



Eidgenössische Technische Hochschule Zürich  
Swiss Federal Institute of Technology Zurich



*„A Vision of Future Energy Networks“*

Patrick Favre-Perrod, Bernd Klöckl, High Voltage Laboratory ETH Zürich  
and  
Martin Geidl, Gaudenz Koeppel, Power Systems Laboratory, ETH Zürich

---

**Important notice**

**Copyright and all rights in this work are retained by the authors.  
This material may not be reposted without the explicit permission of the authors.**

©2005 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

# A Vision of Future Energy Networks

Patrick Favre-Perrod

Power Systems and High Voltage Laboratories

Swiss Federal Institute of Technology, ETL H29, CH-8092 Zurich, Switzerland

Phone: +41-44-6324334, Fax: +41-44-6321202, Email:pfavre@eeh.ee.ethz.ch

Martin Geidl, Bernd Klöckl and Gaudenz Koepfel

Power Systems and High Voltage Laboratories

Swiss Federal Institute of Technology, CH-8092 Zurich, Switzerland

**Abstract** – *Distributed generation as well as a growing share in stochastic energy sources will lead to deep changes in electricity transmission & distribution (T&D). In the vision of future energy networks project, these changes are investigated by means of a greenfield study. New concepts and analysis methods shall be used to design an optimal energy system regardless of its actual structure. This paper introduces the key elements of an envisioned multi carrier energy system: energy hubs interfacing any type of consumer or producer, managing and storing energy, and energy interconnectors transferring energy in several forms between the hubs. The resulting scenarios and new technologies will serve in strategic planning of research and development (R&D) and network expansion.*

## I. INTRODUCTION

### A. Developments in electricity transmission and distribution

Present power grids in industrialized countries have grown over the last century following a continuous process. The actual grid structure reflects the boundary conditions which have prevailed for decades: few large power plants supply the highest grid level, the transmission grid. In this hierarchical structure, power reaches the consumer over a regional transmission network and eventually over a local distribution network. The system's high level of interconnection, as well as its taut and scheduled operation, traditionally ensured its stability and high availability.

Different developments however alter boundary and operating conditions of present power systems:

- The integration of renewable energy sources introduces growing amounts of generator power which cannot be dispatched.
- The integration of distributed energy sources impacts on protection, e.g. by causing an energy flow reversal.
- Some areas currently experience dramatic increase in electricity consumption. System expansion is getting increasingly difficult with current T&D technologies.
- Power quality issues are a growing concern. The inherent system interconnection however involves higher risks of voltage sags, outages and further power quality issues.

In the planning of future power systems the importance of the following constraints is growing:

- The environmental consciousness of the public is increasing. For T&D technologies, this means lowering emissions and radiation, improving equipment recycling and minimizing the optical impact of the system.

- Energy needs are not limited to electricity. Technical and economical considerations may lead to joint management, transport and delivery of several energy carriers (e.g. electricity, hydrogen, natural gas, district heating or cooling, etc.).

### B. Motivation for the project

The forces acting on our power systems will obviously lead to deep structural and technological changes. Admittedly, changes in power systems occur rather slowly due to long component lifetimes and the capital intensive nature of this business. Systems will also evolve steadily, as new concepts cannot be implemented overnight in order to completely replace existing ones.

The vision of future energy networks project aims to figure out the shape of energy networks in the long term horizon (around 50 years). We chose a so-called greenfield approach in contrast to other studies aiming at improving actual grids. The structure of the participants (i.e. producers and consumers) is assumed to be given and an appropriate network (including transmission, storage and conversion of energy) between them is to be build up from scratch. The transition phase from traditional to future power systems is consciously omitted in the first project step.

Roughly spoken, traditional power systems require the participants to conform to the operational necessities. This means that loads may be shed, spinning reserve must be granted and power exchanges can be hindered. We expect this relationship to be reversed in future power systems: the network has to adapt to the needs of the participants, managing energy in a way to compensate the mismatch between momentary production and consumption.

