Multi-Energy Delivery Infrastructures for the Future

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Abstract— **This paper presents an overview of the methods and modeling concepts developed in the framework of the project "Vision of Future Energy Networks". It outlines the fundamentals of the project comprising a) the development of modeling and analysis tools for systems involving multiple energy carriers (e.g. electricity, heat and gas) and b) a Greenfield approach for the integrated planning and realization of future energy infrastructures. This paper especially focusses on a layout procedure for the so-called Energy Interconnector being a device for combined transportation of electrical, chemical and thermal energy. Concluding the paper, the potential application of the Energy Interconnector is illustrated with an exemplary case study. The presented modeling and analysis framework can be used to evaluate multi-energy networks as development option for future energy networks.**

I. INTRODUCTION

The main part of today's energy delivery infrastructures was built during the second part of the last century. Nowadays these infrastructures are the origin of several problems and challenges. Due to extended cross-border electricity trading and exchange activities, transmission lines are congested in some parts of the system. Furthermore, many facilities are approaching the end of their lifetime. Additionally, the continuously growing energy demand, the dependency on finite fossil energy resources, the restructuring processes of power industries and the increasing societal desire to utilize more environmentally sustainable energy sources represent further challenges. All these issues suggest to scrutinize if piecewise changes of the existing systems are adequate to ensure an affordable, reliable and environmentally sustainable energy supply in the long run. The described issues together with recent trends in various domains of electric power systems spur researchers to reassess the structure of today's energy delivery systems [1], [2].

For this reason the authors' institution launched the research project "Vision of Future Energy Networks" [3], which applies a so-called Greenfield approach to the design of future power systems. The Greenfield approach implies that major boundary conditions given by today's systems are neglected in order to reveal hidden potentials for system improvement. In this project, the use of multiple energy carriers (not only electricity) and distributed energy resources for energy conversion and storage is emphasized. The visionary concept bases on two key elements. Converters and storage devices are described by the so-called Energy Hub concept [4]. The second novel approach concerns a device named Energy Interconnector, which permits the combined transportation of electrical, chemical and thermal energy in one single underground device. The whole energy system can then be designed using Energy Hubs, Energy Interconnectors and conventional elements.

The remainder of this paper is structured as follows. In Section II the key approaches of the project will be briefly reviewed. Section III presents the developed system designs concepts. In Section IV potential variants with respect to the design of an Energy Interconnector will be outlined and Section V illustrates the corresponding layout procedure providing an application example. Eventually, Section VI concludes the paper.

II. PROJECT KEY APPROACHES

A. Greenfield Approach

Recent scientific investigations have addressed scenarios for the future limited by boundary conditions imposed by today's system structures, e.g. standardized electric voltage and gas pressure levels. Even though these studies may provide important findings, they often result in solutions representing merely an upgrade of existing system designs; possibly more sustainable long-term oriented solutions can not be identified as they are outside of the boundaries given by today's systems. One major difference with respect to conventional studies is that the "Vision of Future Energy Networks" project does not focus on a stepwise change of current networks. Instead, existing infrastructures are ignored at first in order to develop new topologies independent from today's systems. The generic procedure comprises two phases (see Fig. 1).

In the first phase, an optimal energy supply structure is developed for different criteria (e.g. cost of energy supply, emissions, or failure rate) by applying a Greenfield approach, i.e. by neglecting restrictions given by existing system structures. In the second phase of the project, the resulting optimal structures will be compared with today's structures in order to develop strategies for stepwise changes and upgrades of the existing system and to determine bridging systems allowing the transition from today's systems to the identified optimal structures.

This approach allows to take into account innovative solutions, thus determining optimal systems, which might remain undiscovered when relying on boundary conditions imposed by existing systems. The only boundary conditions adopted from today's systems are the projected energy demand, the possibilities of modern information technology and state of the art as well as emerging energy technologies like fuel

This work was supported by ABB, Areva, Siemens and the Swiss Federal Office of Energy.

