ICT-Challenges in Load Balancing across Multi-Domain Hybrid Energy Infrastructures

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** Summary **
Addressing the "storage gap" in future energy systems with a high penetration of renewable and volatile resources is a major challenge. Hybrid Energy Grids represent a possible solution to this problem by interconnecting energy systems and infrastructures and thus allowing energy to be transformed between various alternative forms of energy. This provides the means for higher flexibility along the energy system. The paper discusses the concept of Hybrid Energy Grids from an ICT perspective and presents a regulation framework to assess use cases in multi-domain Hybrid Energy Infrastructures.

** Keywords **
Hybrid Energy Grids, Hybrid Energy Networks, Power-to-Gas, Smart Grids, ICT, Energy Information Systems

** 1 Introduction and Motivation **
The paradigm shift in the German energy sector caused by the nuclear fade-out implies ambitious goals regarding the installation of renewables and necessary power network extensions. In order to achieve these goals it is not sufficient to merely replace fossil power plants with renewables and to reduce the costs of renewable generation. In fact, switching to renewable energy resources yields significant challenges in terms of quality of supply and stability within the electric power grid.

Due to the increasing amount of electric power that is fed into the power grid through volatile and fluctuating renewables, the need for transportation and storage in order to satisfy the geographically and timely decoupled demand increases as well. In [1] it is pointed out that, as soon as a share of 40% of renewables in electricity generation is reached, a significant demand for electric storage will occur. This requirement however cannot be satisfied by the grid extensions that are planned in the context of the German “grid development plan” [2].

** 1.1 The Lack of Storage Capabilities in the Power Grid **
On the one hand, the lack of storage capabilities requires increasing flexibilities in generation and consumption within the electric power domain (Smart Grids) in order to synchronize these two processes from a perspective of time – decreasing the need for storage. On the other hand,
if this measure is not sufficient and appliances would otherwise have to be curtailed or shedded completely, it is possible to couple infrastructures across different energy domains through appropriate transition and coupling processes, e.g. Power-to-Gas.

Thus, significant potential in terms of efficiency in operating the energy system can be found outside the electricity domain: in Germany, gas storage capabilities have a capacity that is 1500 to 3000 times bigger than the capacity of the existing pumped-storage hydropower plants. Furthermore, from an economical system’s perspective, long-term storage realized through Power-to-Gas processes can be efficient although efficiency of the conversion process itself is rather limited. Power-to-Gas offers an opportunity to utilize the existing gas infrastructure as a seasonal high-capacity storage in order to balance the fluctuating electricity generation caused by renewables.

However, Power-to-Gas is only one possibility for cross-domain process coupling aiming at load shifting or long-term storage of energy. Referring to the overall energy flows in Germany 2010 [3], the most important energy grids – in order of the total amount of energy consumption – are:

- the mineral oil grid,
- the gas grid,
- the electric power grid, and
- the long-distance heating infrastructure.

Through the coupling of these hitherto independently operated energy grids and systems, additional flexibilities and degrees of freedom arise along the domain-specific energetic process and value chains including generation, storage, transmission, distribution, and consumption.

2 Process Coupling across Multi-Domain Hybrid Energy Infrastructures

Such a cross-domain energy system is called a Hybrid Energy Grid. Within the boundaries of a Hybrid Energy Grid, energy can be consumed, stored or distributed within a single energy domain in its current form or it can be converted into another form of energy through conversion processes, where it can be consumed, stored or distributed again. Thus, a Hybrid Energy Grid offers alternative ways to make use of – especially electric – energy which is fed into the power grid during times of oversupply and to make power supply more flexible in times of undersupply. From this point of view, a Hybrid Energy Grid pursues the overall goal of efficiently integrating fluctuating renewables into the changing German power grid.

Energy conversion offers significant potential for increasing the flexibility and stability of the overall energy system. Overall costs may be decreased when either using cheaper storage or transport capabilities and thus avoiding curtailment or shedding of volatile energy sources.

