

A GREENFIELD APPROACH FOR FUTURE POWER SYSTEMS

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SUMMARY

Recent developments in electric power system technology, power electronics, and information technology motivate researchers to reconsider today's power delivery systems. Emerging technologies for transmission, conversion and storage of energy constitute an opportunity for power system improvement. Traditional systems are not deemed to meet future requirements in terms of economic and environmental sustainability. Therefore the authors' institution initiated a research project entitled *Vision of Future Energy Networks* that aims at a greenfield approach for future power systems; this means that boundary conditions given by today's systems are basically neglected in order to achieve better overall system performance. In this project emphasis is put on the use of multiple energy carriers (not only electricity) and distributed energy resources for energy conversion and storage.

The visionary concept is based on two key elements. Converters and storage devices are integrated in so-called energy hubs. These hubs are supplied by various energy infrastructures and deliver power to loads consuming different forms of energy. The second novel approach concerns the combined transmission of different energy carriers in one device, which is called energy interconnector. Electricity and gaseous (e.g. hydrogen) energy carriers can be transported together in this underground transmission element. The whole energy system is then designed using energy hubs, interconnectors, and conventional elements.

Since only a few established tools are available for the analysis of such systems, the project focused in a first phase on developing a modeling framework. Besides detailed component models for interconnector and storage devices, power flow and reliability models have been developed for system analysis. These models as well as approaches for economical evaluation were used in a number of case studies. The results generally show increased system performance in terms of cost, environmental impact, reliability of supply, but also in other aspects.

KEYWORDS

Hybrid energy systems, multiple energy carriers, greenfield approach, energy transmission, energy conversion, energy hub, energy interconnector, power system modeling, power system optimization.

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I. INTRODUCTION

Recent developments in electric power system technology, power electronics, and information technology provide, beyond other sciences, a number of tools and techniques motivating researchers to reconsider today's power delivery systems. Using emerging and looming technologies constitutes an opportunity for drastic improvements of power systems, whereas new approaches far beyond today's way of thinking are needed. Traditional AC systems, which have been growing incrementally over more than a century without experiencing radical changes, are not deemed to meet future requirements in terms of economic and environmental sustainability. The project *Vision of Future Energy Networks* (VFEN), initiated from the authors' institution and supported by industry and authorities, aims at a greenfield approach for sustainable future power systems [1, 2]. Economical, ecological, and technological/functional aspects define boundary conditions for the investigations.

A general hybrid approach includes different energy carriers focusing on synergies between electrical, chemical, and thermal energy (and possibly other energy carriers). Distributed generation, energy storage, and combined transmission of different energy carriers are important aspects in this approach. So-called energy hubs include power in- and output, conversion of power into other forms, and storage. Also local generation (e.g. wind, solar, hydro) is connected to these units. Typical elements in an energy hub are power electronic converters, (micro) gas turbines, fuel cells, heat exchangers, batteries, gas tanks, etc. The hubs exchange power via a hybrid network transporting different energy carriers.

This paper presents the most important aspects, developments and results of the ongoing research project. Section II introduces the general visionary idea focusing on the key approach—the hybrid energy hub. Section III outlines modeling and optimization tools which have been developed for the analysis of the proposed system. In section IV preliminary results of different case studies are presented. Section V concludes the paper and gives an outlook to the future.

II. THE VISIONARY HYBRID APPROACH

An important characteristic of the research project is that investigations are not restricted to electricity only. An integrated view of multiple energy carriers is believed to be necessary for the development of optimal components, system structures, and operation strategies. Systems integrating different forms of energy are commonly called *hybrid energy systems* [3] or *multiple energy carrier systems* [4]. In the following sections, a novel approach for modeling and analysis of such systems is presented.

A. Hybrid Energy Hubs

A conceptual approach based on *hybrid energy hubs* is presented in [5], where an energy hub is defined as an interface between energy producers, consumers, and the transportation infrastructure. An energy hub can be seen as a unit that provides the basic features input and output, conversion, and storage of different energy carriers. Loads and primary sources of energy (e.g. hydro, wind, solar) are considered to be connected to the hub. Figure 1 shows an example of an energy hub.

