning[7]
- portability

[2] Operating a storage technology at these 'emergency' ratings results in lower storage efficiency and increased equipment wear and tear.
[3] A similar characteristic is the ramp rate, which refers to the rate the storage technology can change its output.
[4] Energy and power density refer to the amount of power and energy a technology can deliver for a given volume or mass. This has direct impact on footprint and space requirements that could prove to be substantial in urban areas.
[5] Cost of buying electricity to charge the storage technology and make up for efficiency losses.
[6] Labor, plant maintenance, equipment costs.
[7] Most storage technologies require some modifications to comply with the requirements of the local grid.

Potential Applications

Electricity storage has provided benefits to the power sector through a range of applications over the past decades. However, with increasing shares of renewables, the necessity of storage and the emergence of additional potential applications have intensified. The majority of applications have requirements that are related to the power/energy rating, deployment time and discharge duration of the storage technology. These applications could be classified according to which part of the power sector chain they provide benefits to: generation, transmission, distribution and end-user. In some applications it is debatable when a storage technology provides benefits to generation, transmission or both. For this reason, we will provide a general overview of potential applications related to generation and transmission capacities[8].

Arbitrage: Electricity is bought at periods of low demand when the price is low to charge the storage technology. Thereafter, the stored energy is re-converted back to electricity and sold at periods of peak demand and high prices. Typically, a discharge of 2 hours (up to 5 hours) is required. The operating costs, electricity prices and efficiency of the technology are vital as many financial transactions are required for this application.
Renewables angle: Renewable generation can greatly benefit from arbitrage due to day/night differences in generation. Particularly for wind, dependant on the wind profile, generation could be high during off-peak periods (during the night). Hence, storage technologies can provide this much-needed time-shift. Moreover, renewables curtailment could be avoided altogether during periods of peak generation, low demand and/or congested transmission capacity. Particularly in the coming years, the latter could become a common phenomenon due to the expected high growth of renewables penetration (especially for remote areas) and the uncertainty regarding grid expansion.

Generation/Transmission capacity displacement: The capacity that storage offers could displace of transmission capacity. The storage technology can mitigate the need for this additional capacity at times of insufficient generation or transmission. The operating characteristics of such applications are dependent upon the market conditions that exist. For example, whether the generation capacity cost is included in wholesale energy prices or whether and what capacity payments mechanisms exist in the market. A key feature of storage technologies for this application is its reliability. The discharge period required ranges between a few hours up to several hours. For this application, storage would compete with demand side management measures (distributed generation, demand response, energy efficiency).
Renewables angle: Wind/PV large-scale installations require dedicated storage technologies to provide a generation profile that is similar to that of a baseload conventional power plant, i.e a smooth generation output. This combination effectively removes intra-day and/or medium-term variable generation and allows renewables to displace conventional generation.

Balancing: Variations in supply and demand can lead to balancing differences and create system frequency instability. This requires generation resources to follow demand either in an upward or downwards fashion. The up or down regulation required to avoid this issue can be supplied by part-load conventional power plants. Conventional power plants can be operated at part-load in order to be able to adapt to imbalances. If conventional power plants are not designed to operate at part-load and/or provide variable output, storage hydro plants (non-pumping) help importantly. This can have significant negative impacts on fuel consumption, equipment lifetime and maintenance, and CO_2 emissions. Additionally, as renewables penetration increases, the available conventional capacity will be limited. Storage can be used for balancing through adjusting its charging and discharging rate. The features of storage technologies that are important for balancing services are the deployment time, discharge rate and efficiency. Balancing services respond to supply/demand imbalances in different timeframes and are classified as primary[9], secondary and tertiary. The deployment time requirements range within a few seconds (primary), to a few minutes (secondary) and up to 10 minutes (tertiary). Accordingly, the discharge time ranges from 15 minutes (primary and secondary) to up to a few hours (tertiary). Efficiency (higher for primary/secondary and lower for tertiary) is also important for the applicability of storage technologies, as primary and secondary

[8] Storage can also provide voltage support and improved power quality
[9] Balancing supply/demand on a minute-by-minute basis

require frequent discharge cycles in contrast to the infrequent use of tertiary. The electricity price at which the storage technology is charged/discharged is also key towards its financial viability. As with capacity displacement, storage would compete with demand side measures for balancing services.
Renewables angle: In a system of large penetration of renewables and reduced available part-load conventional generation, intra-day variations in renewable generation can increase the need for primary and secondary reserve. Accordingly for tertiary reserve, the seasonal variability of renewables could potentially increase its required capacity. The above factors constitute an increasing need for additional balancing capacity to be supplied by other means such as storage.

Storage strategies

Storage technologies can aid in the grid integration of renewables in two ways; by system-focused storage strategies, and by dedicated storage technologies to each renewables plant. They both aim at compensating for the variability of renewable generation using a different approach. Essentially, system-focused storage mitigates variable generation while dedicated storage removes it.

