
©2010 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.

Multiple-Energy Carriers: Modeling of Production, Delivery, and Consumption

In this unifying framework for modeling and supporting multiple-energy delivery systems, energy forms are converted in an energy hub, then delivered in a controlled manner.

By THILO KRAUSE, *Member IEEE*, GÖRAN ANDERSSON, *Fellow IEEE*, KLAUS FRÖHLICH, *Fellow IEEE*, AND ALFREDO VACCARO, *Senior Member IEEE*

ABSTRACT | This paper presents a generic framework for the modeling of energy systems comprising multiple-energy carriers, such as electricity, heat, gas, biomass, etc. The modeling framework is based on the so-called energy hub approach. The core idea of the energy hub is the definition of a conversion matrix capable of describing the interactions of production, delivery, and consumption in multiple-energy carrier systems. Based on the energy hub concept a broad spectrum of modeling extensions and applications is presented, such as a multiple-energy carrier optimal power flow, risk management and investment analysis tools, agent-based control schemes for decentralized generation units as well as the possibility to analyze the influence of plug-in hybrid electric vehicles (PHEVs) on future energy systems. The paper is concluded with a section presenting the key benefits of the energy hub modeling framework, followed by a discussion on the main design principles generality, scalability, and modularity as well as a discussion on the possibility to follow top-down or bottom-up modeling strategies.

KEYWORDS | Multiple-energy carrier optimal power flow; multiple-energy carrier portfolio theory; multiple-energy carrier reliability; multiple-energy carrier systems

Manuscript received October 2, 2009; revised July 28, 2010; accepted September 12, 2010. Date of publication November 18, 2010; date of current version December 17, 2010. This work was supported by ABB, Areva T&D, Siemens, the Swiss Federal Office of Energy, Swisspower, and the municipalities of Baden and Bern.

T. Krause, **G. Andersson**, and **K. Fröhlich** are with the Power Systems and High Voltage Laboratories, Swiss Federal Institute of Technology (ETH), 8092 Zürich, Switzerland (e-mail: andersson@eeh.ee.ethz.ch; froehlich@eeh.ee.ethz.ch; krause@eeh.ee.ethz.ch).

A. Vaccaro is with the Dipartimento di Ingegneria, Università degli Studi di Sannio, 82100 Benevento, Italy (e-mail: vaccaro@unisannio.it).

Digital Object Identifier: 10.1109/JPROC.2010.2083610

I. INTRODUCTION

Bulk electricity generation and transmission technologies often exhibit large economies of scale. Driven by these scale effects, power systems historically evolved into large, interconnected structures, where electricity is mostly produced in “centralized” power plants with ratings ranging from several hundreds to thousands of megawatts. On the contrary, climate change, fossil resource depletion, policy incentives as well as higher public awareness in term of sustainability have promoted the deployment of small decentralized and renewable generation technologies, typically including photovoltaics, microturbines, combined heat and power (CHP), waste and wood incineration plants, etc. [1]. Nonetheless, the size of distributed generation facilities is not the only aspect influencing the currently prevailing power system structure. A number of these technologies also provide the possibility for so-called cogeneration or trigeneration [2], [3]. Using, e.g., CHPs or microturbines, it is possible to produce electricity and heat out of natural or biogas, biomass etc. Together with the deployment of distributed storage technologies or the prospective integration of plug-in hybrid electric vehicles (PHEVs) complex interactions between the different energy carries and systems arise [4], [5]. The traditional “setup” of the power system with the typical power flow from higher to lower voltage levels may be altered. Infeeds from lower voltage levels are becoming increasingly common. Additionally, new building standards promote energy efficiency benefiting from advanced information and communication technologies to “exploit” the intensified couplings between both production, transmission, and consumption as well as the different

energy carriers. Such an operational and topological flexibility calls for a generic framework to describe the effects on economic, ecological, and technical indicators related to energy systems. In that, the contribution of this paper is the formulation of a generic framework for the modeling of energy systems comprising multiple-energy carriers.

The remainder of the paper is organized as follows. Section II describes the basal principles of the modeling framework, further detailing the need for an integrated multiple-energy carrier approach. Additionally, the energy hub is introduced as key concept. Section III presents several applications of the energy hub concept in order to assess questions related to multiple-energy carrier optimal dispatch and power flow, risk management and investment analysis, agent-based control schemes for decentralized generation as well as a framework to assess the influence of PHEVs on future energy systems. In the subsequent Section IV, information on modeling concepts similar to the energy hub approach is provided, conclusions are drawn regarding key benefits and feasibility, and further applications and extensions of the hub concept are proposed. The paper is concluded with a summary of the main findings.