An energy hub exchanges energy with the surrounding systems via hybrid ports. As an example, the hub shown in figure 1 has two hybrid ports. At the input port, electricity, natural gas, district heat, and wood chips are demanded from the corresponding infrastructures. The output port provides (transformed) electricity, heating, and cooling. In general, all types of gaseous, liquid, and solid fuels as well as other forms of energy can be inputs (and outputs). Typically the hub is supplied by common grid-bound energy carriers such as electricity, natural gas, and district heat. Different energy carriers are also provided at the output ports. Basically, all mentioned input carriers can be transmitted to the output without converting them into other forms. In addition, energy can be converted for the purpose of cooling, production

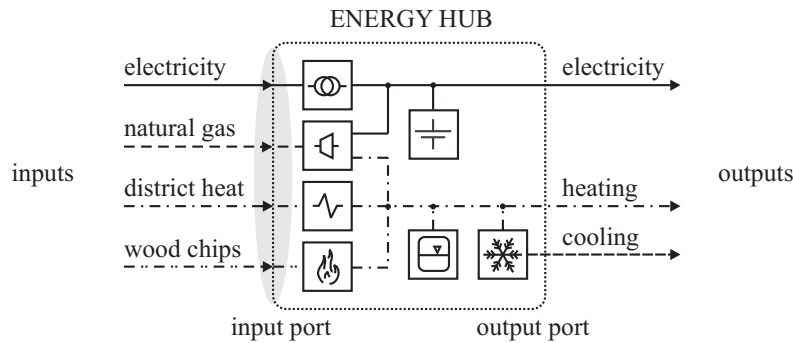


Fig. 1. Example of a hybrid energy hub that contains typical elements: electrical transformer, gas turbine, heat exchanger, furnace, battery storage, hot water storage, absorption chiller.

of compressed air, or steam. Besides the mentioned energy carriers one could also consider in- and output of chemical reactants and products such as water, air (oxygen), emissions, lubricants, and waste.

In terms of technology, energy hubs contain three basic elements: direct connections, converters, and storage. Direct connections are used to deliver an input carrier to the output without converting it into another form or significantly changing its quality (e.g. voltage, pressure). Electric cables, overhead lines, and pipelines are examples for this type of element. Besides that, converter elements are used to transform power into other forms or qualities. Examples are steam and gas turbines, reciprocating internal combustion engines, Stirling engines, electric machines, fuel cells, etc. Compressors, pumps, transformers, power-electronic inverters, heat exchangers and other devices are commonly used for conditioning, i.e. converting power into desirable quantities and/or qualities. The third type of element, energy storage, can also be realized with different technologies. Solid, liquid, and gaseous energy carriers can be stored in tanks and containers employing comparably simple technology. Electricity can be stored directly (e.g. supercaps, superconducting devices) or indirectly (e.g. batteries, hydro reservoirs, flywheels, compressed air storage, reversible fuel cells).

Figure 1 outlines one simple realization of an energy hub. There are a number of examples that can be modeled as an energy hub, for instance

- industrial plants (steel works, paper mills, refineries),
- big buildings (airports, hospitals, shopping centers),
- rural and urban districts, villages, cities, and
- island power systems (trains, ships, aircrafts).

The energy hub approach is not restricted to any size of the modeled system. It enables the integration of an arbitrary number of energy carriers and products, and thus provides high flexibility in system modeling.

From a system point of view, the energy hub shows a number of advantages over conventional, decoupled supply. The redundant paths within the hub offer a certain degree of freedom in supplying the loads. Consider for example the electricity output in figure 1: It can be supplied by consuming electricity directly from the corresponding input or by generating part (or all) of the load power using the gas turbine. The fact that various inputs and different combinations of them can be used to meet the output requirement yields to the question of optimal supply. The different inputs can be characterized by different cost, availability, and other criteria. Then the input of the hub can be optimized using the additional degree of freedom established by redundant connections.

