PATHWAYS AND CRITERIA FOR HIGH INTEGRATION OF RE INTO THE ELECTRICITY SYSTEM

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ABSTRACT: Matching electricity generation and demand is a task to be accomplished by any electricity supply system, but it is a greater challenge if a large part of the supply is provided by volatile generation from PV and wind power systems. Combination of the latter and of flexibilities in the system, that is to say generation and demand side management, storage and spatial balancing via grids are means to meet that challenge. Their optimum combination is subject of debate and there is some degree of uncertainty in all models as forecasts for important parameters such as storage costs are difficult to make. In any case, it is widely agreed that a combination of PV and wind and of different flexibilities rather than a single one minimizes overall costs and risks. Further, it can be reasonably assumed that gradual application of flexibilities from the household level up to inter-connected transmission grids, involving a broad range of market actors at all levels, bears more advantages than application at a single level. The best strategy to pave the way for high integration of RE is therefore to provide a framework allowing PV and wind generators being spatially distributed, a combination of flexibilities being applied at different levels, and a range of market actors being involved. Means to achieve this include flexible electricity tariffs, exemption of self-consumed renewable electricity from any fees and administrative burden, grid use fees reflecting power rather than energy, and facilitated trade of very small amounts of energy and power.
Keywords: grid integration, storage, demand side

1 BALANCING GENERATION AND DEMAND

An electricity supply system, from a simple solar home system to a national electricity supply system, is understood here as an entity providing energy in form of electricity for satisfying a range of needs by means of electric devices. Generally, the electric power absorbed by these devices is determined by the operational characteristics of the latter and the needs they meet, and the generation of electricity follows the demand.

In conventional energy supply systems involving large grids that connect suppliers and consumers, this is achieved by a combination of flexible power stations (hydropower, gas and oil-fired combustion plants), semi-flexible (hard coal) and inflexible ones (nuclear and lignite). From this, the distinction between peak, medium and base-load is derived.

For smaller conventional systems supplying islands, villages or individual consumers with electricity, this distinction is not useful. Such systems usually combine a few rather flexible generation units and occasionally storage in order to match the demand.

Most renewable power stations are very flexible. In particular PV plants can even react in fractions of seconds on a changing power demand, but their maximum power output is not constant and depends on the level of insolation. The situation is similar for wind power. As the potential for PV and wind power generation exceeds by far the potential of other renewables, RE-dominated supply systems use to have a strong PV/ wind component and are characterized by high volatility of generation and a strong need for balancing generation and demand. Again, the distinction between peak, medium and base-load is not useful to discuss the issue.

A better insight is obtained and conclusions can be drawn more straightforwardly if one takes a step back and considers simply that electricity supply systems of any kind can be characterised by two time-dependent electric power functions, one mapping the demand, the other the generation. The law of conservation of energy implies that both functions have to coincide completely at any time in closed systems without stores. Widening the scope of the consideration, and including open systems and storage, there are physically four ways to balance generation and demand:

1. **Generation management**: modification of the generation power (main way in large conventional electricity supply systems)
2. **Demand side management**: modification of the demand power (load management; to some extend done in large conventional electricity supply systems)
3. **Storage**: storage of electric energy if the generation exceeds the demand and depletion of stores in the opposite case (done mainly in smaller conventional and in renewables-dominated electricity supply systems)
4. **Spatial balancing**: balancing of generation-demand differences of opposite sign at different sites
   (a) transport of electricity with grids from sites within the electricity supply system where the generation exceeds the demand to sites where the situation is the opposite (intra-system spatial balancing; very important in conventional electricity supply systems)
   (b) export of electric power out of the considered electricity supply system if the generation exceeds the demand and import if the opposite is the case (inter-system spatial balancing; important between sub-systems of national electricity supply systems and increasingly applied between different national systems within the EU)

All these ways provide flexibility to the operation of the electricity supply system and it will be referred to them as "flexibilities" in the following. Flexibility can be expressed in terms of electric power, energy per unit time (e.g. a year), that is average power in this time-unit, or as percentage of the maximum power demand or the energy demand per unit time. A comprehensive discussion is provided in the National Framework Assessment Germany established within the AlpStore project [1].