Lastly, our energy needs go beyond electricity. Room heating as well as industrial appliances already make use of district heating today. The potential for thermal consumers however is greater. Even direct delivery of chemical power for classical use (cooking, chemical processes and transportation) might increase.

## II. THE VISIONARY NETWORK

### A. Multi-carrier system

Energy storage and management could also be done more efficiently by making more extensive use of energy conversion. E.g. in periods of high electrical demand fuel cells could convert chemical into electrical energy, while electrical storage could be implemented indirectly by converting surplus electricity into chemical energy (e.g. hydrogen). Furthermore, solutions combining conversion of energy, transmission of the stored energy, e.g. in chemical form, and backward transformation at another location can also be implemented in multi-carrier networks.

System planning can also profit from the synergetic use of several energy carriers. Future transportation systems may require area-wide availability of hydrogen or electricity. Instead of building a new separate infrastructure for this purpose, distributed hydrogen generation from electricity and dual energy delivery to customers may be a potential solution.

Multi-utilities already offer multiple delivery contracts from one hand to their customers. Until now the synergies in these businesses are mostly reduced to administrative aspects. In the future, technological synergies may be expected.

### B. Non-hierarchical approach

The hierarchical structure of current grids relies on conditions which no longer apply. The greenfield approach enables to overcome the limitations imposed by actual structures and to design a system conform to the conditions expected in the future.

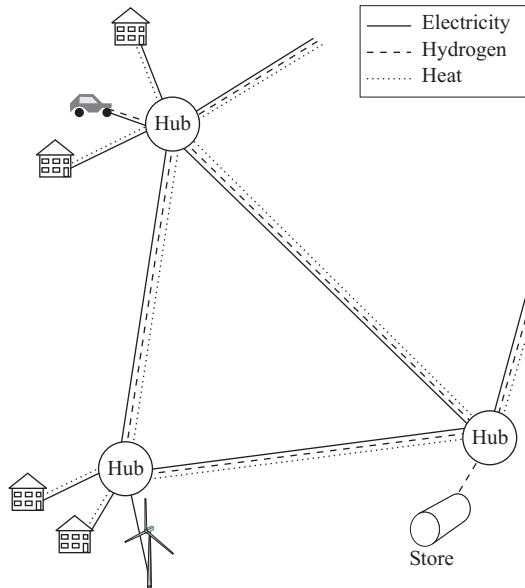


Figure 1. Illustration of the envisioned structure of a future power system.

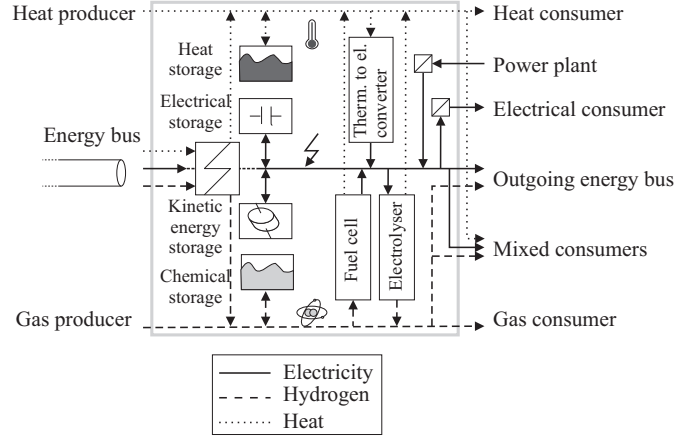


Figure 2. An example for an energy hub.

### C. Hub networks

The first step in the investigation of future power systems is the selection of a basic network structure. The possible structure of a future energy network is shown in figure 1: network participants are connected to so-called energy hubs which are the interface between participants and transmission system. Hubs condition, transform and deliver energy in order to cover consumer needs.

An example for an energy hub is shown in figure 2. The hub interfaces with consumers, producers, storage devices and transmission devices in different ways: directly or via conversion equipment, handling one or several carriers. We call each of these interfaces a port. Between two ports different conversion and transmission equipment can be installed. Some examples are given in table I.

The hubs are interlinked by means of energy interconnectors or traditional transmission systems. Energy interconnectors are conceptual devices transmitting several energy carriers at the same time.