The energy hub processes different energy carriers, each of which showing specific characteristics. Electricity, for example, can be transmitted over long distances with comparably low losses. Chemical energy carriers can be stored employing relatively simple and cheap technology. Time constants in natural gas transmission systems are huge compared with electrical networks, thus the network itself can be seen (and used) as a storage. However, the

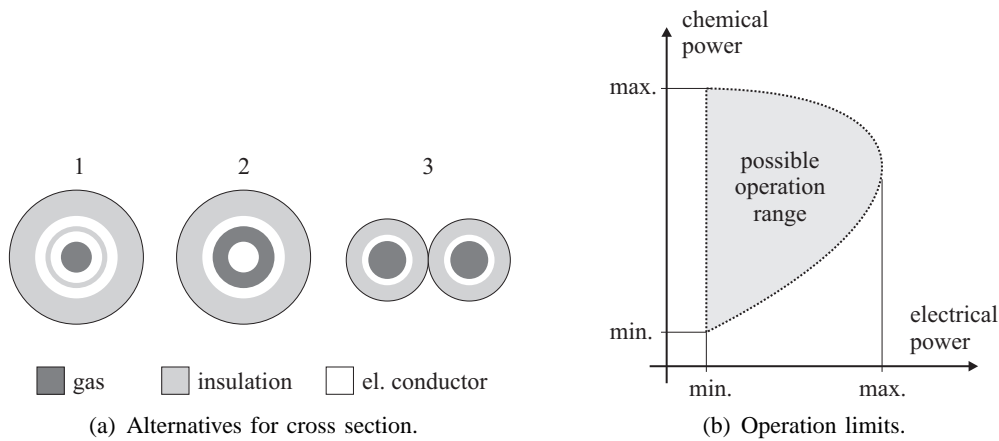


Fig. 2. Possible layouts and operating range for an energy interconnector.

different characteristics of the various energy carriers included in the systems could be used synergetically, i.e. one can take advantage of the specific virtues of different energy carriers.

Considering multiple inputs of an energy hub which can be used to meet the demand at the output makes clear that the hub generally increases availability of energy for the load. But this effect is limited since certain infrastructures are dependent on others, i.e. the different inputs are not really redundant. For example, pumps in district heating systems are usually driven by electricity. Whenever the electric system fails, district heat gets unavailable as well (except there is some emergency supply installed). Such systems are thus less reliable than the systems they depend on.

B. Hybrid Transmission Concept

The integration of different energy carriers can also be considered concerning transmission. In this project, a device for dual transmission of chemical and electrical power named *energy interconnector* is proposed and investigated. A similar concept based on high temperature superconduction is presented in [6]. Figure 2(a) shows concepts for a technological layout of an energy interconnector. So far, the most promising layout seems to be a hollow two-layer electrical conductor carrying a gaseous medium inside (nr. 1 in figure 2(a)).

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 transmission link. Alternatively, losses could be used for increasing the temperature of the gas before expanding it at the interconnector terminal. (Heating the gas before expanding it is often necessary in order to keep the temperature within required limits.)

Comparing the dual concept with conventional transmission lines shows advantages and disadvantages. From an energetic point of view, combined transmission is more efficient if heat losses can be recovered and used at the end of the link. Another advantage could be that information technology necessary for operating the device is likely to be less extensive than for two separated systems. 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 at once. Like normal pipelines, the energy interconnector can be used as a gas storage as well. A clear disadvantage of combined transmission devices is the dependability of the subsystems, 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 flexibility is limited due to certain power flow restrictions. Figure 2(b) sketches the operational boundaries for chemical and electrical power flow under steady state conditions. Simply speaking, a certain gas flow is necessary to provide sufficient cooling of the electrical conductor.