II. GENERAL MODELING FRAMEWORK

A. A Greenfield Approach for Future Energy Systems

Most of the work described in this paper was developed in the scope of the project “Vision of Future Energy Networks (VoFEN)” conducted at the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland [6]. The project was started in 2002 with the underlying assumption to take today’s transmission and generation technologies and design an optimum system “from scratch” without considering the current power system structure. The idea is to investigate how a fictitious optimum system would look like and then backcast the main findings onto the current energy infrastructure. In a subsequent step, bridging systems can be designed in order to move from today’s structure towards optimal future structures. This general research approach is depicted in Fig. 1.

In terms of electricity networks, a standard set of tools exists allowing for the assessment questions of topology optimization, operational strategies, investment options, reliability, etc. One objective of the VoFEN project was to extend the capabilities of this “classic” modeling framework to multiple-energy infrastructures.

Generally, the proposed framework can be seen as modeling example for an open-access, interconnected system. “By an open system, we mean a system that interacts with its environment, for example, by exchanging matter, energy, or information. By an interconnected system, we mean a system that consists of interacting

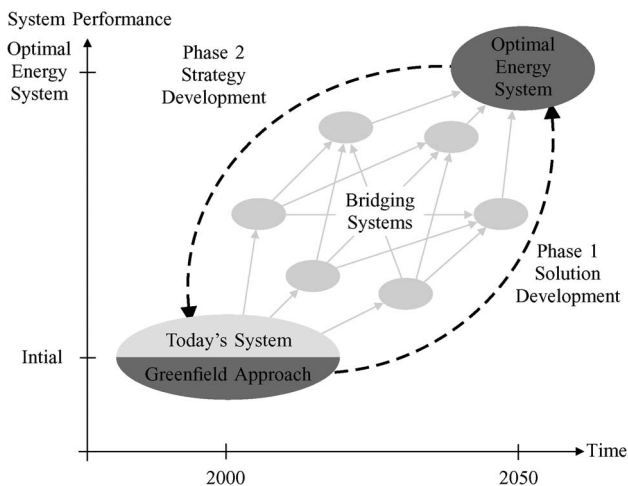


Fig. 1. A greenfield approach for future energy systems [7].

subsystems” [8]. The framework as a whole mostly relies on steady-state models, i.e., the internal dynamics of the different networks and network components are neglected. However, the approach can be extended to account also for dynamic phenomena as, e.g., described in [9]. A selection of the developed modeling tools is described in Section III, whereas the next paragraph motivates the idea to design a modeling framework explicitly considering multiple-energy carriers.

B. Coupling of Multiple-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. However, standard planning tools for the design of energy networks typically do not provide an integrated view on the different infrastructures. The production, transmission, and distribution of the various energy carriers is treated as a set of independent problems, where each system is optimized without taking the interfaces and interactions of the different energy carriers into account. It is questionable if this approach will be sufficient for an efficient planning and operation of future energy systems. New generation and conversion technologies change the traditional setup of transmission, distribution, and consumption. The power flow is no longer solely unidirectional, “descending down” from higher to lower voltage levels. Due to the increasing penetration of distributed generation, the flow may become “bidirectional.” Hence, questions arise whether, for instance, to produce and infeed electricity locally instead of just “consuming” the energy from higher network levels. Subsequently, the characteristics of network nodes change from “passive” points of withdrawal to entities which

provide the flexibility to store, convert, and condition energy. In the proposed research framework, such network nodes with local production, conversion, and storage facilities are called “energy hubs.” One objective for the definition of energy hubs was the idea to extend the traditional network modeling framework in order to capture the new operational flexibility of formerly “passive” network nodes [10]. The developed theory to define and describe energy hubs is presented in the next paragraph.

C. The Energy Hub

1) *General Concept*: As outlined above, there is an increasing penetration of distributed generation and storage technologies in power systems, changing “formerly” passive network nodes into so-called energy hubs, where multiple-energy carriers can be converted, conditioned, or stored. Fig. 2 illustrates a sample energy hub.