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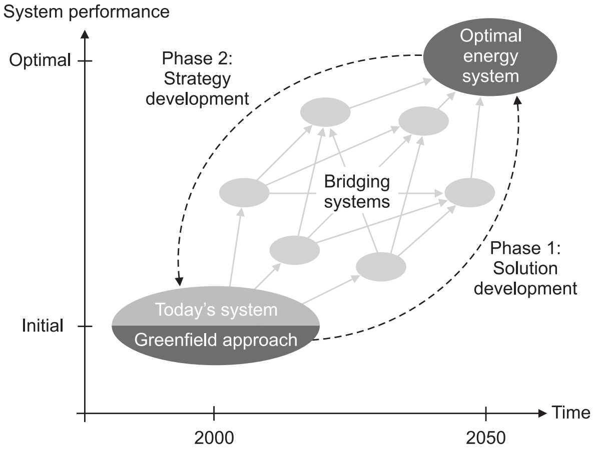

Fig. 1. Generic procedure and phases of the project ”Vision of Future Energy Networks”.

cells. The time horizon for implementation is set to 30 to 50 years from now. The overall question to be answered by the ”Vision of Future Energy Networks” project is: How should energy delivery infrastructures look like in 30 to 50 years in order to cope with the prevailing challenges?

B. Multiple Energy Carriers and Synergies

The consideration of multiple energy carriers in addition to electricity represents a further key characteristic of the project. Different consumers (industrial, commercial, or residential) require different forms of energy services provided by different infrastructures. Typical grid-bound energy carriers are electricity, natural gas, and district heating/cooling. So far, the different energy delivery infrastructures have been considered and operated independently. However, combining the different systems can result in a number of synergy effects representing a great opportunity for system improvements.

When designing multi-energy systems, it is possible to exploit these synergies among various energy carriers by taking advantage of their specific complementary characteristics. Electricity, for example, can be transmitted over long distances with relatively low losses whereas chemical energy carriers such as natural gas can be stored using relatively simple and cheap technologies. The so-called ”line packing” represents a possibility to store compressible fluids in pipeline networks even if no dedicated storage devices are installed. The combined transmission of different energy carriers in one single device by means of the Energy Interconnector opens up the possibility to recover loss energy, e.g. the ohmic losses of electricity transmission, and to reuse it in another form, in this case as thermal energy. In this way, the overall efficiency of energy transmission can be improved. Furthermore, it may be easier to obtain rights of way for one single device than for several lines each of them being exclusively dedicated to one energy carrier.

Hence, making use of synergies between various energy carriers represents an opportunity to reduce environmental as well as social externalities.

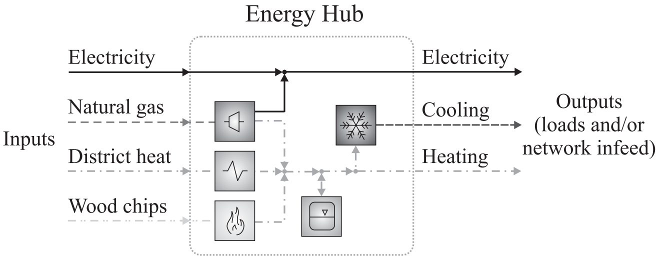

Fig. 2. Example of an Energy Hub containing a transformer, a microturbine, a heat exchanger, a furnace, a heat storage and an absorption chiller.

III. SYSTEM DESIGN CONCEPTS

A. The Energy Hub

Combining infrastructures means to couple them at certain networks nodes or branches, thereby enabling exchange of power between previously separated systems. These couplings can be described by the *Energy Hub* concept. An Energy Hub generally represents an interface between energy producers, consumers, and the transportation infrastructure. From a system point of view, an Energy Hub provides the functions of in- and output, conversion and storage of multiple energy carriers. An Energy Hub can thus be seen as a generalization of a node in an electrical network. Fig. 2 shows an example of an Energy Hub.

The Energy Hub concept is not limited to a certain size of the system to be modeled. It enables the integration of an arbitrary number of energy carriers and products and thus provides high flexibility in system modeling. Due to this high flexibility various real facilities can be modeled as Energy Hubs, for example co- or trigeneration power plants, industrial plants like paper mills or refineries, and supply areas like urban districts or whole cities.

Combining and coupling different energy carriers in Energy Hubs provides a number of potential benefits. Since multiple input carriers can be used to meet the output demand, the reliability of energy supply to the load is increased because the load does not depend on one single infrastructure [5]. Load flexibility is also increased because redundant paths within the hub offer a certain degree of freedom in satisfying the output demand. When operating the Energy Hub in Fig. 2, for instance, it is possible to avoid consuming expensive electrical energy from the electricity network during peak periods by using the microturbine. This means that from a system point of view an Energy Hub appears to be flexible and elastic in terms of its price responsiveness, which may be a favorable characteristic when aiming at the implementation of smart grid management schemes. In addition, the redundant connections within an Energy Hub, i.e. the possibility of providing an output carrier with various input carriers, offers the potential for optimization. Input carriers can be characterized by different criteria (e.g. costs and/or emissions). Applying these criteria, the hub input power flows can be optimized. In addition to this operational optimization, the structure of a hub can be optimized by carrying out a topological optimization [6].