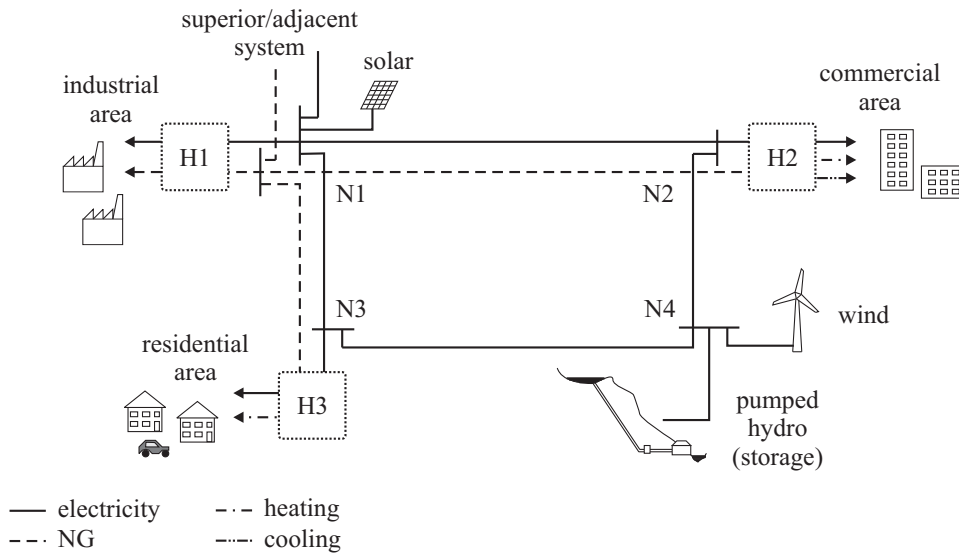


Fig. 3. Sketch of a system of interconnected energy hubs.

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.

C. General System View

We consider the hybrid power system to consist of hybrid energy hubs and different networks interconnecting them. The energy hubs' primary functions are conversion and storage of energy, whereas networks are intended for transmission of power between hubs. However, features dedicated to hubs may be provided by transmission elements (and vice versa): energy can be stored in pipelines and conversion takes place in energy interconnectors.

Figure 3 shows an example of a system of energy hubs supplied and interconnected by natural gas and electricity networks. This is an example for the supply of a town that is divided into three areas: industrial, commercial, and private/residential. Each area is interfaced with the natural gas and electricity distribution networks by a hub. The internal layout of the hubs is adapted to the specific loads. The system in figure 3 contains also power generation outside the hubs. A solar power plant is connected to the network node N1. Besides that, N4 connects with hydro and wind power plants. N4 could represent a remote station in the mountains where hydro reservoirs are available.

This system view—hubs interconnected by networks—is also reflected in the system model outlined in the following section III.

III. MODELING AND ANALYSIS

Economic and physical performances of different energy carrier systems are well understood, whereas global features of integrated, hybrid systems have not been investigated extensively yet. Since there are only a few tools available, the development of a modeling and analysis framework for hybrid energy systems has been identified as a milestone in the project VFEN. This section shortly presents some of the achievements so far.

A. Power Flow

Power flow analysis is an important task in the process of network planing. Therefore models have been developed that enable analysis of coupled flows of different energy carriers.

1) *Converters*: Power can be converted from one form of energy to another one, e.g. from natural gas to electricity. The process can be characterized by a conversion efficiency. In this paper, we define the conversion efficiency as the ratio of steady state power output P_{out} and input P_{in} of the converter:

$$\eta_c = \frac{P_{out}}{P_{in}} \quad (1)$$

where P_{in} and P_{out} may represent different forms of energy. Most converter technologies show decreased efficiency in part load operation, i.e. when less than the rated power is converted. Power-dependent efficiency can be considered by expressing η_c as a function of the converted power P_{in} .

2) *Lines and Networks*: A number of different line and network models have been developed and used for different types of analysis. However, depending on the application, we propose to use one of the following three models.

