FLEXIBILITY ROADMAP FOR A NEAR 100% RENEWABLE ENERGY SYSTEM

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ABSTRACT

This paper presents an extensive review of flexibility options available now and in the future to enable high penetration levels of renewables in power systems. The study presents a comparison of an extensive list of flexibility options available from the supply side, demand side, market side, system operations and storage technologies. Each option has different time, cost and capacity characteristics. The results show that ample flexibility options are available over the relevant operational timeframes. Further, a roadmap is presented, for power system flexibility needing to accommodate very high penetration levels of variable renewable energy generation in power grids. We distinguish three key penetration regimes and discuss the key challenges for the needed power system transformation.

INTRODUCTION

Carbon dioxide emissions from burning fossil fuels are responsible for more than half of carbon emissions contributing to global warming [1]. Blunting the worst effects of climate change requires moving power systems away from fossil-based fuels. The three most cost effective and prevalent alternatives are energy efficiency, solar power, and wind power. Transitioning to low carbon energy sources has become an economic and technological possibility, as the cost of wind and solar power begins to match traditional technologies [2]. Depending on such renewable resources, however, means relying on variable and less predictable energy sources. An important question is how power systems depending primarily on such resources can operate reliably.

Electric power production and consumption must occur simultaneously. Balancing supply and demand has historically been accomplished by adjusting the output of certain controllable power plants to maintain the system frequency in some predefined acceptable band. This practice largely continues today, except that the variable output of wind and solar plants increases the need for flexibility in the power system to respond.

Broadly speaking, flexibility is the ability of controllable power system components to produce or absorb power at different rates, over various timescales, and under various power system conditions. To date, controllable power plants used to address load variability have done double-duty to cover the additional variability from renewable resources. The stresses from this business-as-usual approach are already being felt as conventional generators reach their flexibility limits. Although it is tempting to think that the solution to this issue is energy storage, other options could be used to provide the needed flexibility including demand, networks, or adjustment of system operation rules.

This paper presents results from two projects on the investigation of the role of power system flexibility in power systems with high penetration levels of variable renewable energy sources (VRES) [3], [4]. Results have been reviewed by panel of experts in series of webmeetings followed by written comments. We first present a broad overview of options that can be used for the provision of power system flexibility and then discuss the key challenges for the transition to systems with very high VRES penetration levels. The paper concludes with the key steps required for enabling such a transition.

OVERVIEW OF FLEXIBILITY OPTIONS

Power systems should deploy the most economic resources for provision of energy and operational flexibility. New flexibility resources will compete with the flexibility capabilities of the existing system, such as network expansion and existing supply flexibility. A broad categorisation of flexibility options is presented in Figure 2, based on five basic flexibility categories:

1. **Supply**:
Power plants have traditionally provided nearly all system flexibility. Flexibility options in power supply include conventional generation systems (coal, gas, oil, biogas, CHP and nuclear) but also flexibility provided by VRES.

2. **Demand**:
Flexibility options in demand side are significant. Demand management programs enable two-way communication with loads as small as 5 kW. Such options, including demand management in electricity sector (energy intensive industries, services and smart applications) and options that come from the electrification of other sectors, as electric vehicles and heat pumps and water heating.

3. **Energy Storage**:
Energy storage can be seen as both generation and

demand in the system, allowing the time-shifting of energy between periods of over- and under supply from VRES. Key options here are pumped storage, (AA-) CAES, flywheels, batteries, as well as hydrogen and its successor power-to-gas.

4. **Network**:
Power system transmission and distribution networks are a key enablers of flexibility in the system, allowing the spatial sharing of flexibility resources. Strengthening the network and alleviating congestions effectively reduces VRES variability by netting often-offsetting changes in generation over larger geographic areas. Key options here are increasing the capacity of network lines (HVAC or HVDC technology) or improving the network utilisation by adding power flow control devices (like Phase Shifting Transformers, FACTS devices, HVDC lines).

5. **System**:
Improvement of the system operation principles can be highly beneficial for better VRES integration and for uncapping the flexibility resources of the system. Key options here is the tuning of market operation rules (e.g. reducing gate closure times) and improving market integration by the expansion of market and control zones (which in turn will allow effective reduction of VRES variability due to spatial aggregation).