More customized energy services become possible. This will have to be evaluated with appropriate modeling tools.

TABLE I  
EXAMPLES OF ENERGY CONVERTERS IN ENERGY HUBS.

	From			to		
	electrical	chemical	thermal	electrical	chemical	thermal
Fuel cell		x		x		x
Electrolyzer	x		(x)		x	
Thermoelectric converter			x	x		
Power electronic converter	x			x		
Heat pump	x		x			x

### III. TECHNOLOGICAL ASPECTS

#### A. New technologies

As energy hubs are designed to handle several energy forms, the energy exchange among them will also involve several carriers. Several solutions may apply:

- Use a separate infrastructure for each carrier.
- Use a combined device which transmits a second carrier as a side effect, e.g. a hydrogen cooled superconductive cable [1].
- Use a combined device specifically targeted at this application, i.e. build a device capable of transmitting electrical, chemical and eventually thermal energy.

The third solution, a combined device does not exist today. We therefore introduced the energy interconnector concept: an electrical conductor which also serves to transmit gaseous hydrogen. As a side effect, the flowing hydrogen cools the electrical conductor.

The basic representation of such a device is shown in figure 3: electrical power  $P_{el}$  is transmitted through an electrical conductor while chemical power  $P_{ch}$  is transmitted through a nearby hollow structure (e.g. the electrical conductor itself). The ohmic losses in the electrical conductor  $P_V$  are transmitted to the surroundings  $P_{Umg}$  and partly absorbed by the flowing chemical carrier  $P_{CM}$ . Additionally, the friction heat  $P_R$  is also absorbed by the chemical carrier (and the total absorbed heat is  $P_Q$ ).

The expected advantages of the energy interconnector over traditional distinct infrastructures for each carrier are:

- Simpler handling of rights of way.
- Potential for simpler overall transmission systems.
- Possibility to use the interconnector as a storage device.
- Potentially more economical underground transmission.

Obviously several properties of the energy interconnector can be varied: its geometry (coaxial conductor, vs. parallel conductors), the used materials, the operation concept (reuse

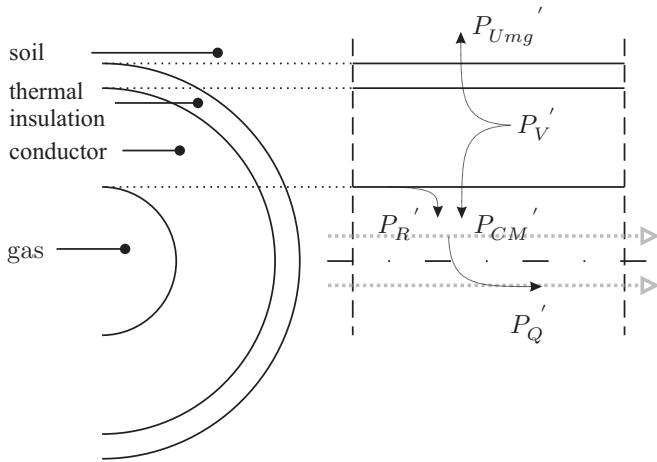


Figure 3. Cross section and longitudinal view of an energy interconnector model.

of waste heat) and the interconnector ratings (bulk transmission vs. distribution). In order to assess the potential for an energy interconnector in the envisioned future network, a simple, but general model of an interconnector was developed. Basically, the thermal power absorbed by the hydrogen per unit length  $P'_Q$  is the sum of the electrical and friction losses minus the heat transmitted to the surrounding soil:

$$P'_Q = P'_V + P'_R - P'_{Umg} \quad (1)$$

A one-dimensional description of the non-isothermal hydrogen flow involves coupled differential equations of the temperature  $T(x)$  and pressure profile  $p(x)$ . The hydrogen absorbs heat by rising its temperature and by expanding, thus the absorbed heat  $P_Q$  is not proportional to the temperature difference between inlet and outlet.