System-focused storage strategies are best suited for balancing applications. Storage technologies need to have rapid response and short deployment time as they aim at mitigating supply/demand imbalances by offering additional available capacity to the grid operator of a particular area.
Dedicated storage strategies are best suited for capacity displacement and arbitrage. A dedicated storage technology smoothens the variable generation of a renewables plant; thus re-positioning the renewables/storage system in the market as a predictable generation asset and enabling it to seize power market opportunities. This enables this hybrid power plant to operate either as a baseload, mid-merit[10] or peak plant. Depending on the renewable source profile and the selected operational strategy, the characteristics of the storage technology can be defined.

It is most likely that a combination of system-focused and dedicated storage strategies is required for the most efficient grid integration of renewables. Dedicated storage would most be suited for large-scale remote renewables power plants as it could provide significant benefits; on the generation side, by smoothening the plant's generation profile it would reduce the economic risk of intra-day forecast errors, and on the transmission side it would reduce the required transmission capacity. On the contrary, depending on the case system-focused storage for a particular area could prove to be the more optimal solution.

Overview of storage technologies

Storage technologies can be classified according to their conversion type. Within each conversion type key technologies are emerging:

Conversion	Technology
Mechanical	Pumped hydroelectric
	Compressed Air Energy Storage (CAES)
	Flywheels
Thermal	Molten-salt
	Other various methods of thermal storage
Electrical	Supercapacitors
	Superconducting Magnetic Energy Storage (SMES)
Chemical	Batteries
	Hydrogen

[10] A mid-merit power plant essentially fills the gap between baseload and peak plants. It operates between 30-60% of its capacity using its flexibility to follow demand patterns (load following).

Each of the above technologies is in a different level in terms of maturity, implementation and costs. Thermal storage, supercapacitors and superconducting magnets are not yet fully developed technologies but could play a role in future storage systems and should be included in a broader overview of storage technologies. Pumped hydroelectric, CAES, flywheel, batteries and hydrogen will be briefly described in the following pages[11].

Pumped hydroelectric

In pumped hydroelectric storage[12], electricity is stored in the form of dynamic energy through pumping water from a lower to a higher reservoir. This mechanical work is performed through electricity bought at period of low prices. The water is released during periods of high demand and electricity is generated through turbines. The key components of a hydro system are the turbine/generator equipment, the high and low reservoir and the passage that the water is released.

Hydro is most suitable for large-scale applications and its capacity can reach up to 1-2 GW with efficiency of the order of 70-85%. Hydro is a prominent candidate for complementing renewable generation, as it can be suitable for accommodating different types of variability. As with other storage technologies, it can store any excess renewable electricity during periods of high generation/low demand for later use. Also, hydro can provide electricity during peak periods and reserve capacity. Over the past years, hybrid wind/hydro or PV/hydro systems are being developed to store electricity directly. This improves the overall efficiency of the process and directly smoothens the variability of wind/pv. Hydro's deployment time is within a few seconds, which makes it also suitable for stabilising the network's frequency and voltage caused by rapid generation and/or demand changes.

Pumped hydroelectric storage is an established, mature technology with many years of operational experience across a number of countries in Europe. The storage capacity of hydro plants in Europe is by far the largest amongst storage technologies. However, developers of such plants, face several difficulties. Firstly, hydro plants can only be constructed at locations of particular geographical features (significant amount of water, altitude difference). Secondly, when a location is deemed suitable, project developers face public and/or political resistance due to environmental concerns regarding the plant's impact on the landscape and natural life. For these two reasons, the further growth of hydro is considered rather limited. Currently, in Europe there are a few potential new sites that could be developed into large-scale hydro plants but it is not expected that Europe will experience increasing shares of hydro capacity. However, in Switzerland and Norway, the installed pumped hydroelectric storage power is planned to increase several GWs within the next 10 years.

Compressed Air Energy Storage (CAES)

In CAES, energy is stored through compressing air so that at a later time it can be released to drive a turbine. The compressed air is stored either into underground geologic formations[13] (for large-scale applications) or above ground in a tank (for small-scale applications). The main components of such a system are the motor/compressor, the air storage facility and the turbine/generator. CAES's function is similar to hydro, as it buys electricity at low prices to store it and re-generate electricity at periods of high demand.