“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 input and output, conversion, and storage of multiple-energy carriers” [12]. The energy hub in Fig. 2 has its input ports supplied with electricity, natural gas, and heat. Inside the energy hub, several technologies reside which allow conversion and conditioning of the input energy carriers. In the example, the following technologies are present: a transformer, a gas turbine, a gas furnace, and a heat exchanger. At its output ports, the energy hub supplies electricity and heating. Energy hubs can be used as mere modeling concept, but additionally there exist a number of “real” facilities with the actual capabilities of an energy hub, such as industrial plants (steel works, paper mills), big building complexes (airports, hospitals, shopping malls), rural and urban districts, and small isolated systems (trains, ships, aircrafts).

2) *Mathematical Model*: Fig. 3 presents a generic schematic of an energy hub.

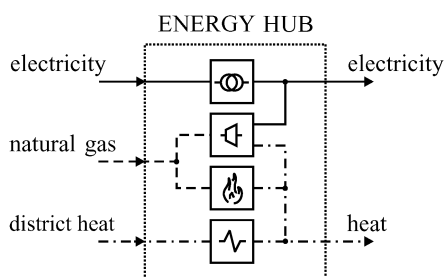


Fig. 2. Example of a hybrid energy hub that contains an electrical transformer, a gas turbine, a gas furnace, and a heat exchanger [11].

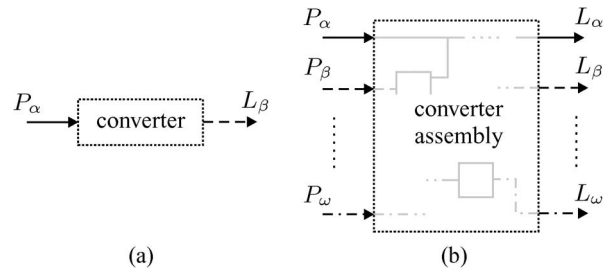


Fig. 3. Model of power converters with inputs $P_\alpha, P_\beta, \dots, P_\omega$ and outputs (loads) $L_\alpha, L_\beta, \dots, L_\omega$ [11]. (a) Converter with single input/output. (b) Converter arrangement with multiple inputs/outputs.

The hub is characterized by a set of energy carriers $\alpha, \beta, \dots \in \mathcal{E} = \{\text{electricity, natural gas, heat, } \dots\}$, where each energy carrier may be a hub input and/or a hub output. The set of input powers (output powers) is defined by $P_\alpha, P_\beta, \dots, P_\omega$ ($L_\alpha, L_\beta, \dots, L_\omega$). As described in the above example, specific technologies inside the hub allow for the conversion of energy carriers. A simple conversion device with one input and one output can be described as follows [see Fig. 3(a)]:

$$L_\beta = c_{\alpha,\beta} P_\alpha. \quad (1)$$

The device converts an energy carrier α into β , where input and output powers are coupled through the coupling factor $c_{\alpha,\beta}$ given by the converter’s steady-state energy efficiency. Accordingly, an energy hub can be modeled as a combination of different converters covering multiple inputs and outputs. Equation (2) provides the mathematical description of the energy hub

$$\underbrace{\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha,\alpha} & c_{\beta,\alpha} & \cdots & c_{\omega,\alpha} \\ c_{\alpha,\beta} & c_{\beta,\beta} & \cdots & c_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha,\omega} & c_{\beta,\omega} & \cdots & c_{\omega,\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}}. \quad (2)$$

The entries of the coupling matrix \mathbf{C} are the converter coupling factors. Each coupling factor relates one particular input to a certain output incorporating the specific conversion efficiencies.¹ For a more detailed discussion on the definition, modeling, and use of energy hubs the reader is referred to [11] and [14].

¹Such a constant coupling matrix \mathbf{C} is the most simple case. Actually, one energy carrier may serve as input to more than one converter. This constellation makes the use of internal dispatch factors necessary. We restrain to present the underlying theory in the scope of this paper. The reader is referred to [13] for more details.

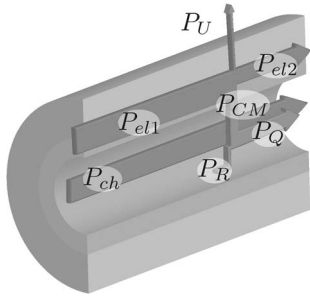


Fig. 4. Representation of the principle of the energy interconnector. P_{el} : electrical power, P_{ch} : chemical power, P_U : losses transmitted to the soil, P_{CM} : losses absorbed by the chemical medium, P_R : internal viscous friction in the chemical medium, P_Q : thermal power delivered by the chemical medium [15].