As an analytical solution to these differential equations does not exist, a numerical model of the energy interconnector was created, to define its operation characteristics. For illustration, an example is shown in figure 4: for the assumed energy interconnector, the curves show the required inlet and outlet pressures necessary to vary the chemical throughput  $P_{ch}$  at constant electrical loading. Inlet and outlet temperatures were assumed to be constant (in order to match the needs of a waste heat recovery system).

Remarkably, the nearly constant electrical losses  $P_V$  can be extracted by a variable hydrogen mass flow (at a constant outlet temperature). This is however done at the expense of higher friction losses  $P_R$  in the pipe, thus a growing share of the heat absorbed by the hydrogen  $P_Q$  is friction heat.

Some restrictions however apply on these power flows. Two classes of restrictions may be distinguished:

- Physical constraints: e.g. the maximum extractable heat  $P_Q$  is limited. For this reason, a minimum mass flow  $\dot{m}_{min}$  exists<sup>1</sup> (it can be zero).
- Constraints by the equipment: pressures in the energy interconnector, ratings of compressors, thermal resistances, etc. are limited.

A detailed study of the limitations is part of the investigations. The curves in figure 4 only provide information about a particular interconnector layout.

#### B. Integration of emerging and existing technologies

The layout of a hub will rely on descriptions and models of the converters forming a hub. Therefore, a database oriented procedure is presently followed: the database will contain all necessary data about hub components to assess any hub. This is useful in developing an algorithm which will deliver the best layout with respect to technical, environmental or economical criteria.

<sup>1</sup> In the example above:  $\dot{m}_{min} = 0.06838$  [kg/s]

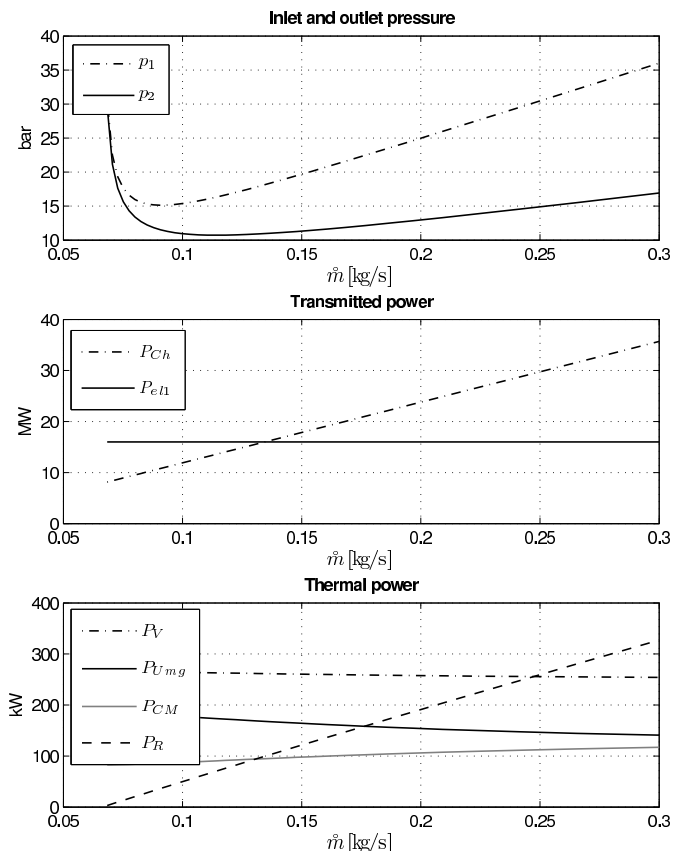


Figure 4. Example for an energy interconnector (total conductor cross sectional area  $2000 \text{ [mm}^2\text{]}$ , length  $10 \text{ [km]}$ , cross sectional area of gas duct  $795 \text{ [mm}^2\text{]}$ , friction factor  $0.05$ , inlet temperature  $20 \text{ [}^\circ\text{C]}$ , outlet temperature  $100 \text{ [}^\circ\text{C]}$ , thermal resistance of soil and insulation  $3.22 \text{ [K m/W]}$ ).  $p_1, p_2$ : gas inlet, resp. outlet pressure.