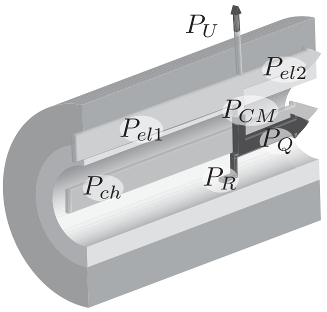

Fig. 3. Generic representation of the energy interconnector for the combined transmission of electricity and chemical energy.

The mapping of input carriers to output carriers is established by an Energy Hub and can be described mathematically by the coupling matrix $\mathbf{C}$. Additionally stating all power inputs $P_\alpha, ..., P_\omega$ and power outputs $L_\alpha, ..., L_\omega$ in vectors $\mathbf{P}$ and $\mathbf{L}$ leads to the general formulation of multi-input multi-output conversion:

$$\underbrace{\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & \cdots & c_{\omega\alpha} \\ \vdots & \ddots & \vdots \\ c_{\alpha\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}} \tag{1}$$

The entries of the coupling matrix $\mathbf{C}$ are the converter coupling factors. Each coupling factor relates one particular input to a certain output and incorporates conversion efficiencies and dispatch factors that take into account the dispatch of an input energy carrier to the devices converting this energy carrier.

B. The Energy Interconnector

The second key element of the "Vision of Future Energy Networks" framework is the *Energy Interconnector*. Since Energy Hubs will deliver customized energy services to a broad range of consumers using different energy carriers, the need for transmission and distribution of these additional carriers will be given. Two concepts may be used for this "multi-energy transmission":

- Dedicated infrastructures for each energy carrier, i.e. the current situation.
- A combined transmission infrastructure for several energy carriers: the Energy Interconnector.

The latter provides more synergies (e.g. sharing of auxiliary equipment, metering and control) but requires a dedicated layout procedure due to the novelty of the concept.

The main factors influencing the achievable transmission capacity will be discussed in Section IV and an example will be given in Section V. The concept of the Energy Interconnector is introduced in more details in [7].

IV. POTENTIAL VARIANTS OF THE ENERGY INTERCONNECTOR

A. Variants spectrum

In a first step, the general concept of multi-energy transmission has to be chosen. For that purpose, two decisions must be made in order to define the preferred interconnector variant, which will be used in further investigations: the choice of the energy forms or carriers and the choice of the "operation principle", i.e. how the power flows for each carrier will interact.

The transmitted energy forms can basically be selected among several alternatives: electricity, chemical energy (liquid or gaseous, open or closed cycles), thermal energy, compressed media, etc. Considering the potential use, interchangeability and ease of conversion of these energy forms, the combination of electrical and chemical energy transmission has the highest potential. The opportunity to transmit heat or to reuse waste heat should be discussed.

Since the chemical medium will flow close to the lossy electrical conductor, a heat transfer from the conductor to the medium will occur. This transfer introduces a coupling between the transmitted electrical and chemical powers, which will require special attention. Several scenarios are possible for the thermal part of the described interconnector system:

- **Cryogenic energy transmission**: The chemical carrier (e.g. liquid hydrogen) might be used to cool down the interconnector to a temperature below ambient temperature. This would lower the electrical transmission losses and increase transmission capacity but require additional cooling power.
- **Waste heat recovery**: The ohmic losses are partly absorbed and transported by the chemical carrier, which reaches the outlet of the interconnector at a temperature well above ambient temperature. This heat can be reused or recovered (e.g. using thermoelectric converters).
- **Heat transmission**: The chemical carrier enters the interconnector at a temperature level well above ambient temperature.

Cryogenic transmission and heat transmission may bring additional constraints and uncertainties, and thus waste heat recovery will be considered primarily.

Finally, two main classes of chemical energy carriers can be used: liquid or gaseous carriers. The essential difference is the nature of the resulting coupling between the electrical and chemical power:

- **Liquid carriers are incompressible**. This means that for given inlet and outlet temperatures, the ratio between the electrical losses and the transmitted chemical power is fixed (since both quantities are proportional to the mass flow rate).
- **Gaseous carriers are compressible**. The inlet to outlet pressure ratio also influences the relation of electrical to chemical transmitted power. This reduces the operational constraints arising from the coupling between the electrical and chemical power compared to the case of liquid carriers.