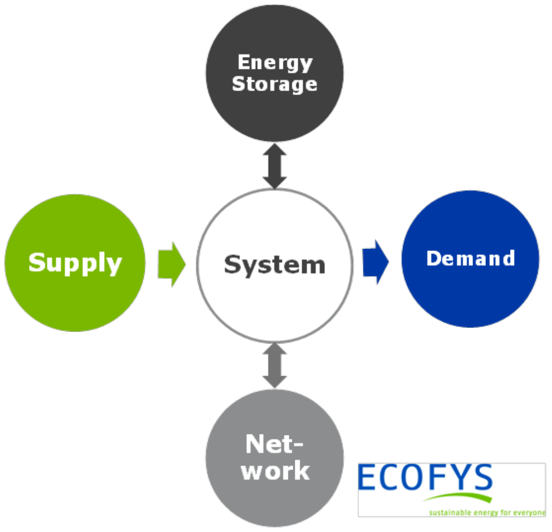

Figure 1: Categorisation of power system flexibility options

MAPPING OF FLEXIBILITY OPTIONS

The report [3] presents detailed factsheets with the key characteristics of each of these options, allowing a comparison of their effectiveness. The key conclusion of the analysis is that different flexibility options are best suited to different operational timeframes. Figure 3 shows a summary of the potential of the analysed options with respect to three key operational timeframes: short term flexibility (balancing markets with a timeframe of up to one hour), mid-term flexibility (spot markets - up to days), and long term flexibility (future contracts – seasonal variations). Colour shades show the suitability of the technology. As expected, the main mature options are on the supply side; on the demand side, key mature option is the large-scale industrial DR, while pumped hydro is the main mature storage technology. Most of the new demand and storage options are small scale technologies. The development of these options depends on the enabling of communication and control infrastructure, which for such small scale units will represent a relatively higher share of costs.

The variety of options show that there are several options to be considered in the different timeframes. Below we discuss the key conclusions for each timeframe under investigation.

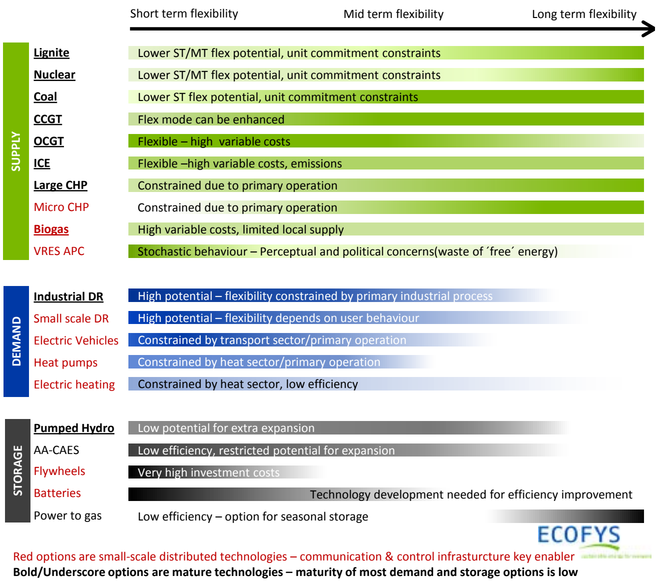

Figure 2: Comparative assessment of the characteristics of flexibility options in different operational timeframes

Mid-Term Flexibility

Zero-marginal cost VRES create downward pressure on market prices making it difficult for flexible units to cover variable and investment costs. In systems with high VRES shares, base-load and mid-load operation of power plants is restricted. Key supply options for mid-term flexibility are flexible coal, gas and ICE plants, while the potential of CHP depends on thermal storage and on primary operation constraints. Active power control of VRES is an option for mid-term flexibility, but risks perceptual and political concerns over lost clean energy.

Bulk electric energy storage plants such as pumped hydro have traditionally operated when the price difference between low and high prices is high enough to recover energy losses. Pumped storage plants are a mature option in this respect, but their potential is restricted by geographic constraints, while AA-CAES present lower efficiencies. Large scale storage capacity for several hours is expensive for batteries and other small scale storage options.