The energy hub as defined throughout this sections forms the basal concept for all subsequent modeling extensions, which are described in Section III.

D. Transmission and Distribution Modeling, the Energy Interconnector

In the above, an energy hub was presented as a generalized network node interfacing transmission, generation (conversion), and storage. Typically, energy hubs will not be operated as isolated entities. They will rather be part of a system of interconnected hubs, where the different energy carriers have to be transported to and from the hubs. For the transmission, dedicated infrastructures exist, e.g., electricity, gas, or district heat networks. When modeling a system of interconnected hubs, each network may be described independently according to the “traditional” flow equations defined for each network.² A more visionary approach was taken by the conceptual design of a so-called “energy interconnector” allowing for the simultaneous transmission of heat, electricity, and chemical energy in one single device (see Fig. 4 for a schematic layout).

In [15], the underlying assumptions as well as possible applications and benefits are extensively described. However, in the scope of this paper, the different grid-bound energy carriers are modeled independently, i.e., each energy carrier in conjunction with its dedicated infrastructure.

III. SPECTRUM OF MODELING FRAMEWORK APPLICATIONS

Based on the energy hub concept several submodels have been developed, including:

- optimal energy hub dispatch;
- optimal multiple-energy carrier power flow;
- reliability assessment of energy hubs;

²See [11] for a summary on gas and electricity flow modeling in conjunction with the energy hub approach.

- generation portfolio and risk management techniques based on the energy hub approach;
- distributed control of a network of energy hubs;
- a framework for the assessment of multiple-energy carrier markets;
- a framework to model PHEVs and their influence on energy systems;
- a framework for the assessment of investment decision in urban networks (case studies).

This section intends to give an overview on the above listed models. Generally, the objective was to transfer “classic” power systems’ modeling concepts (e.g., for optimal power flow (OPF), reliability, distributed control, etc.) to a multiple-energy carrier framework. Sections III-A–F are structured similarly. First, the research is motivated, followed by a description of the main assumptions and a brief sketch of the modeling principles. At the end relevant publications are listed providing deeper insights in the conducted research work.

A. Optimal Dispatch of an Energy Hub

1) *Motivation:* Fig. 2 depicted a sample hub with typical converter units. As described in Section II-C similar hub configurations might represent industrial plants (steel works, paper mills), big building complexes (airports, hospitals, shopping malls), or rural and urban districts. From an operational viewpoint, a relevant question is the performance optimization of such an entity in terms of, e.g., cost, losses, or emissions, where the flexibility of the hub approach provides significant optimization potential. It is, for instance, possible to avoid consuming expensive electrical energy from the electricity network during peak periods by using the microturbine. The 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. With regard to these questions, a multiple-carrier cost optimal dispatch was developed, where we present the most basal case characterized by a constant coupling matrix (see Section II-C2), while neglecting storage devices.

2) *Main Assumptions and Model Overview:* Typically, an optimal dispatch problem consists of an objective function and a set of constraints. In this paper, we present the problem for the minimization of the total energy costs, where the costs are a function of the input powers during a certain time period. With the input power vector \mathbf{P} , the objective function can be written as

$$f(\mathbf{P}). \quad (3)$$

The optimization problem is constrained by the power flow through the hub [see (2)] as well as the limitations

determined by the input power vector \mathbf{P} of the hub. For \mathbf{P} , lower limits $\underline{\mathbf{P}}$ or upper limits $\bar{\mathbf{P}}$ may exist. Subsequently, the optimal dispatch of an energy hub can be formulated as follows:

$$\text{minimize } f(\mathbf{P}) \quad (4)$$

$$\text{subject to } \mathbf{L} - \mathbf{C}\mathbf{P} = 0 \quad (5)$$

and

$$\underline{\mathbf{P}} \leq \mathbf{P} \leq \bar{\mathbf{P}}. \quad (6)$$

The optimization problem presented above has linear constraints. In conjunction with a convex objective function, the dispatch can be solved using numerical methods. However, it has to be noted that (4)–(6) only describe the most basal case—an energy hub with a constant coupling matrix. In reality, one energy carrier may be dispatched to more than one converter resulting in a set of hub-internal dispatch factors. The related modification of the original problem is described in [11]. Further extensions are necessary to incorporate storage devices in the optimization problem. For a comprehensive discussion of such configurations, the related optimization problem, and its solution, the reader is referred to [13], [14], and [16].