2 OPTIMUM PV-WIND MIX

Within electricity supply systems with high integration of RE, the challenge of balancing generation and demand, and the need for flexibilities, can be reduced if the right combination of PV and wind power is achieved. Model calculations of the flexibility needed for different ratios of PV and wind power have been made for different electricity supply systems. The higher the geographical latitude is, the higher the seasonal imbalance of PV generation. Hence, the PV component in the mix should be lower for higher latitudes and vice-versa in order to minimize flexibility needs, in particular seasonal storage needs. The exact optimum ratio depends also on the local PV and wind potentials. For Denmark for instance, the optimum mix consists of 80% wind and 20% PV with respect to energy generated per year [2].

For the east of Germany (50hertz transmission grid zone), a model calculation of the optimum PV-wind mix in a PV-wind-only supply scenario with 15 minute time-steps and respective resolution of meteorological and consumption data has led to a mix of 71% energy from wind and 29% from PV. The optimum is not very sharp, i.e. the need for flexibility does not increase very much if the system is out of the optimum. Further calculations of the optimum mix were done for time-steps of one day and one week. This is equivalent to assuming the existence of short-term balancing of supply-demand differences at these time-scales by appropriate measures (demand-side management and short-term storage) and it provides an estimate of the optimum mix of wind and PV electricity generation with regard to the need for long-term storage. The result is that the optimum is shifted to about 40% wind and 60% PV if intermittent generation is balanced at the scale of one day, and to about 50% wind and 50% PV if it is balanced at the scale of one week [3]. I.E. short-term system flexibility allows for more PV.

3 FLEXIBILITIES

3.1 Generation management

In the case of high penetration of RE into an electricity supply system, there are basically the following options for generation management:

- Curtailment of PV and wind power generation, i.e. operation of PV and wind power plants below the instantaneous maximum power output. Non-use of a few percent of the available energy due to curtailment is already common practice in areas with high RE generation and used to prevent local grid congestions. Even a strong limitation of the electric power leads to the non-use of only a few percent of the available energy: The limitation of the power fed into the grid from PV installations to 70% of the nominal generator power leads to 1-2% less energy fed into the grid, because the accumulated time for which the PV installation output exceeds 70% of its nominal power is extremely short [4].
- Electricity demand-driven or local grid capacity-driven operation of biogas plants. This requires the installation of larger biogas stores upstream and larger heat stores downstream the CHP as well as higher CHP power with respect to the biogas production rate compared to common designs. Presently, experience is gathered with the refurbishment of existing biogas plants. Installing additional biogas stores able to buffer the biogas production of 10-12 hours and doubling the CHP power have turned out to be cost-effective measures [5]. Biomass power stations are, contrarily to biogas plants, generally not flexible enough for generation management.
- Electricity demand-driven or local grid capacity-driven operation of run-of-the-river and storage hydropower plants. Note that the latter is generation management involving stores.

3.2 Demand side management

Demand side management can be done with any electrical load which provides a service that can be shifted: cooling, heating, charging of electric vehicles, provision of pressurised or liquid air, and the production of industrial goods and intermediaries. Demand side management is very often some kind of storage, but the stored energy is not converted back to electricity. Instead, cold, heat, compressed or liquid air, industrial goods and intermediaries are stored and further processed or used.

Demand side management in cooling houses has been demonstrated in the wind-rich Cuxhaven region at the German North Sea coast within the eTelligence project in the German smart grid programme E-Energy: Two cooling houses participated in a local market place for energy and profited from a flexible electricity tariff designed to reward shifting electricity consumption to times of high wind energy generation. Electricity purchase cost savings of 6-8% were achieved on the average. Savings were higher in winter than in summer due to higher flexibility of cooling houses at low outside temperatures [6].