Industrial demand management could offer a good demand shifting option with low variable costs. Small-scale DR presents a potential but this option requires enabling communication and control infrastructure.

Options driven by developments in other sectors (electric vehicles and heat pumps) have the advantage of not presenting an power sector related investment, but are restricted by their primary operation.

Short-Term Flexibility

Traditionally, the supply side provided the majority of short term flexibility. With increasing VRES shares, key options for provision of short term flexibility from cold start are OCGT and ICE, but at the expense of high variable costs. Active power control of VRES presents a potential, however hindered by the inherent operational uncertainty due to the stochastic prime mover.

Storage options present a potential for short-term flexibility. Pumped storage is a mature and cost-effective option, however with a low potential for extra capacity due to the constraints on geographic siting. Imbalances of up to 15 minutes can be solved by flywheels and the technology is particularly suited for very short term flexibility requirements. Batteries (and EVs) offer the required technological characteristics, but further technology development is required.

Demand management could provide economical short term flexibility. Industrial DR is the low hanging fruit but should include management involvement for industrial customers while small-scale DR is restricted by primary operation and by the relative cost of control and communication infrastructure.

Long term flexibility

In the long run, only one storage technology competes with thermal power plants: Power to gas. Thermal power plants can be seen as facilities, that store electricity in form of fuels. Power to gas is the technology that transforms electricity back into a fuel (gas or hydrogen), however in the expense of low efficiency. This is only economical in systems with very high shares of VRES, and correspondingly high numbers of oversupply events. On the demand side, no significant options appear, since shifting demand in longer periods is not generally applicable.

KEY CHALLENGES AND SOLUTIONS FOR 100% VRES SYSTEMS

As the share of wind and solar electricity rises above a few percent, more significant changes to the power system will be required to ensure its reliability and efficiency. Accommodating higher penetration levels of roughly 50% can likely be accomplished through operational and market enhancements that leverage the flexibility in existing infrastructure, including tapping flexibility available from the renewable generators themselves. Reaching the highest penetration levels, potentially approaching 100%, will require more active measures that likely entail large infrastructure investments in transmission and energy storage. The integration challenges can thus be grouped into three broad phases of transformation, as shown in Figure 4.

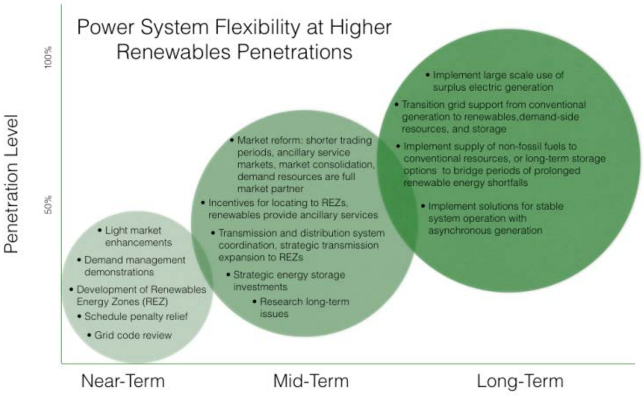

Figure 3 Three phases of Power System Transformation

Integrating Low Levels of Variable Resources (Near-term regime)

Relatively low levels of variable renewable generation can generally be integrated using existing infrastructure and operating procedures that are already in place to accommodate the variability and uncertainty of the pre-existing system. However, there are a number of challenges that emerge even in such regimes, signalling issues that become more evident at higher penetration levels.

Cost of holding reserves sufficient to cover lower than expected generation is an important part. Ensuring the best possible by reducing gate closure times can result in far lower reserve requirements, and similarly lower system operating costs.

Distributed energy resources (DER) and distribution networks: the design and operation of distribution grids is changed due to the connection of distributed energy resources (e.g. see [5]).. Such changes can include technical design aspects (e.g. protection coordination) and more fundamental aspects on enhancing the responsibilities of distribution system operators)

DER and system: DER may bring challenges at system level mainly due to the fact that they were generally connected according to the so-called “fit and forget” approach, i.e. treating them as “negative loads”. These aspects include high- and low-frequency cut outs, and low voltage ride through schemes that may represent reasonable requirements at lower penetration levels, but can cause significant problems at higher levels by exacerbating grid contingencies, or introducing instabilities by simultaneous disconnection of large populations of units (e.g. see [5]).

