ENERGY HUBS FOR THE FUTURE

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Energy Hubs for the Future
MOST OF TODAY’S ENERGY INFRASTRUCTURES EVOLVED DURING THE second half of the twentieth century, and it is questionable if they meet the requirements of tomorrow. Besides congested transmission systems, many facilities are approaching the end of their prospected lifetime. In addition, other issues such as the continuously growing demand for energy, the dependency on limited fossil energy resources, the restructuring of power industries, and the general aim of utilizing more sustainable and environmentally friendly energy sources raise the question of whether piecewise changes of the existing systems are sufficient to cope with all these challenges.

Various scientific studies have investigated future scenarios based on boundary conditions given by today’s structures, such as standardized electric voltage and gas pressure levels. Although these studies provide important insights, they often result in solutions that comply with the existing systems; possibly interesting and more long-term oriented solutions are hidden, as they lie beyond system-given boundaries. In contrast to these studies, a project named “Vision of Future Energy Networks” was initiated at ETH Zurich together with partners (see Table 1), which aims at a greenfield approach for future power systems. Restrictions given by the existing systems are basically neglected in order to determine real optima. The consideration of multiple energy carriers, not only electricity, represents one of the key characteristics of this project. There is a belief that synergies among various forms of energy represent a great opportunity for system improvements. Besides the possibilities of modern information technology, state of the art as well as emerging and looming energy technologies, e.g., fuel cells, are taken into account. The time horizon for implementation is set to 30–50 years from now. Thus, the basic question to be answered is: “How should energy systems look in 30–50 years, and what can be expected from them?”

Under these conditions, two key approaches are reasonable: transformation, conversion, and storage of various forms of energy in centralized units called energy hubs and combined transportation of different energy carriers over longer distances in single transmission devices called energy interconnectors.

The project team soon realized that only a few established tools were available for the integrated analysis of multiple energy carrier systems, thus they focused in a first phase on developing a modeling and analysis framework. In the second phase, which recently started, optimal system structures and operation strategies are determined and compared with conventional infrastructures using the developed tools. The result of this phase is the greenfield approach. The final phase of the project is dedicated to identifying transition paths and bridging systems leading from today’s systems to the identified optimal structures. Figure 1 outlines this process.

In the remaining part of this article, the key approaches, some developments, and first results of the project “Vision of Future Energy Networks” will be presented.

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Combining Energy Infrastructures
Industrial, commercial, and residential consumers require various forms of energy services provided by different infrastructures. In the industrialized part of the world, coal, petroleum products, biomass, and grid-bound energy carriers such as electricity, natural gas, and district heating/cooling are typically used. So far, the different infrastructures are considered and operated almost independently. Combining the systems can result in a number of benefits. Synergy effects among various energy carriers can be achieved by taking advantage of their specific virtues. Electricity, for example, can be transmitted over long distances with comparably low losses; chemical energy carriers such as natural gas can be stored employing relatively simple and cheap technologies. With so-called line packing techniques, compressible fluids can be stored in pipeline networks, even if there are no dedicated storage devices installed.

Combining the infrastructures means to couple them, thereby enabling exchange of power among them. Couplings are established by converter devices that transform power into other forms. The question to be answered is, of course, where to put which devices and how to operate them. Answering this question is essential for the system layout and therefore one of the central issues in the project. Therefore, models and methods have been developed to find the optimal coupling and power exchange among multiple energy carriers based on various criteria such as cost, emissions, energy efficiency, availability, security, and other parameters.

The Energy Hub Concept
The key approach in the “Vision of Future Energy Networks” project is the so-called energy hub. An energy hub is considered a unit where multiple energy carriers can be converted, conditioned, and stored. It represents an interface between different energy infrastructures and/or loads. Energy hubs consume power at their input ports connected to, e.g., electricity and natural gas infrastructures, and provide certain required energy services such as electricity, heating, cooling, and compressed air at the output ports. Within the hub, energy is converted and conditioned using, e.g., combined heat and power technology, transformers, power-electronic devices, compressors, heat exchangers, and other equipment. Real facilities that can be considered as energy hubs are, for example, industrial plants (steel works, paper mills), big building complexes (airports, hospitals, shopping malls), rural and urban districts, and small isolated systems (trains, ships, aircrafts). Figure 2 shows an example of an energy hub.

The components within the hub may establish redundant connections...
between inputs and outputs. For example, the electricity load connected to the hub in Figure 2 can be met by consuming all power directly from the electricity grid or generating part or all of the required electricity from natural gas. This redundancy in supply results in two important benefits, which can be achieved using energy hubs. First, reliability of supply can be increased from the load’s perspective because it is no longer fully dependent on a single network. Alternatively, reliability of the individual infrastructures could be reduced (e.g., by reducing maintenance) while availability for the load remains high. Second, the additional degree of freedom enables optimization of the supply of the hub. Energy carriers offered at the hub’s input can be characterized based on their cost, related emissions, availability, and other criteria; the inputs can then be optimally dispatched based on these quantities. In addition, utilizing energy storage represents an opportunity for increasing the overall system performance, therefore, storage is already taken into account in the planning phase. Especially when energy sources with intermittent primary energy (e.g., wind, solar) are considered, storage becomes important since it enables affecting the corresponding power flows. Compensation of fluctuating power flows is possibly the most evident application of energy storage technology. However, investigations have shown that storage can be utilized in such a way that it positively affects all of the aforementioned criteria, especially when considering a liberalized market environment.