B. Multiple-Energy Carrier Optimal Power Flow

1) *Motivation*: The optimal dispatch problem of a single energy hub can be extended to a system of interconnected energy hubs, resulting in a multiple-energy carrier OPF. Such an OPF can be used to optimize the operation of a network of interconnected hubs.

2) *Main Assumption and Model Overview*: To formulate the multiple-energy carrier OPF, an additional set of variables defining a set of hub numbers \mathcal{H} has to be introduced: $i, j, \dots \in \mathcal{H} = \{1, 2, \dots, N_H\}$. Each hub i is then characterized by a coupling matrix C_i , by the power inputs P_i and the hub loads L_i . The network power flows are denoted by \mathbf{F}_α . The term $\mathbf{G}_\alpha(\mathbf{P}_i)$ refers to the set of power flow equations of the hubs and the different networks (e.g., electricity and gas). We restrain from presenting the flow equations as this exceeds the scope of this paper. In [11], the flow modeling of electricity and gas networks is described comprehensively. Again the hub input power might be constrained with lower limits \underline{P}_i or upper limits \bar{P}_i . Network flows are also likely to be constrained by lower flow limits $\underline{\mathbf{F}}_\alpha$ and upper flow limits $\bar{\mathbf{F}}_\alpha$. With the above nomenclature it is

possible to formulate the multiple-energy carrier OPF as follows:

$$\text{minimize } f(\mathbf{P}_i, \mathbf{F}_\alpha) \quad (7)$$

$$\text{subject to } \mathbf{L}_i - \mathbf{C}_i\mathbf{P}_i = 0, \quad \forall i \in \mathcal{H} \quad (8a)$$

$$\mathbf{G}_\alpha(\mathbf{P}_i) = 0, \quad \forall \alpha \in \mathcal{E} \quad (8b)$$

and

$$\underline{P}_i \leq P_i \leq \bar{P}_i, \quad \forall i \in \mathcal{H} \quad (9a)$$

$$\underline{\mathbf{F}}_\alpha \leq \mathbf{F}_\alpha \leq \bar{\mathbf{F}}_\alpha, \quad \forall \alpha \in \mathcal{E}. \quad (9b)$$

Note that the objective function $f(\mathbf{P}_i, \mathbf{F}_\alpha)$ is also dependent on the network flows \mathbf{F}_α as the line utilization causes losses, which have to be covered by additional generation. In line with the optimal dispatch problem, the OPF has been stated with constant coupling matrices. The introduction of dispatch factors is described in [11]. In compliance with the OPF in electricity networks, the problem defined in (7)–(9b) yields marginal cost of the different energy carriers at the different hubs, i.e., a system of locational marginal prices. Comprehensive examples related to the optimal dispatch and OPF problem can be found in [13], [14], and [17]. Note that the optimization problem can be formulated with a “full” alternating-current representation of the electric network or with the so-called direct-current approximations. The same applies to the gas network. It is possible to use flow equations considering linepack effects, losses, and compressor-dependent pressures or build more simplified gas pipeline models.

The models for the multiple-carrier optimal dispatch and the multiple-carrier OPF form the baseline of analysis tools. Subsequent research, i.e., the works on PIHV integration, distributed control of a network of energy hubs as well as the case studies rely to a significant extent on the above described methods.

C. Distributed Control of Multiple-Energy Carrier Systems

1) *Motivation*: The increasing penetration of distributed generation facilities induces also changes in terms of power systems’ control paradigms. Traditionally, large power plants are controlled by a central entity, i.e., the network operator. However, the increasing number of small generation units renders it difficult to apply centralized control paradigms on all networks levels. Subsequently, a framework was developed in order to deal with problems of distributed control in multiple-energy carrier networks.

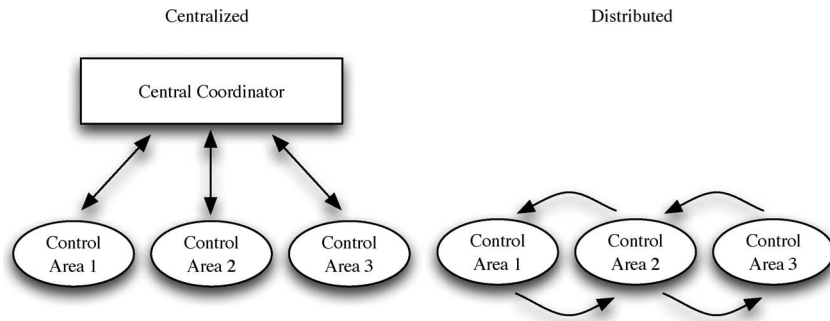


Fig. 5. Three control areas which are optimized in a centralized (left-hand side) and distributed (right-hand side) control scheme. The arrows indicate the information exchange [18].