A comprehensive assessment of the demand side management potential in industry has been done for the two southern German federal states Baden-Württemberg and Bavaria in the frame of the debate about the reinforcement of north-south grid connections in Germany. The study shows that 850 MW of industrial loads can be shifted for two hours and 1.2 GW for 30 minutes [7]. This is to be compared to the total national electric load which varies between 29 and 74 GW all over Germany, less than half of which is the load in Baden-Württemberg and Bavaria.

3.3 Storage

Storage in electricity supply systems does not only include conversion of electricity to another form of energy and back to electricity. Very often electricity, heat and gas supply systems are linked by stores as figure 1 shows.

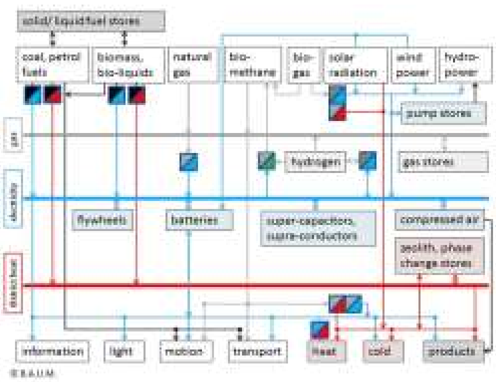

Figure 1: Different storage options in an inter-connected electricity-heat-gas supply system

Linking electricity and heat supply is possible in the case of co-generation or whenever electricity is used to generate heat, i.e. with heat pumps. Then generation or demand of electricity can be shifted and heat can be stored. This is attractive because storing heat is much cheaper than storing electricity. Doing this can be looked at as generation/demand side management or storage. The achieved flexibility has a range up to a few days except if large seasonal heat stores are involved.

Linking electricity and gas supply is interesting because of the huge volume of existing natural gas stores which allow, contrarily to all other storage options, for seasonal storage of amounts of energy of the same order of magnitude than national energy demands. The existing gas stores in Germany can buffer sufficient gas to generate about one quarter of the annual national electricity demand if being used in gas power stations with 60% efficiency. Present extensions and new constructions of gas stores will extend this storage capacity to one third of the annual electricity demand. The situation in other countries is similar. Models of the energy supply have shown that the storage capacity needed in a fully renewable electricity system is rather in the order of 10% of the annual electricity demand [8]. Hence, there is a huge storage capacity left in most countries for gas needed in the heat and transport sector even if gas stores are the only long-term stores in fully RE-based electricity supply systems.

Table I: Energy charge/ discharge capacity of existing natural gas stores in 2011/2012 [9]

Country	Energy charge/ discharge capacity (upper heating value of gas) [TWh]
USA	1,186
Russia	934
Ukraine	320
Germany	199
Italy	170
Canada	163
France	121
Austria	73

Gas stores which are presently filled with natural gas for supply security reasons can be filled successively with biogas up-graded to bio-methane, hydrogen produced by electrolysis using surplus electricity (up to a few percent of the total gas volume), and synthetic methane produced by the Sabatier process from carbon-dioxide and hydrogen (power-to-gas). This gas-mix can be used in the electricity, heat and transport sector with almost no changes in the gas infra-structure. Gas stores are therefore a linking element allowing for a smooth transition into a fully RE-based economy.

The short-term storage capacity needed for a high integration of RE in the electricity supply system is less well known and more strongly dependent on the degree up to which generation/ demand side management and grid extensions are implemented. However, model calculations indicate that the short-term storage capacity needed for a fully RE-based electricity supply system is much smaller than the required long-term capacity, i.e. in the order of a few percent of the annual electricity demand [8].

A number of studies have been made on the need for storage as a function of the RE integration rate into electricity supply systems [10]. This function depends on the assumptions made for generation/ demand side management and the grid infrastructure. Generally, very little generation and demand side management, but more or less ambitious grid reinforcement and extension is considered in these studies. The main result is that significant short-term storage is only needed when the RE integration rate exceeds 50% and long-term storage only when the 80% mark is achieved.