Based on smart Information and Communication Technologies (ICT) such a Hybrid Energy System may combine energy systems across various domains and lead to an efficient, flexible, secure, and stable energy supply infrastructure. The resulting convergence of supply and information infrastructures satisfies the requirements of the German energy turnaround more efficiently than before.

2.1 Load Shifting along Process and Value Chains of Power and Gas Grids

An important and already discussed building block supporting the efficient realization of Hybrid Energy Systems could be storing surplus electric energy in the gas grid based on Power-to-Gas concepts. Here, electricity is used for the production of hydrogen (H₂) and methane (CH₄) respectively to be stored in the gas grid. Figure 1 exemplarily depicts a closed process cycle for coupling power and gas grids (Power-to-Gas) and vice versa. Optimizing generation and consumption processes can be done within the closed boundaries of either the power or gas domain considering the domain-specific flexibilities (i.e. in power grids: Virtual Power Plants (VPP), Demand Side Management (DSM), Demand Response (DR), short-term storage of electricity in electric vehicles.
Moreover, it is possible to flexibilize and optimize processes across the two domains by coupling the power system with the gas supply system. Coupling can be realized through a material transformation process from electric power into appropriate kinds of gas through hydrogen electrolysis and if applicable through subsequent methanation. In this example, electric re-conversion can be realized through combustion processes or fuel cells. These transformation processes of course generate specific losses based on their efficiency factors (chemical/physical efficiency of transformation processes: Power-to-Gas 65%–75% and Gas-to-Power 40%–60%).

Furthermore, a more efficient coupling of both energy systems (power and gas) is possible through so called bi-valent consumers, which can either run on electricity or gas (i.e. thermal (industrial) melting processes and compressor stations as part of a gas supply infrastructure). Hence, bivalent consumers enact – where it is supported by the infrastructure and if such kinds of system couplers are available – so called virtual transformation or coupling processes because they can either use more electricity and thus less gas or more gas and therefore less electricity.

2.2 Regulation Framework for Hybrid Energy Infrastructures

In order to analyze and evaluate flexibility potentials of processes in cross-domain energy grids as well as requirements for necessary ICT and automation infrastructures (energy control and information systems) the German Academy of Science and Engineering (acatech) has developed a regulation framework for Hybrid Energy Grids for assessing specific technology setups for cross domain Hybrid Energy Grids [4]. In the process of developing this framework it was clearly pointed out that coupling and storage processes must be differentiated with respect to temporal and geographical properties since energy must be stored and made available for different time periods and in addition, there may be a huge spread in the distance between generation and consumption.

In order to be taken into account as a distinct energy domain within the regulation framework to be of relevance for cross-domain Hybrid Energy Grids, a domain must provide storage and transport capabilities that can be differentiated temporally and geographically as mentioned above. An additional and essential requirement that must be met is a geographically comprehensive infrastructure including decentralized (bidirectional) connection points.

Applying this pattern to the four energy domains (mineral oil, gas, electricity, and heat) identified above, it is apparent that while the mineral oil grid consists of a comprehensive infrastructure, only limited actors (e.g. refineries, harbors) are connected with this infrastructure. For that reason, the mineral oil grid is not considered within this framework for the remainder of this paper.

The following Table 1 presents the regulation framework for Hybrid Energy Grids that can be used to assess efficiency and effectiveness of common and available cross-domain coupling processes and technologies.