2) *Main Assumptions and Model Overview:* Fig. 5 provides a schematic of the different control paradigms. A centralized approach relies on a central coordination entity, where for the distributed concept the control areas exchange data among each other in the absence of a supervisory entity.

To implement, e.g., a distributed multiple-carrier OPF, the original problem presented in Section III-B was decomposed into a number of subproblems. We restrain to present the mathematical formulation in the scope of this paper. The reader is referred to [19]. Generally, the control areas (hubs) exchange data with each other, where the objective is to reach the optimal solution point derived from the centralized OPF problem. Data exchange may, for instance, take place in a serial way, i.e., the control areas coordinate each other one after another or they may follow a parallel setup, where the coordination takes place simultaneously. Fig. 6 illustrates the implementation results. The control areas (hubs) exchange data; after a number of iterations the generation vector remains unchanged indicating that the solution point was found. Applying the serial approach, a coordination is obtained

within fewer iterations. The main results of this research are documented as follows. In [19], a distributed multiple-carrier OPF is developed. In [20], a model taking into account storage devices is presented, where model predictive control methods are applied in order to optimize the network over a defined time horizon (typically 24 h).

D. Reliability Assessment of Multiple-Carrier Energy Systems

1) *Motivation:* Previously, it was outlined that the energy hub offers a certain degree of flexibility and responsiveness. When prices are high it is possible to generate electricity locally using, e.g., a CHP device instead of “consuming” electricity from the network. This flexibility is due to the inherent hub redundancy, i.e., there are different conversion paths to provide a certain output energy carrier. The redundancy may be used for various optimization tasks (cost, emissions, etc.). Apart from economic benefits, it is obvious that this operational flexibility will also have an influence on the reliability of supply.

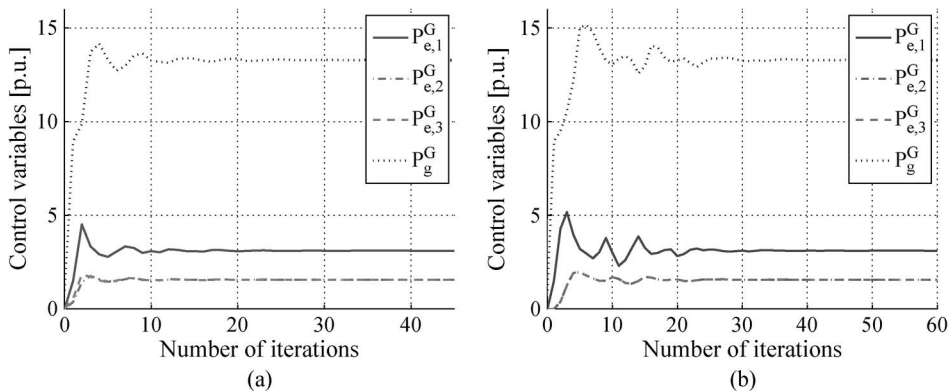


Fig. 6. Active power generation ($P_{e,1}^G, P_{e,2}^G, P_{e,3}^G$) and natural gas import P_g^G for (a) a serial coordination scheme and (b) a parallel coordination scheme [20].

2) *Main Assumptions and Model Overview*: In (2), the coupling matrix \mathbf{C} was introduced mapping the input carriers to the output carriers using coupling factors derived from the specific conversion efficiencies. “Analogous to the coupling matrix \mathbf{C} , a failure rate matrix $\mathbf{\Lambda}$ and a repair matrix \mathbf{M} can be defined, containing the failure and repair rates, respectively” [21]