Challenges in the Mid-Term, Penetration in the 50% Range—the big leap

As penetration levels grow past about 10%, harnessing as flexibility out of the existing power system is the key priority. Sources of untapped flexibility in existing systems can be grouped into the six main categories:

1. **Market Incentives and harnessing available flexibility**

Reaching the mid-range penetration levels will almost certainly require ensuring that markets and market prices exist for flexibility. i.e. provide appropriate price signals and define new services. Key examples here are:

Reserve services: markets should provide clear and consistent pricing signals to other potential sources.

Market expansion over greater geographic regions, and *market* incentives *to more participants* allowing access to more potential sources of flexibility and averaging system variability.

Occurrences of zero or negative wholesale market prices should be visible to retail market participants, as a mechanism to organize uses of occasional surpluses of renewable energy.

Harnessing flexibility at the distribution system level presents institutional issues since generation at these systems have often no economic incentive to respond to flexibility needs. Further, a key challenge is optimizing between system level and distribution levels needs.

2. Demand side flexibility

There is a growing appreciation of the potential role of energy demand in providing flexibility to the power grid. It is important to open markets to end-use loads and to encourage their participation. In many cases the only needed encouragement may be appropriate price signals.
Depending on demand resources for flexibility products is facilitated when markets allow a diversity of products. Different demand resources may be dependent on time of day, frequency of use, duration of use, and seasonality. Markets requiring a single, high standard of deliverability instead of multiple products can effectively exclude significant demand resources.

3. Managing distribution grids.

Systems increasingly reliant on DER encounter a key challenge in controlling and communicating with the shear number of units. This two-way communication and control infrastructure translates into investments but also a new paradigm in system operation. A key challenge is optimizing the operation DER devices to the satisfaction of end users, distribution system operators, and the larger power system and defining a proper institutional framework. Coordination among transmission system operators, distribution system operators, and aggregators will be necessary to uncap the flexibility potential. Further, the changing role of distribution system operators likely will require a change in regulation, in order to incentivise DSOs to activate DER flexibility [7].

4. Transmission Network flexibility

Transmission build-outs for accessing VRES (often located in remote areas) or reinforcement continental scale backbone transmission for merging larger geographic areas face challenges concerning social acceptability. A key challenge involves using existing infrastructure more efficiently by enabling dynamic assessment of transmission capability and by enabling more control over power flows, using power flow control devices such as phase-shifters, HVDC lines and other FACTS devices.

Another aspect to efficient use of transmission is more geographic specificity to market prices. Uniform market prices over large areas imply a "copper plate" zone where the transmission system characteristics are not visible to generators. This often leads to congestions, that are resolved by re-dispatching generation units. Nodal pricing reflects local effects of transmission conditions, helping to provide signals for placement of new generation or for transmission expansion.

5. Market and System operations challenges.

The first step to tapping available flexibility is for power markets to trade on a sub-hourly basis. In some cases, finer geographic market delineations could be beneficial, since there can be locally important needs that differ from system-wide needs. This can occur for example in transmission-constrained regions with high build-out of variable generation where local storage could have higher value locally, than it would if viewed from a system-wide perspective.

There is a long list of key market and system operation characteristics that affect the need for and cost of flexibility, including: shorter operating periods and more frequent generator set-point adjustments; reduction of gate closure times; grid support services by VRES; VRES active power management; VRES participation in day-ahead markets; Negative Price Bidding; removing of imbalance penalty structures, etc. Although most power systems have begun implementing some of the available improvements, there are likely no systems today that do all that is possible to uncap market flexibility.

6. Energy storage

In a broader sense, energy storage corresponds to a shifting of energy production and consumption in time. In this respect, there are three main types of energy storage in the system, as shown in Figure 4. Energy storage can occur at the primary energy input level (e.g., water in hydro reservoirs, coal piles), at the grid level (e.g., batteries, pumped storage, etc.), and at the end user level (e.g., hot water tanks, electric vehicles, ice storage, etc.). In this respect, it is important to take advantage of all aspects of economic energy storage.