Figure 2 depicts an exemplary use case for multi-domain process coupling, starting with electric power that is transformed into methane through the appropriate Power-to-Gas process where it is stored and subsequently transformed into heat. The efficiency factors are taken

| Table 1 Hybrid Energy System Regulation Framework. |
|---|---|---|---|
| **Power** | **Gas** | **Heat** |
| **Power** | **Gas** | **Heat** |
| Short-Term Storage: Efficiency 90% Costs: high | Short-Dist. Transp: Efficiency 90% | Power-to-Gas: Efficiency 75% / 65% (H₂, CH₄) Costs: medium |
| Long-Term Storage: Efficiency 40% (Energy-Air) / 70% (Pumped Storage) Costs: high | Long-Dist. Transp: Efficiency 93% Costs: medium | Power-to-Heat: Efficiency 100% / 100% (Resistance, HP) Costs: low / medium HP: multi-pump |
| **Gas** | **Heat** |
| Gas-to-Power: Efficiency 40% / 60% (CHP, Gas & FC) Costs: medium (GF, GuD, FC) GF: Gas Furnace, GuD: Gas and Diesel, FC: Fuel Cell | Heat-to-Power: Efficiency Costs: |
| Short-Term Storage: Efficiency 100% Costs: low | Heat-to-Gas: Efficiency Costs: medium |
| Long-Term Storage: Efficiency 90% Costs: low | Long-Dist. Transp: Efficiency 99% Costs: low |
| **Heat** |
| Heat-to-Power: Efficiency Costs: |
| Heat-to-Gas: Efficiency Costs: medium |
| Long-Term Storage: Efficiency 95% Costs: medium |
| Long-Dist. Transp: Efficiency 99% Costs: high |

Caption: Technically and economically irrelevant Efficiency and costs with respect to the cross-domain coupling between the two domains Storage and transport within the energy domain
from the regulation framework (Table 1) and represent values for state-of-the-art technology processes as well as their approximate costs [4].

3 ICT as a Basis for Implementing Hybrid Energy Grids

Smart ICT in the form of an energy information system has to take on the responsibility of optimizing the system during run-time and decide whether a given energy supply process – starting from the generation process to its consumption – may be executed within one domain only or if there is a more efficient process chain utilizing storage or transport capabilities in other energy domains through cross-domain coupling.

There are many alternative forms of energy that have to be evaluated specifically with respect to a given appliance or application. Taking into account the dynamic demand and supply (both in terms of timely and regional volatility) there is a need for re-evaluating regional supply and demand situations continuously and then – when indicated and where appropriate – autonomously switching between different energy domains and infrastructures.

Such an optimal on-line operation of a Hybrid Energy System is only feasible through innovative ICT and automation technologies. There is a need for an inter-connected adaptive control and communication system along the value chains of the considered energy domains. Adequate interfaces and processes have to be defined between the hitherto independently operated energy infrastructures. Thus, the standardization activities ensuring interoperability are expected to be of similar (if not higher) importance compared to the development of electrical Smart Grids. The development of adequate ICT-standards and protocols has to take precedence when implementing and deploying Hybrid Energy Systems.

4 Conclusion

The regulation framework developed within this paper and discussed in detail in the acatech study [4] presents a formal basis for identifying promising business cases and their related use cases within future Hybrid Energy Grids.

A given use case’s low degree of efficiency does not automatically imply that the identified cross-domain process chain should not be embarked upon. However, following a systematic approach those use cases, which allow for the maximum energy usage should be investigated first. Hence, cross-domain process chains based on the regulation framework in Table 1 are first-order observations that need further investigation in terms of (dynamic) overall system costs. Such analysis may yield different degrees of efficiency and thus an adjustment in the assessment of complex use cases.

To this end, the efficiencies in Table 1 as well as the rough cost estimates are suggestions that should inspire further discussion on the topic. Especially costs have not yet been quantified thoroughly for many of the conversion, storage and transportation processes depicted in Table 1 and need to be investigated (and further differentiated into distribution/transmission-level specific technologies) in upcoming studies and R&D projects.

Applying an established methodology for developing requirements for energy information systems [5; 6] to multi-domain hybrid energy use cases this framework can then be used to assess the technical specifications (and thus related costs) of the underlying ICT and automation infrastructure as well as to identify interoperability gaps. This methodology has been demonstrated in [7; 8]. In this vein, the authors will investigate specific use cases in Hybrid Energy Systems in related and upcoming publications.

References

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Autonomie in verteilten Systemen – tiefgreifend untersucht

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