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda_{\alpha,\alpha} & \lambda_{\beta,\alpha} & \cdots & \lambda_{\omega,\alpha} \\ \lambda_{\alpha,\beta} & \lambda_{\beta,\beta} & \cdots & \lambda_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{\alpha,\omega} & \lambda_{\beta,\omega} & \cdots & \lambda_{\omega,\omega} \end{bmatrix} \quad (10)$$

$$\mathbf{M} = \begin{bmatrix} \mu_{\alpha,\alpha} & \mu_{\beta,\alpha} & \cdots & \mu_{\omega,\alpha} \\ \mu_{\alpha,\beta} & \mu_{\beta,\beta} & \cdots & \mu_{\omega,\beta} \\ \vdots & \vdots & \ddots & \vdots \\ \mu_{\alpha,\omega} & \mu_{\beta,\omega} & \cdots & \mu_{\omega,\omega} \end{bmatrix}. \quad (11)$$

The use of the above matrices is based on the assumption that the operational behavior of the hub can be modeled as stationary Markov process. From the matrices, the probabilities for an operating conversion or a failed conversion can be derived. In conjunction with a state–space diagram the expected reliability of supply and the expected energy not supplied can be computed. The two indicators allow for assessing the potential benefits and risks associated with the operation of multiple-carrier energy systems in terms of reliability. The modeling framework is described in detail in [21]–[23].

E. Risk Management and Investment Strategies for Multiple-Energy Carrier Systems

1) *Motivation*: With the technological evolution of small-scale renewable generation, such as CHP, photovoltaics, microturbines, etc., the traditional large-scale thermal and hydro generation portfolio was significantly diversified. These recent technological advancements increase the complexity for policy and decision makers when it comes to choosing among different investment options, i.e., which mix of generation technologies should be deployed to satisfy the future energy demand. To support this decision process with quantitative analysis tools, the energy hub approach was linked to classical measures of investment and portfolio theory, such as the mean-variance portfolio model. In contrast with the previously presented tools, the risk management and investment model has a time horizon of several years, typically in the range from 10 to 40 years.

2) *Main Assumptions and Model Overview*: The objective of standard mean-variance portfolio theory [24] is to determine efficient portfolios that minimize risk for any

given level of return. Hence, a so-called efficient frontier can be computed, representing all portfolio combinations with the highest possible return for a given risk level. In the context of a greenfield approach to future multiple-energy carrier systems, the tradeoff between risk and return of investments in different generation technologies can be taken into account. “The multiple-energy portfolio model is based on a set of scenarios, which incorporate factors that have an influence on future energy generation cost and thus on the return of the investment in the respective generation portfolio [25].” Sample factors are, for instance, the future prices for carbon emissions and fossil fuels. As certain output energy carriers, such as electricity or heat, may be supplied by more than one technology, a matrix similar to the coupling matrix \mathbf{C} is used to describe the different efficiencies and capabilities of the individual technologies. Fig. 7 shows an example with heat and electricity as necessary output energy carriers. Different technologies (see the legends of the figure) can be used to satisfy this energy demand, where the change of the different technologies shares for a given risk level σ_p can be seen. Note that for low risk levels the diversification is at maximum, where with increasing risk (increasing σ_p values) diversification decreases.

In the basal multiple-energy portfolio model as presented in [26] only monetary risks can be taken into account. In [27], the method was extended to include all types of uncertainty, i.e., also nonfinancial indicators. In [25], a multiple-period, multiple-energy portfolio model is described capable of computing so-called bridging portfolios to move “smoothly” from today’s system to future structures (see Fig. 1). Current research targets the

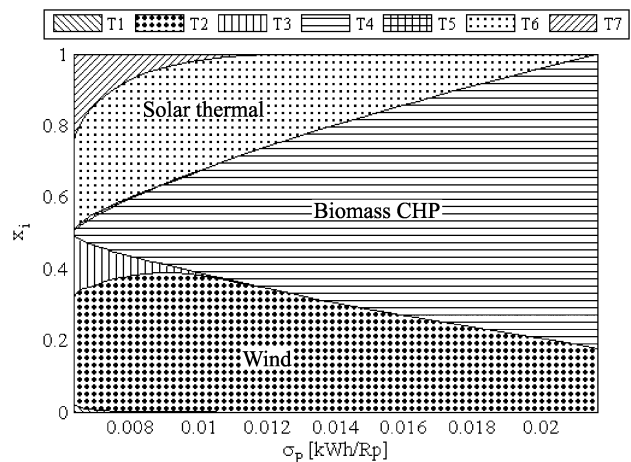


Fig. 7. Shares of technologies x_i on the efficient frontier for different risk levels σ_p . The example includes the following technologies: **T1** photovoltaics, **T2** wind onshore, **T3** small hydro (< 10 MW), **T4** biomass (wood chips) CHP with extraction condensing turbine, **T5** natural gas CHP with extraction condensing turbine, **T6** solar thermal collectors, and **T7** gas boilers [25].

application of real option theory in order to evaluate specific energy hub investment options.