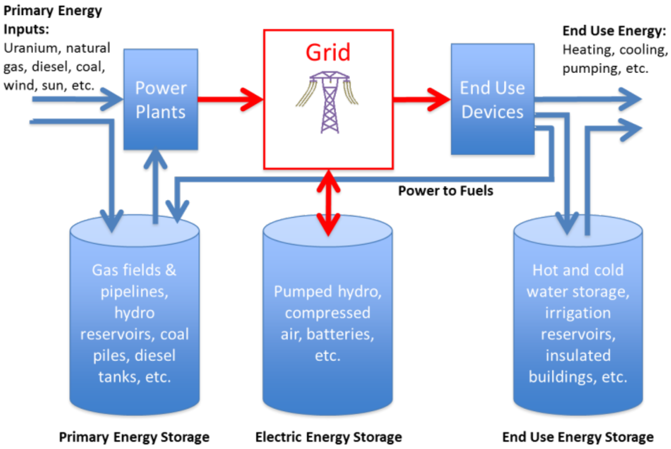

Figure 4: Generalised view of energy storage

Energy storage has an increasingly important role to play as penetration levels increase and along with them, incidents of potentially wasted energy that could otherwise be usefully stored. Systems with large fractions of generation coming from baseload units and isolated systems will generally find energy storage of greater value. In the mid-term, many power systems will find it difficult to justify adding dedicated energy storage solely to provide flexibility, but in combination with other values such as participating in energy markets and averting other infrastructure investments it may be found economic.

Long-Term Challenges, Very High Penetration Levels

Once the flexibility in the existing systems is harnessed, reaching even higher levels of penetration requires addressing three main challenges:

Supplying Power During Low Output Level Events

Actions taken to fully utilize existing system flexibility will not be sufficient to address sustained periods of low renewable resource production. Ensuring service reliability under these difficult conditions is perhaps the central challenge in reaching the highest levels of renewable penetration, and places additional emphasis on energy storage. A likely cost effective approach will rely on conventional fossil power plants burning unconventional fuels or synthesized fuels from renewable electric energy (power-to-gas).

Efficient Use of High Output level Energy

Supply of generation in excess of local demand becomes a serious economic issue at very high levels. To some extent, this issue can be mitigated by providing market incentives to renewable generators for more constant levels of output (higher “capacity factors”) at the expense of energy output. Another strategy is to embrace the occasional over-supplies of electric energy to displace energy use in other energy sectors, and provide price incentives for energy storage devices (electric, thermal, chemical, etc.) that may be able to take advantage of periodic episodes of low-cost electric power available in the market.

Stable Operation with Non-synchronous Generation

Grid support services include reactive power support, frequency support, contingency reserves, balancing services, black start capability, and system inertia. In very high penetration levels, the wholesale market value of energy will be diminished due to the abundance of low cost renewable electricity. At the same time, the market value of system services will constitute a key value stream for market participants. At very high levels of penetration these services should be provided by VRES, demand-side resources and dedicated energy storage.

Most variable renewable generators are not synchronously coupled to the system frequency. Grid instabilities (e.g., wide swings in frequency or voltage) can occur if the asynchronous generator controls and interactions are not carefully worked out. This is of concern for high penetration systems working with little to no synchronous generation, especially given that many legacy distribution level generators may not be accessible to grid operators. Developing a full set of “future-proof” code requirements is an active area of research.

CONCLUSIONS

Building power systems with sufficient flexibility that rely primarily on power from variable energy resources involves a significant system transformation. There is a plenty of flexibility options that can be used in this respect. In both near-term and mid-term challenges are largely institutional. They focus primarily on accessing untapped flexibility in existing infrastructure and improving efficiency of electric markets to correctly reflect the value of flexibility and reaching out to greater participation— including end use loads. The biggest institutional and policy changes are needed in the mid-term to access the inherent power system flexibility.

Relying almost entirely on variable renewable generation requires grid support services fully transitioning away from fossil generators to other sources, including the renewable generators, end use sources, and energy storage. Significant challenge will be to ensure the highest value use of occasional large power surpluses. and to enable reliable and continuous service during periods of low renewable energy production. Renewable energy-sourced fuels for conventional generation can be part of the solution.

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