For general investigations in the system behavior, transportation cost models are commonly used (e.g. in [7]) that model the specific cost of a line expressed in monetary units per unit of power, e.g. in € per MW (and km). Often the flow itself is considered to be lossless, i.e. the line input equals the output.

Network flow models can be used for a more detailed representation of power flows [8]. Line losses can be considered as a function of the transmitted power. The power output of a line equals then the input minus the losses. Losses of electricity lines can be modeled as quadratic functions of the power flow, whereas pipeline losses grow approximately with the cube of the flow.

Classical steady state power flow models for electric and hydraulic systems are used for power flow optimization in real systems (see e.g. [9]). These models incorporate not only conservation but also constitutional laws describing the relationship between voltages and currents, pressure and flows, etc. Detailed discussions on electric and hydraulic power flow models can be found in [10, 11].

3) *Storage*: Modeling storage devices for steady state power flow requires to consider time as an additional variable, since the terminal power affects the energy content of the storage by a time integral function. In order to develop a consistent power flow model, efforts focused on describing storage and converter devices in a similar way. However, stating a steady state energy efficiency for storage devices is different than for converters, because it depends also on the energy stored and its time derivative [12]:

$$\eta_s = f\left(E, \frac{\partial E}{\partial t}\right) \quad (2)$$

where E is the stored energy. For power flow simulations in the time domain (e.g. using 24 hour load profiles), the efficiency function can be approximated by discretizing energy and time ($\partial E/\partial t \approx \Delta E/\Delta t$).

In terms of power flow it is also important to consider that the deliverable power depends on the actual energy content of the storage. Energy-power characteristics of different storage types are discussed in [12]. An example for the charging efficiency of a kinetic storage device is shown in figure 4.

Besides time domain methods, a new approach for storage design based on stochastic models has been developed. Similar to probabilistic power flow models, power and energy of storage devices can be described by probability density functions [13].

4) *Energy Hubs*: Energy hubs convert a number of different energy carriers provided at the input and deliver the power to the output. The corresponding transformation of power can mathematically be described as a mapping. We state all input powers in an input power vector \mathbf{P}_{in} and all output or load powers in \mathbf{P}_{out} . The power vectors can be linked as follows [14]:

$$\mathbf{P}_{out} = \mathbf{C} \mathbf{P}_{in} \quad (3)$$

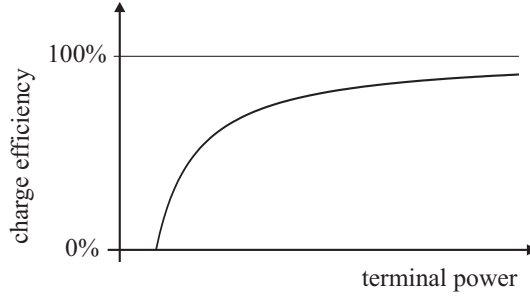


Fig. 4. Charging efficiency for a kinetic energy storage device. The energy content of the storage cannot be increased if the terminal power is below a certain value, since stand-by losses have to be covered. When the storage is charged below this value, then its energy content decreases.

The so-called coupling matrix \mathbf{C} can be derived from the internal structure of the hub and the converter efficiencies. Examples are given in [14, 15]. In general (3) is a nonlinear equation since efficiencies might be dependent on the converted power.

5) *Energy Interconnectors*: Steady state power flow through and conversion within an energy interconnector can be modeled like the flows through an energy hub. The pipe can be described as a converter device with electricity and gas input, and electricity, gas, and heat output, where the heat output grows approximately with the square of the electrical power (as losses do). Terminal equipment such as gas compressors, heat exchangers, transformers, and power electronic devices can also be included in this hub representation.

B. Reliability

Besides other aspects, reliability of supply is an important issue. Therefore a model has been developed that enables to determine the influence of energy hubs on the reliability and availability of supply.