3.4 Spatial balancing

Spatial balancing of generation-demand differences of opposite sign at different sites provides an important flexibility in conventional electricity supply systems. Existing grids are designed for centralised generation and decentralised demand and the pattern of spatial balancing changes if high PV/ wind power generation capacity is set up in areas with presently weak grids. It has been shown that non-redundant generation/ collection grids, from which the generated electricity is directly fed into transmission grids, can easily and quickly be set up and deal with RE integration rates even higher than 70% (e.g. in the German federal state of Mecklenburg-Vorpommern). Remaining bottlenecks have to be overcome by new or strengthened grid lines or adjustable transformers.

3.5 The optimum combination of flexibilities

Generally, spatial balancing of generation-demand differences of opposite sign at different sites with grids is cost-effective and considered as main means to deal with high integration rates of RE into electricity supply systems. A lively debate has been sparked in Germany about the question at which level of RE integration stores will be cost-effective, respectively will be needed [11,12,13]. Opponents in this debate make different assumptions, notably about the rate at which costs of batteries will decrease in the forthcoming years. The learning curve presented by Winfried Hofmann at this conference shows that battery costs are decreasing much more rapidly than anticipated, thus giving storage a more important role compared to other flexibilities at an earlier stage [14]. But even today, storage is cost-effective compared to other flexibility options in specific situations [13].

A comprehensive investigation of the optimum combination of flexibilities in electricity supply systems considering the different options is still lacking at this stage. However, a synopsis of the existing investigations lets appear a few insights:

- A combination of different flexibilities rather than a single one minimizes costs and risks.
- The optimum combination depends on the respective electricity supply system and the level at which generation and demand is balanced.
- Generation and demand should neither be completely balanced at the lowest level, e.g. a single household (effectively the boundary case of off-grid supply), because seasonal storage is too expensive at this level, nor completely at the highest level, i.e. trans-national level, because this requires too much and too costly grid extension, and leads to a high overall vulnerability of the entire supply system.
- The need for flexibilities can be reduced if not only the right PV-wind mix is achieved, but also if PV and wind power plants are spatially spread, including sites with lower solar and wind potential.
- The need for flexibilities is influenced by the way how respective technical installations are operated. I.E. operating PV systems with a battery in a grid-optimized mode can allow for 66% higher nominal PV power in existing grids compared to minimization

of electricity purchase from the grid [15]. In other words, the choice of the battery management strategy strongly influences the need for grid extension, respectively generation management.

- The only option for long-term balancing of larger generation-demand differences which is known at this stage is power-to-gas. Given sufficient grid capacity in the EU-MENA region, about 10% of the annual electricity demand needs to be stored from summer to winter in order to balance the difference in PV power generation. Less grid capacity leads to higher storage needs.

From this, it can be reasonably deduced that gradual compensation of generation and demand, from the level of individual consumers to the international level, presents a strategy that is the closest to the optimum for most pathways towards fully RE-based electricity supply systems. It is a strategy that suits best to the rapid and difficult to predict development of performance and costs of different flexibility options.

4 CRITERIA FOR THE RIGHT FRAMEWORK

Optimum pathways for the development of electricity supply systems are not only difficult to calculate, but also difficult to impose. For this reason, it is avoided here to describe an optimum pathway. However, criteria and recommendations for the right framework allowing that electricity supply systems will develop along close-to-the-optimum pathways can be outlined. The following can be deduced from the above considerations:

- Stimulate the installation of PV and wind power plants even at sites with lower potential, thus facilitating a good mix of PV and wind power generation.
- Allow easy access of new market actors that offer electric energy and related services, including regional aggregators who bundle small amounts of electricity into marketable packages, and prosumers, i.e. electricity consumers such as companies, farmers and individuals who cover a part of their electricity needs by own generation facilities.
- Exempt self-consumption of generated RE electricity from fees and difficult administrative procedures.
- Motivate producers, consumers and prosumers to behave such that overall costs of electricity supply are reduced, e.g. by flexible electricity consumption and feed-in tariffs.
- Allow for trade with small amounts of energy and power, e.g. in 15min intervals, and promote regional trade platforms.
- Grid use fees should reflect real costs, i.e. should reflect rather power than energy.

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