Gaseous carriers therefore offer more flexibility, also with respect to potential production, conversion and end-use (e.g. hydrogen or natural gas).

In summary, the preferred variant (which will be discussed in the following sections) is the combined transmission of electricity and gaseous chemical energy with waste heat recovery.

B. Layout parameters

For the purpose of this study, a generic representation of the interconnector shown in Fig. 3 has been chosen. This permits to investigate the idea of multi-energy transmission in a general way. In this simplified modeling framework, the interconnector layout implies the determination of the following quantities:

- The interconnector inner radius
- The maximum electrical transmission voltage
- The total electrical conductor cross-sectional area

The inner radius is primarily a function of the required maximum chemical power. The transmission voltage and conductor cross-sectional area result from the required maximum electrical power and from the chemical to electrical power ratio.

C. Design alternatives and constrained parameters

In addition to the previously described layout parameters, other variations are possible:

- The choice of the chemical medium. The different energy content and the varying specific thermal capacity of gaseous media implies that the resulting layout is largely influenced by the choice of the energy carrier.
- The electrical conductor can be varied as well. Since the difference in the material properties are less pronounced, the layout is only slightly modified.

The transmissible power is finally limited by material parameters and construction considerations among which:

- Temperature limitations: the withstand capability of the used material (especially the electrical insulation material) will limit the possible outlet temperature of the chemical medium.
- Maximum operating pressure and electrical current density: construction considerations suggest a limitation of these quantities.

D. Model and layout procedure

Electrical and chemical power flows will be calculated based on a simplified model as shown in Fig. 3. The DC electrical power P_{el1} and the chemical power P_{ch} enter the interconnector. A part P_U of the ohmic heat losses $P_V = P_{el1} - P_{el2}$ is transmitted to the surrounding soil. The remaining thermal power P_{CM} is transmitted to the flowing medium. The total absorbed thermal power P_Q is the sum of the internal viscous friction and the absorbed ohmic losses.

Since the gas flow is non-isothermal and non-adiabatic, it is described by a set of partial differential equations. The absorbed thermal power P_Q is a function of the temperature and pressure profiles, which depend on the transmitted chemical power. Since P_Q is related to the ohmic losses as well, a coupling exists between the transmitted electrical and chemical powers. This means that for a given value of the chemical power, the range of the permissible electrical power is limited.

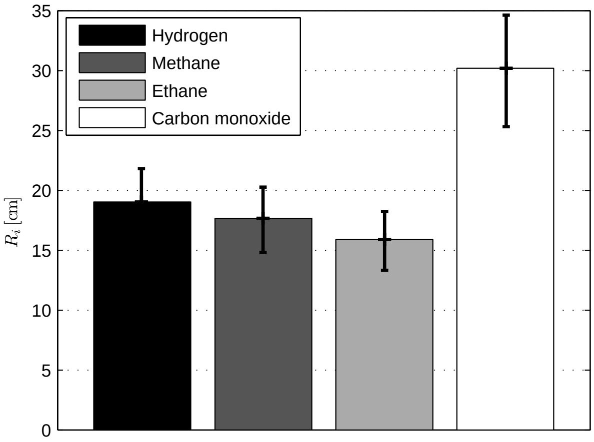

Fig. 4. Resulting interconnector inner radius R_i for different energy carriers (example).

The developed model has been used to determine the transmissible power for a given interconnector layout and on this basis a layout strategy was developed yielding the required inner radius, maximum transmission voltage and conductor cross-sectional area for set values of the maximum electrical and chemical powers. Its application will be illustrated in the following example.

V. POTENTIAL APPLICATION OF THE ENERGY INTERCONNECTOR PRINCIPLE

The implications of different chemical energy carriers on the interconnector layout are illustrated in an example for a maximum transmissible electrical power of $300\,\mathrm{MW}$ and a maximum chemical power of $400\,\mathrm{MW}$. The total transmission length is $60\,\mathrm{km}$.

In this application example, a broad spectrum of potential gaseous energy carriers has been considered: hydrogen, methane (major constituent of natural gas), ethane and carbon monoxide.[1] Fig. 4, 5 and 6 show the resulting inner radius, the conductor cross-sectional area and the maximum transmission voltage respectively. The error bars represent the effect of a variation of $\pm 25\%$ of the transmitted powers and line length.