CAES is mainly suitable for large-scale applications with current efficiency levels ranging from 45-55% and deployment time of 10 minutes. The low efficiency levels of CAES can be attributed to both the losses through the conversion process but also due to the need to re-heat the decompressed air upon removal from the storage facility. CAES is a relatively mature technology but with proven operational experience in

[11] Costs related to these technologies still involve a high degree of uncertainty as most of them have not yet achieved wide-scale commercialization. It is beyond the scope of this background paper to include economic considerations for these technologies and the focus will rather remain on their operational features and applicability

[12] For the rest of this document pumped hydroelectric storage will be referred to as hydro for simplicity

[13] Cavern type such as salt formations, aquifiers, depleted natural gas fields

Europe only in one plant in Germany (290 MW). The promising aspect of CAES lies within its forthcoming development of its process to an adiabatic[14] one. In adiabatic storage, the heat produced through compression is retained[15] and re-used to heat the de-compressed air before driving the turbine. This is implemented through a natural gas-fired engine. This approach has not yet been implemented on large-scale installations but its efficiency is expected to reach up to 70-80%.

CAES, or A-CAES for adiabatic storage, has similar applications to hydro as they have both have large discharge times of order of several hours. Hence, as A-CAES develops into a mature large-scale technology, it can also be applied for smoothing variable renewable generation, storing excess renewable generation and reserve capacity.

As with hydro, CAES's main hurdle towards its wide-scale commercialisation lies on the availability of suitable geological formations to store the compressed air. Certain locations will favour the installation of CAES plants while in some countries the installation of such plants will be limited.

Flywheels

Flywheel energy storage systems store kinetic energy through the rotation of a rotor. Currently, such systems use electricity (through a motor/generator) to accelerate the rotor but in the future, systems that use mechanical energy directly could be developed. The amount of energy stored is proportional to the rotational speed of the rotor. The stored energy is re-converted to electricity through the motor/generator and effectively reduces the rotor's speed. The main components of such a system are the rotor, motor/generator and bearings[16].

The operational characteristics of flywheels position them a suitable solution for small-scale applications such as primary response (frequency regulation). Flywheels can achieve very high efficiency of the order of 90-95%, deployment time in the range of milliseconds and discharge time from milliseconds to up to a few minutes. Flywheel plants usually comprise of several flywheels of up to 5-10 MW each. Such systems have not yet reached maturity and there is not a lot of operational experience. However, the technology is developed and plans of flywheel plants in the US are being implemented. Currently, flywheels for large-scale applications are not available and are rather at a research stage.

Flywheel systems are not expected to experience any non-operational hurdles towards their implementation.

Molten salt

Different methods have been implemented for thermal storage. Typically, a thermal reservoir is maintained at a temperature above or below ambient temperature. When needed, the stored thermal energy can be converted to steam to drive a turbine for generating electricity. Thermal storage systems usually have large discharge times, efficiency levels of the order of 90% and are intended for large-scale applications. Depending on the reservoir size they could reach power ratings of several tens of MWs.

A promising thermal storage method is the use of molten salt[17] to retain heat collected through a solar plant such Concentrated Solar Power (CSP). The salt melts at a cold reservoir before being heated through the solar collectors and stored at a hot reservoir. Molten salt could be used as both the working and storing fluid due to its high heat capacity. Molten salt is a developed technology with a few CSP/molten salt power plants already operating in Europe.

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[14] Adiabatic refers to a process with no heat transfer

[15] Heat can be retained in fluids (hot oil, molten salt solutions) or solids (concrete)

[16] The rotor is suspended by the bearings inside vacuum to reduce friction. For reduced friction magnetic bearings are used

[17] Molten salt is a mixture of 60% $NaNO_3$ (sodium nitrate) and 40% KNO_3 (potassium nitrate)

Besides molten salt, other forms of thermal storage exist that are mostly under development (ice, cryogenic). Additionally, a promising and cost-effective method of thermal storage has proven to be distributed heat storage for residential applications.

Supercapacitors

Supercapacitors are a developed technology but yet unproved on a commercial scale. They differ compared to conventional electrolytic capacitors[18] as they have significantly higher energy and power density. They offer efficiency levels of the order of 95%, high discharge and charge rates. As they have high self-discharge they need to operate under frequent discharge cycles. Their deployment time is in the millisecond range, which along with the rest of its characteristics position them as a candidate for small-scale applications such as frequency regulation. The power ratings of supercapacitors are up to 0.3 MW but in the coming decade it is expected to reach levels up to 30-50 MW whilst maintaining their fast discharge time.

Superconducting Magnetic Energy Storage (SMES)

SMES, as with supercapacitors, are a developed technology with no commercial experience. SMES store energy in the magnetic field of a coil made of superconducting material. They require a power-conditioning unit such as an inverter as they use DC to store energy. Also, a cryogenically cooled system is needed for the coil. SMES can reach power ratings up to 10MW and efficiency levels of the order of 95% at high charge and discharge rates. Their deployment time is within the millisecond range and they are well suited for frequency regulation. A key characteristic that differentiates them from supercapacitors is their ability to store energy with practically zero self-discharge.