**The Interconnector Concept**

Integrating different energy carriers is also possible in terms of transmission. In the “Vision of Future Energy Networks” project, a device named energy interconnector is proposed that enables integrated transportation of electrical, chemical, and thermal energy in one underground device. So far, the most promising layout seems to be a hollow electrical conductor carrying a gaseous medium inside (see Figure 3).

The basic motivation for combined transmission is the possibility of efficiency improvement due to waste heat recovery. The heat losses generated in the electrical conductor are partially stored in the gas (whose temperature increases consequently) and could be recovered at the end of the link. Alternatively, losses could be used for increasing the gas temperature before expanding it to keep the temperature within required limits. Comparing such dual concepts with conventional, decoupled transmission lines shows advantages and disadvantages.

From an energetic point of view, combined transmission is more efficient if the heat losses can be used at the end of the link. From a legal point of view, the device could be interesting since rights of way and other issues could be managed for electrical and chemical transmission simultaneously. Like normal pipelines, the energy interconnector can also be used for gas storage (line pack). An issue to consider is the dependability of the interacting power flows (electricity and gas), which could reduce supply redundancy. Considering contingencies on the one hand, common mode failures could be a serious issue. On the other hand, investigations have shown that operational boundaries arise from the coupling of the flows. Simply speaking, a certain gas flow is necessary to provide sufficient cooling for the electrical conductor. Studies have shown that these operational restrictions can be relieved when combining energy interconnectors with energy hubs. However, under certain circumstances, the energy interconnector promises better performance than traditional, separated transmission technologies. The integration of gaseous and electrical energy transmission is only one of several possible approaches. Concepts involving liquid chemical carriers or further forms of energy may be advantageous as well.

**New Models and Analysis Tools**

Economic and physical performances of different energy carriers are well understood, but global features of integrated systems have not yet been investigated extensively. Since there are only a few tools available for the analysis of such systems, the development of a modeling and analysis framework for multicarrier energy systems has
been identified as an essential need. The aim was to develop the same tools as are available for electricity systems—e.g., power flow, economic dispatch, reliability, and stability. In addition, models for storage and interconnector technology were developed that are capable of integrating into the system analysis framework.

**Power Flow**

For general investigations on the system level, steady-state flow models are appropriate and commonly used. The flows through power converter devices is simply analyzed, defining their energy efficiency as the ratio of steady-state output and input. With multiple inputs and outputs, a conversion matrix can be defined that links the vectors of the corresponding power flows. Figure 4 outlines this modeling concept. The coupling matrix describes the transformation of power from the input to the output of the hub; it can be derived from the hub’s converter structure and the converters’ efficiency characteristics. Describing the behavior of storage devices requires considering time and energy as additional variables. Various flow models are available for hydraulic and electric networks, from general network flow to more detailed steady-state power flow models. The appropriate degree of approximation depends on the kind of investigation. Combined transmission links (interconnectors) can be modeled similar to energy hubs via coupling matrices.

**Reliability**

Reliability and availability of energy supply is an important design criterion; therefore, models have also been developed for this kind of investigation. Failure and repair rates can be defined for all components in the system. Considering an energy hub, failure and repair rates of the coupling elements can be stated in matrices similar to the conversion matrix. The influence of the energy hub, i.e., an increase or decrease of availability between input and output of the hub, can be analyzed with this approach. Furthermore, the model can be used in the optimization process.

**System Optimization**

Various optimization problems can be identified when considering integrated multicarrier systems. The basic question of combined optimal power flow is how much of which energy carriers the hubs should consume and how they should be converted in order to meet the loads at their outputs. This is an operational problem. In the planning phase, the optimal structure of the hub may be of interest, which can be found by determining the optimal coupling matrix that describes the conversions within the hub. Converters can then be selected to establish this optimal coupling, and missing technologies can be identified. These and other optimization problems have been formulated and analyzed using various criteria such as energy costs, system emissions, and transmission security measures. Multiobjective optimization can be performed by combining different criteria in composite objective functions.

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**Figure 4.** Modeling the transformation of power through an energy hub.