The inner radius is similar for the three considered hydrocarbons. The gases with larger molecules (methane and ethane) cause less friction losses and consequently the inner radius can be slightly smaller for those. Since carbon monoxide has a lower energy density, a larger inner radius results (to accommodate the higher mass flow rates).

The significant difference in the ratios of the specific chemical energy content and the specific thermal capacity results in a large variation of the required total conductor cross-sectional area (the total of the cross-sectional area

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[1] The use of synthetic gas, i.e. mixtures consisting of carbon monoxide and hydrogen, could also be envisaged from a system perspective. This would, however, raise safety issues and the number of direct users or producers of this gas mixture is certainly smaller than e.g. in the case of hydrogen.

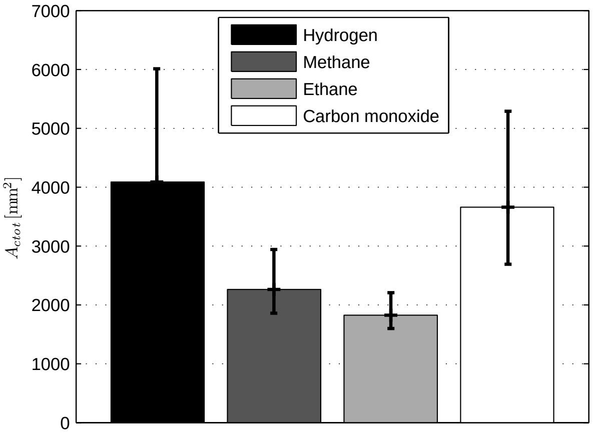

Fig. 5. Resulting total conductor cross-sectional area A_{cTot} for different energy carriers (example).

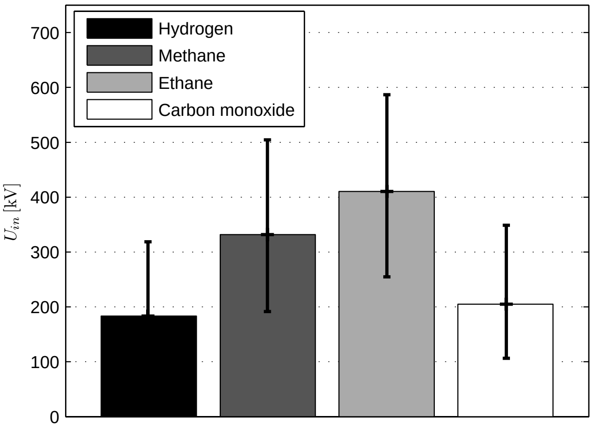

Fig. 6. Resulting maximum transmission voltage U_{in} for different energy carriers (example).

required for the two poles). This ratio is highest for ethane, which means that for the same transmitted chemical energy, lower losses are permissible. Combined with the assumption of an invariant maximum current density, a higher required conductor cross-section results for the carriers with a lower ratio.

The maximum transmission voltage is highest for ethane (due to the smaller conductor cross-sectional area) while it is in a more reasonable range for hydrogen and methane. In summary, using hydrogen as chemical energy carrier requires one of the smallest inner radii and the lowest transmission voltage and thus appears to be the best choice for the energy carrier in the investigated application.

The presented application examples illustrates how the developed interconnector layout procedure can be used to design a multi-energy transmission link satisfying the requirements in terms of transmitted electrical and chemical power and transmission length. Such comparative studies will be useful in further project stages when infrastructure scenarios will be compared.

VI. CONCLUSIONS

The ”Vision of Future Energy Networks” project aims at developing a general framework for the study of multi-energy networks. The flexibility and broad applicability of the Energy Hub and Energy Interconnector principles permit the elaboration of a broad spectrum of scenarios for long-term oriented infrastructure evolution. The developed modeling and analysis framework provides adequate tools for the planning and operation of multiple energy carrier systems and enables new design approaches for future energy networks. This framework will be used for the consideration of multi-energy networks as a development option in infrastructure roadmaps.

Future work includes the development of a control scheme for a system of interconnected Energy Hubs (centralized versus decentralized) as well as risk assessment and development of investment strategies for multi-carrier energy systems. The already developed methods and concepts will be further improved and elaborated in more detail by applying them to realistic examples and case studies.

VII. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from ABB, AREVA T&D, Siemens and the Swiss Federal Office of Energy.

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