Batteries

Batteries use electrochemical processes to store energy. This process typically consists of a cell, two electrodes and the electrolyte material. As batteries use DC, an inverter is required in each battery system during charging and discharging. A chemical reaction[19] between the electrodes and the electrolyte creates electron flow (electric current) and electricity is transmitted through an external circuit. This process is reversible allowing the battery to re-charge by applying a voltage across the electrodes. These systems are referred to as static batteries. The most common materials are lead-acid (L/A), nickel-cadmium (NiCad), lithium-ion (Li-ion), sodium/sulphur (Na/S). Vanadium-redox (VRB) and zinc/bromine (Zn/Br) are battery types termed as flow batteries. Their difference compared to static batteries lies in the fact that the electrolyte material is stored in a separate tank from the stacked battery cells. During operation, the electrolyte is transported between the electrolyte tank and the stacked cells. The key advantage of flow batteries is that the electrolyte material can be easily increased or replaced. This essentially provides flexibility in the scalability of the energy and power rating of flow battery systems.

Batteries are most suitable for small-scale applications (balancing services) up to 7 MW for flow batteries (VRB) and for medium-scale application up to 50 MW for static batteries (Na/S). Depending on the battery type the efficiency levels range between 70% and 90%, and deployment and discharge times range from seconds to a few hours. This set of characteristics make batteries attractive for applications that require frequent discharge cycles. Particularly, there is increased interest for batteries in two areas; decentralized storage aimed at mitigating the variability of renewables and grid congestion, and vehicle-to-grid[20] applications.

[18] An electrolyte solution between two solid conductors is used to store energy

[19] This process is termed oxidation-reduction. Ions in the electrolyte supply electrons in one electrode and accept electrons in the other

[20] Vehicle-to-gird applications refer to plug-in electric cars that sell electricity back to the grid by either discharging or adjusting their charge rate. This type of application is not expected to become a reality until an increased share of electric cars is present in the market. Even then, vehicle-to-grid is expected to face significant obstacles due to the reluctance of car owners to discharge their batteries

As with flywheels, battery systems are not expected to experience any non-operational hurdles towards their implementation.

Hydrogen

In hydrogen storage, electricity is converted to chemical energy through a reversible electrolysis[21] process. The main components of a hydrogen storage system are a cell, the electrolyte material, electrodes and water. As with batteries, an inverter is required due to the fact that hydrogen systems operate with DC. The produced hydrogen is stored underground or in a tank above the ground, as with CAES. It is then used in a gas turbine to generate electricity. Typical configurations for hydrogen cells are proton exchange membranes or alkaline ones.

Hydrogen storage systems are still being developed and they are yet to be implemented on a commercial scale. Its low efficiency (20-50%) and high energy density constrain it to large-scale applications with long discharge cycles, essentially positioning it as a suitable candidate to mitigate the seasonal variability of renewables. Additionally, its scalability and flexibility are features that are attractive for decentralized applications.

The main operational challenge that hydrogen faces is related to the maturity of the technology. Currently, demonstrations have been limited to a couple of MWs. Given the suitability of hydrogen for large-scale applications, the success of hydrogen is dependent upon its ability to retain satisfactory levels of efficiency on a large-scale. Another possible obstacle hydrogen might need to overcome lies in the public's perception of hydrogen as a threat to public safety.

Challenges ahead

Besides the technology challenges some storage options face, there are other challenges that are related to storage as a whole; mainly the uncertainty of the business model for storage, and the lack of a favourable market framework.

From the perspective of the grid operator a storage technology can be seen as a generator or load depending on whether it is charging or discharging. This poses the question on who will be the likely operators and/or owners of storage facilities. Large and small utilities, and independent producers are the prominent candidates for this role. Utilities have been reluctant to take this role, as it currently does not offer them a viable business case for such investments. The price difference between charging and discharging electricity does not offer sufficient economic returns to account for capital and operation expenses, and efficiency losses. Moreover, the uncertainty regarding electricity prices makes it more evident that this price difference alone is not enough in order for investments in storage technologies to be realised. Market rules that are specifically targeted for recognizing the value of storage, such as rapid response and its effect on balancing requirements, are required. Moreover, schemes that favour the development of storage technologies could be implemented. For example, renewables developers could be required to provide compensation through storage capacities. Feed-in-tariff schemes that capture the benefit of combining storage technologies with renewables plants could incentivise such renewables/storage investments. Alternatively, promotion schemes, similar to the ones offered for renewables, could be applied to storage technologies.

Under current levels of renewable penetration, growth in storage capacity is not deemed necessary. However, the technical/operational and market challenges of storage need to be assessed carefully because storage features as a possible option for mitigating the variability of large shares of renewables.

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[21] During electrolysis, DC is used to separate elements of a substance such as hydrogen and oxygen from water