**Figure 5.** Result of investment analysis. The present value of the device (per MW electrical output) increases with its total efficiency, since more energy cost are saved in each period if the efficiency is higher. Today’s investment cost for CHP units of comparable size are in the range of €500,000 per MW electrical output (rated). The conclusion that can be drawn from this plot is that an investment is reasonable if a total efficiency of more than 75% can be achieved.
Evaluation of Investment

When talking about completely new systems on the green field, the question of cost plays one of the most important roles. Energy prices and savings in energy cost can be estimated, although assumptions are often critical. The evaluation of investment costs is more difficult. How much will new technologies such as fuel cells cost in 30–50 years? To avoid speculations based on doubtful assumptions, the question is put differently. The justifiable investment costs are determined by comparing the performances of the conventional and the proposed/assumed system. For example, energy cost and CO2 taxes can be compared for a conventional system and an optimized greenfield structure. From the annual savings due to higher energy efficiency and less emissions of new technologies, a present value can be determined that represents the break-even investment cost of the new technology. With this method, results still depend on critical assumptions as inflation, compounding, and risk. However, using this tool for sensitivity analysis yields deeper insight into economics; it enables identification of the significant parameters.

Figure 5 shows an example where the sensitivity between total energy efficiency of a cogeneration-equipped energy hub and its justifiable investment cost was determined. In this particular case, results show that even state-of-the-art technology could keep up with the requirements, i.e., installing such cogeneration devices would be reasonable from an economic point of view (under certain assumptions).

A First Application

The energy hub idea was picked up by a municipal utility in Switzerland, the Regionalwerke AG Baden, which plans to build an energy hub containing wood chip gasification and methanation and a cogeneration plant. The idea is to generate synthetic natural gas (SNG) and heat from wood chips, a resource which is available in the company’s supply region. The produced SNG can then either be directly injected in the utility’s natural gas system, or converted into electricity via a cogeneration unit and fed into the electric distribution network. Waste heat, which accrues in both cases, can be absorbed by the local district heating network. The whole system can be seen as an energy hub processing different energy carriers—wood chips, electricity, heat, and SNG. In addition to these energy carriers, the gasification process requires nitrogen and steam, which have to be provided at the hub input. Figure 6 gives an overview of the hub layout. The new thing here is not the technology used (converters), but the integrated planning and operation, which is believed to enable better overall system performance.

The developed multicarrier analysis tools can be applied to this energy hub to answer some fundamental questions.

✔ Design/Dimensioning: How should the converters be rated, i.e., how much electricity, SNG, and heat should the hub be able to produce?
✔ Operation: How should the energy hub be operated, how much electricity/SNG/heat should be generated depending on the actual load situation?
✔ Storage: Which and how much of which energy carrier should the energy hub be able to store—wood chips, SNG, heat, electricity?

Figure 6. Sketch of the energy hub to be realized by Regionalwerke AG Baden, Switzerland.
An energy hub is considered a unit where multiple energy carriers can be converted, conditioned, and stored.

which then includes the methanation part (thus enabling infeed of SNG into the natural gas network) should start running in 2011.

Conclusions
The research project “Vision of Future Energy Networks” distinguishes itself from others by aiming at a greenfield approach, integrating multiple energy carriers, and considering a timeframe of 30–50 years from now. The definition of energy hubs and the conception of combined interconnector devices represent key approaches towards a multicarrier greenfield layout. Models and tools for technical (e.g., power flow, reliability), economical (e.g., energy and investment cost), and environmental (e.g., CO₂ emissions) investigations in multicarrier energy systems have been developed and used in various case studies. The main conclusions that can be drawn so far are as follows.

✔ The energy hub concept enables new design approaches for multiple energy carrier systems.

✔ The flexible combination of different energy carriers using conversion and storage technology offers a powerful approach for various system improvements. Energy cost and system emissions can be reduced, security and availability of supply can be increased, congestion can be released, and overall energy efficiency can be improved.

✔ The developed modeling and analysis framework provides suitable tools for the planning and operation of multiple energy carrier systems.

Future work includes the development of dynamic modeling and analysis tools (e.g., for evaluating stability), and the control of a system of interconnected energy hubs (centralized versus decentralized, agent-based). The concepts will be further refined and elaborated in more detail using realistic examples and case studies.

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For Further Reading


Biographies
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Göran Andersson obtained his M.Sc. and Ph.D. degrees from the University of Lund in 1975 and 1980, respectively. In 1980, he joined ASEA, now ABB, HVDC division in Ludvika, Sweden, and in 1986, he was appointed full professor in electric power systems at the Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000, he has been a full professor in electric power systems at ETH Zurich, Switzerland, where he heads the Power Systems Laboratory. He is a Fellow of the IEEE and chairs the IEEE PES Power System Dynamic Performance Committee.

Klaus Fröhlich received the M.Eng. and Ph.D. degrees in technical science from the Vienna University of Technology, Austria. After 11 years in switchgear and high-voltage technology with BBC (later ABB) in Switzerland, he became a full professor at the Vienna University of Technology in 1990. Since 1997, he has been a full professor of High Voltage Technology at the Swiss Federal Institute of Technology Zurich, Switzerland. He is a Fellow of the IEEE and chairs the Cigre Technical Committee.