#### IV. SYSTEM ASPECTS

##### A. Energy content management of storage devices

The effective and simple formulation of efficiencies for energy storage devices (ESDs) is a key point of the modeling efforts in this project. The usual assumption of constant charge/discharge efficiencies was to be extended to a method still reflecting the technological implementation. Complicated modeling efforts for the control, voltages, pressures and other state variables should be reduced to energy contents, power values, efficiencies and limits.

- Energy content: the maximum and minimum energy content of an ESD depends on its design. The available energy is always smaller than the entire amount of stored energy, and in some cases it depends on the demanded terminal power. While the maximum energy content  $E_{max}$  describes (together with the specific energy density) the physical size of the ESD, the minimum energy content  $E_{min}$  represents the utilization and the accessibility of the stored energy. These boundaries can be identified for different technologies.

- Power values: the applied terminal power describes the load flow into and out of an ESD and defines the losses and hence the instantaneous efficiency. This power value may be limited, either by physical boundaries (internal limits) or by design limits of the ESD itself or the converter unit designed to extract the energy (external limits).

A discrimination between kinetic, static and potential ESDs is sufficient to describe the fundamental properties of any ESD technology. The basic power balance equation used for kinetic, static and potential energy storage is (where  $x$  is the state variable):

$$c_1 \ddot{x} \dot{x} + c_2 \dot{x}^2 + c_3 \dot{x} x + c_4 \dot{x} + P = 0 \quad (2)$$

Generally a charge or discharge process is described by the change of energy charge state and a non-constant efficiency:

$$\frac{\Delta E}{\Delta t} = -\eta(P, E, c_n) P \quad (3)$$

This approach accounts for information on the technology and reflects the most important properties of ESD operation in sufficient detail. For each time step in a simulation, the following quantities can be evaluated:

- The deliverable power for a given energy content.
- The achievable discharge for a given power demand.
- The loss energy associated with a given initial energy content, a given demanded power and a given technical implementation.

This approach therefore facilitates either fast and general assessment of distinct technologies at given spots in the system or simple sensitivity analyzes for added values due to ESDs placed in different locations. As an example, this methodology will support a study aiming at optimum sizing of compressed air storage in densely meshed grids with high penetration of wind power.

##### B. Multi-carrier system modeling

Extensive methods for power flow computation in electrical networks are readily available. Chemical power flows can be treated using similar methods [2]. The scope of these methods however does not fit to our investigations: they consider only one energy carrier, and rely on the calculation of node voltages or pressures, which is not suited for our analysis. Some authors indeed proposed overall optimization of power systems [3]. A method had to be developed to model the couplings among different energy carriers and to describe the simultaneous and coupled flows of several energy carriers [4] inside an energy hub (as described in section II.C).

An energy hub will be described as shown in figure 5. Positive power flow means transfer from the participant to the hub. Each port (from 1 to  $n$ ) is described by a power vector  $\mathbf{P}$ . The ports consist of  $k$  nodes (where  $k$  is the number of considered energy carriers), which means that  $\mathbf{P}$  is a  $k$ -dimensional vector. The notation in the following is chosen for a set of three

carriers: electrical, chemical and thermal energy.

$$\mathbf{P} = \begin{pmatrix} P_{el} \\ P_{ch} \\ P_{th} \end{pmatrix} \quad (4)$$

A converter between two nodes introduces a coupling between the node powers, defined by the coupling factor  $\eta_{\alpha\beta}$ :

$$P_{\beta} = -\eta_{\alpha\beta} P_{\alpha} \quad (5)$$

The input power  $P_{\alpha}$  can then be determined:

$$P_{\alpha} = -\kappa_{\beta\alpha} P_{\beta} \quad (6)$$

When determining the reverse coupling factors  $\kappa_{\beta\alpha}$  between two nodes three cases must be distinguished:

1. Only one conversion exists between the nodes. Then the reverse coupling simply is  $\eta_{\alpha\beta}$ .
2.  $P_{\beta}$  is a by-product of another conversion, e.g.  $P_{\beta}$  represents the heat produced in a fuel cell converting chemical energy from port  $\alpha$  to electrical energy to port  $\gamma$ . Then the reverse coupling from  $\beta$  to  $\alpha$  is zero<sup>2</sup>.
3. No conversion exists and therefore the reverse coupling is also zero.