All inputs and hub elements are characterized by failure and repair rates. Based on a Markov approach, these rates can be used to determine the probability of operation as a function of the components present in the hub. This then allows to represent the reliability of the output \mathbf{R}_{out} (vector with entries for each carrier) as a function of the reliability values of the input \mathbf{R}_{in} and the hub components:

$$\mathbf{R}_{out} = f(\mathbf{R}_{in} + \Delta\mathbf{R}) \quad (4)$$

where $\Delta\mathbf{R}$ represents the change in reliability caused by the energy hub.

An alternative approach is investigated which makes use of real options theory. It is intended to be used for illustrating availability in terms of money.

C. System Optimization

Different optimization problems can be identified when considering a hybrid system as outlined in figure 3. In this section, two problems are addressed. The first one is the optimization of power flow and conversion for a given structure, the second one concerns the structure of the system.

1) *Operational Optimization*: Consider again the energy hub shown in figure 1. It was discussed earlier that the electric load of this hub can be supplied via two redundant paths, namely directly from the electricity network or indirectly by converting natural gas using the gas turbine. If the loads \mathbf{P}_{out} are given, the hub can be supplied with different input powers \mathbf{P}_{in} . Different inputs might result e.g. in different energy cost, since the energy carriers may be characterized by different energy prices. The same can be true for other criteria such as emissions, availability, etc. From this point of view it is reasonable trying to find an input vector which is optimal with respect to a certain objective. In analogy to optimal dispatch and optimal power flow problems in electricity networks, models for the optimization of

multiple energy carrier systems have been developed in [14, 15, 16]. A general optimality condition was derived for multiple energy carrier systems, which enables fundamental insight into economic effects of power conversion.

2) *Optimization of System Structure*: Besides the previously described problem—optimizing flows and conversion for given loads—the structure of networks and hubs can be optimized as well. A method was developed that enables to find an optimal hub structure by determining the optimal coupling matrix for given loads [17]. From this theoretical optimum, a practical layout can be derived by selecting the best-fitting elements from a given set of converters.

D. Economic Evaluation

Power systems have to function not only from a technical point of view but also in terms of economy. For this project, investment cost for new technologies (such as energy interconnectors) are of special interest, therefore a model for evaluating investment was developed.

The evaluation method compares two scenarios—conventional system versus hub approach. First a conventional system is assumed to supply given loads; optimal power flow calculations are performed for a number of time periods, e.g. ten years, and operating cost (including energy cost, emission taxes, etc.) are accumulated. In the second step, the same procedure is carried out using energy hubs to supply the same loads. The operating cost can then be compared in each time period and the difference can be calculated. From the resulting stream of savings a present value can be derived which reflects the value of savings arising from utilization of energy hubs. It shows the value of the potential investment and gives an indication of justifiable investment cost for the new technology.

IV. CASE STUDIES

In order to demonstrate the developed models and methods, a few examples of case studies that have been performed within the project are presented in this section.

A. Interactions between Energy Carriers

The developed optimal power flow approach enables analysis of incremental energy prices depending on the location in the network, so-called locational marginal prices (LMP) [18]. Whenever power is exchanged between two energy carriers, the corresponding LMP interact. Usually, the LMP increases if (additional) power is demanded and decreases if (additional) power is injected in a node. Thus LMP in one system (e.g. electricity) can be controlled by injecting a certain amount of power from another system (e.g. natural gas).

These and other investigations have been performed using an example network that contains three hubs interconnected by electricity, natural gas, and district heating networks [15]. Figure 5(a) shows the resulting LMP for a certain operating point. The difference in LMP reflects the loss level in the corresponding network. Since in this example the district heating network is the most lossy system, the LMP vary more than in the natural gas and electricity system.

In this example, every hub contains a cogeneration unit. It can be observed that the utilization of these devices has major technical and economical impact not only on the electrical network but also on natural gas and district heating systems.