More generally several conversion paths will exist between two nodes. A coupling between two nodes is thus defined by the conversion efficiency of each conversion path and a dispatch factor  $\nu_{\alpha}^{(p)}$  for each conversion path as follows:

$$c_{\alpha\beta} = \sum_p \nu_{\alpha}^{(p)} \eta_{\alpha\beta}^{(p)} \quad \text{where} \quad \sum_p \nu_{\alpha}^{(p)} = 1 \quad (7)$$

The coupling factors  $c_{\alpha\beta}$  for each node of two ports  $i$  and  $j$  can be summarized into a coupling matrix  $\mathbf{C}_{ij}$  (and a reverse coupling matrix  $\mathbf{D}$ ) describing the power flow coupling (of several energy carriers) between two ports:

$$\mathbf{P}_j = -\mathbf{C}_{ij} \mathbf{P}_i \quad (8)$$

$$\mathbf{P}_i = -\mathbf{D}_{ji} \mathbf{P}_j \quad (9)$$

This model can be used for optimizing the coupling and power exchange between different energy carrier systems in a combined manner. Including network losses yields an optimal power flow problem for the combined transmission and conversion problem. It can be shown analytically that the transformation of power from the input to the output of the hub results in a related transformation of marginal prices of the energy carriers. Both relationships (power and costs) include the coupling matrix  $\mathbf{C}_{ij}$  [4].

## V. CONCLUDING REMARKS

### A. Planning strategy

The investigation of a power system built on a greenfield will hopefully help to figure out development trends for actual systems. Such information is obviously of greater value, as our

<sup>2</sup> In that case  $\kappa_{\gamma\alpha} = \eta_{\alpha\gamma}^{-1}$

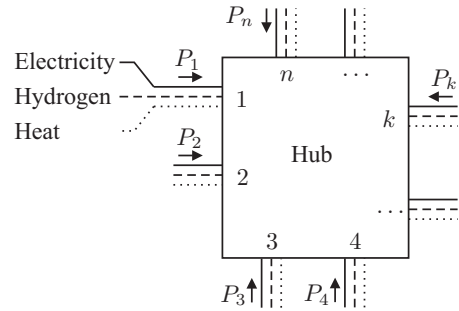


Figure 5. Definition of power flows in a hub.

envisioned system will never be built, at least in one step. The developed tools, shall help in evaluating the impact of storage, additional conversion units between different energy carriers and customized power delivery. This information is important for manufacturers in order to early react to these trends.

### B. Technology identification

The analysis can also show desirable features of future power systems for which no technology is currently available. The multi carrier energy interconnector might be an example. Figuring out the specification of these technologies may also guide industry and researchers.

## ACKNOWLEDGMENT

The authors would like to thank the project leaders Prof. Dr. G. Andersson and Prof. Dr. K. Fröhlich for the constructive discussions and their input into this work.

The vision of future energy networks project is supported by ABB, Areva, VA Tech and the swiss federal office of energy. The authors would like to thank the sponsors for their support.

## REFERENCES

- [1] Paul M. Grant, "The supercable: Dual delivery of chemical and electric power," 2005, To be published in IEEE Transactions on applied Superconductivity.
- [2] Qing Li, Seungwon An, and Thomas W. Gedra., "Solving natural gas loadflow problems using electric loadflow techniques," in *Proceedings of the North American Power Symposium*, University of Missouri-Rolla, 2003.
- [3] Bjorn Bakken, "Simulation and optimization of systems with multiple energy carriers," in *The 1999 Conference of the Scandinavian Simulation Society*, Linköping, 1999.
- [4] Martin Geidl and Göran Andersson, "A modeling and optimization approach for multiple energy carrier power flow," in *PowerTech' 2005*, St. Petersburg, 2005.