B. Cost-Emission Analysis

The operation of energy hubs can be optimized due to different criteria. In [16] bi-objective optimization involving energy cost and CO₂ emissions was performed for the aforementioned 3-hub system. Figure 5(b) shows one of the calculated Pareto curves. Clearly, energy cost and emissions are conflicting criteria. In other studies additional criteria such as security and reliability measures have been used for multi-objective optimization.

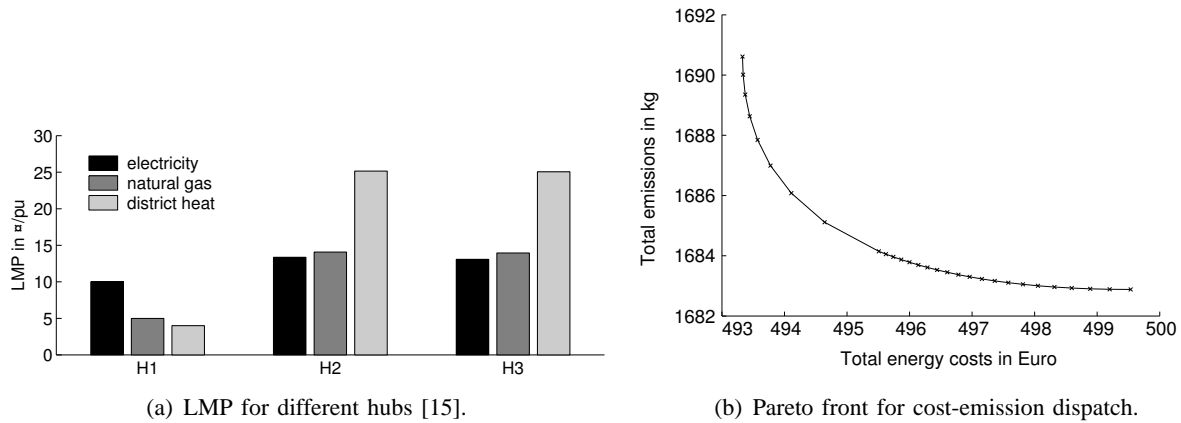


Fig. 5. Case study results: power flow optimization in a 3-hub network.

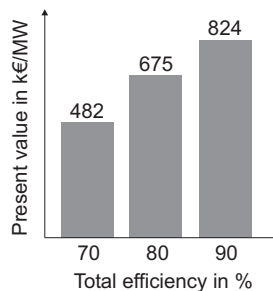


Fig. 6. Case study results: present value per MW electrical rating of cogeneration plant depending on its overall efficiency.

C. Evaluation of Investment

The method for economic evaluation of energy hubs as outlined in section III-D was used in a further example. The question was whether it is reasonable to invest in a cogeneration-equipped energy hub for the supply of an industrial facility or not. From a comparison of operation cost, a present value of the investment was determined depending on the overall energy efficiency (chemical-electrical plus chemical-thermal) of the cogeneration plant inside the hub. Results are shown in figure 6. As expected, the present value of the hub increases with increasing converter efficiency. Today, specific investment cost of the required technology (e.g. combined cycle gas turbines) are in the range of 500 k€ per MW electrical rating. A comparison with figure 6 shows that the investment could be justified if the overall plant efficiency is $\gtrsim 75\%$.

V. CONCLUSIONS

This paper presents the actual state of affairs in the ongoing research project Vision of Future Energy Networks. The main conclusions that can be drawn at this point are:

- The energy hub concept enables new design approaches for hybrid energy systems.
- Investigations have shown that the flexible combination of different energy carriers using conversion and storage technology keeps potential for various system improvements: overall energy cost and system emissions can be reduced, reliability and availability of supply can be increased, congestion can be released, transmission losses can be reduced.
- The developed modeling and analysis framework provides a suitable basis for investigations required for network planning, such as power flow and reliability analysis, and system optimization.

One of the next steps in the project is to create future scenarios based on the energy hub approach for the supply of a town in Switzerland. Investigations will be carried out together with the local multi-utility.

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