F. An Energy-Hub-Based Framework to Study the Network Integration of PHEVs

1) *Motivation*: Recently, PHEVs have received significant public and research attention. (See, for instance, [4], [15], [28]–[30].) PHEV integration and its influence on electricity networks can be adequately studied with the proposed modeling framework as the energy hub approach provides an adequate method for the assessment of the coupling effects between the different energy carriers as well as the different infrastructures involved (transportation and energy systems). For the modeling tasks related to the transportation system, research was carried out in cooperation with researchers from the field of transport sciences. The entire framework is described in [31]. Generally, the transportation model delivers data for the individual transportation preferences and patterns. The data allow to determine the spatial transportation demand which is a crucial input in order to determine the spatial energy demand, the ability of the PHEV fleet to serve as distributed storage, or—related to the vehicle to grid concept—to provide regulation services.

2) *Main Assumptions and Model Overview*: In a first step, an energy hub representation of a PHEV was developed. Fig. 8 provides a schematic.

Input energy carriers are hydrogen, electricity, and gasoline, where the converter configuration can be easily adopted to represent different PHEVs configurations. The PHEV energy hub model in conjunction with the data describing the driving behavior of individuals is used to compute the state of charge of the internal battery during the day. In a subsequent step, the additional electricity demand of the PHEV fleet can be determined, i.e., a load profile for a time horizon of 24 h using a time resolution of 15 min. When it comes to transmission or distribution system management one objective is to minimize stress on the individual components. As a significant penetration with PHEVs may

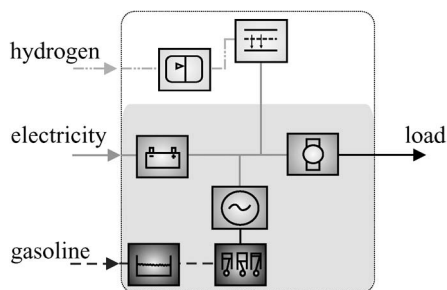


Fig. 8. A PHEV modeled as energy hub comprising a battery, a tank, an internal combustion engine, a fuel cell, a generator, and a motor [32].

induce a substantial rise in electricity demand, a so-called PHEV manager was developed. The PHEV manager coordinates the charging of the individual cars connected to the distribution grid at certain nodes (hubs). The PHEV manager receives a price forecast for every 15 min and then coordinates the charging requests of the individual cars based on the “willingness to charge” taking into account possible network constraints. In that, the charging of the cars is based on price signals, where it is possible to do peak shaving or valley filling as in low-load hours the price is typically lower than in high-load hours. Fig. 9 depicts a sample distribution grid with four nodes (energy hubs) and four PHEV managers coordinating charging demand at the hubs. The PHEV managers communicate with the network operator which “sees” the network as a whole.

The energy hub model of the PHEV is described in [32]. The PHEV manager is described in [34], where in [33] results on the application of the PHEV manager in distribution grids are reported.

G. Investment Decisions in Urban Networks

The previous section mainly described research with a focus on the conceptual side, i.e., the development of a theoretical framework to model energy systems comprising multiple-energy carriers. However, soon after the first results had been achieved, there was rising interest to apply the theoretical concepts to realistic case studies. In that, complementary work has been carried out specifically focussing on the transfer of the energy hub approach to urban networks. Two case studies in partnership with municipalities were defined: one is the city of Baden (AG), and the other is the Swiss capital Bern. Although, the urban energy networks in both cities are today only “loosely” coupled, the analysis shows the different dependencies and mutual influences providing an integrated view on future investment options. One relevant question for the city of Baden is whether to invest into a district heating system or to deploy heat pumps to match the heat demand of newly planned residential areas. In the city of Bern a new combined waste and wood incineration plant will be build, delivering heat and electricity. The energy hub approach is an adequate and flexible tool to assess the opportunities associated with the investments, to derive efficient operational strategies or to suggest further measures in order reduce energy consumption and emissions.

IV. DISCUSSION OF THE ENERGY HUB MODELING APPROACH

A. Related Modeling Concepts

A detailed comparison of modeling concepts similar to the energy hub approach would by far exceed the scope of this paper. This section intends to collect some basic references in terms of related works. The combined modeling and analysis of multiple-carrier energy systems

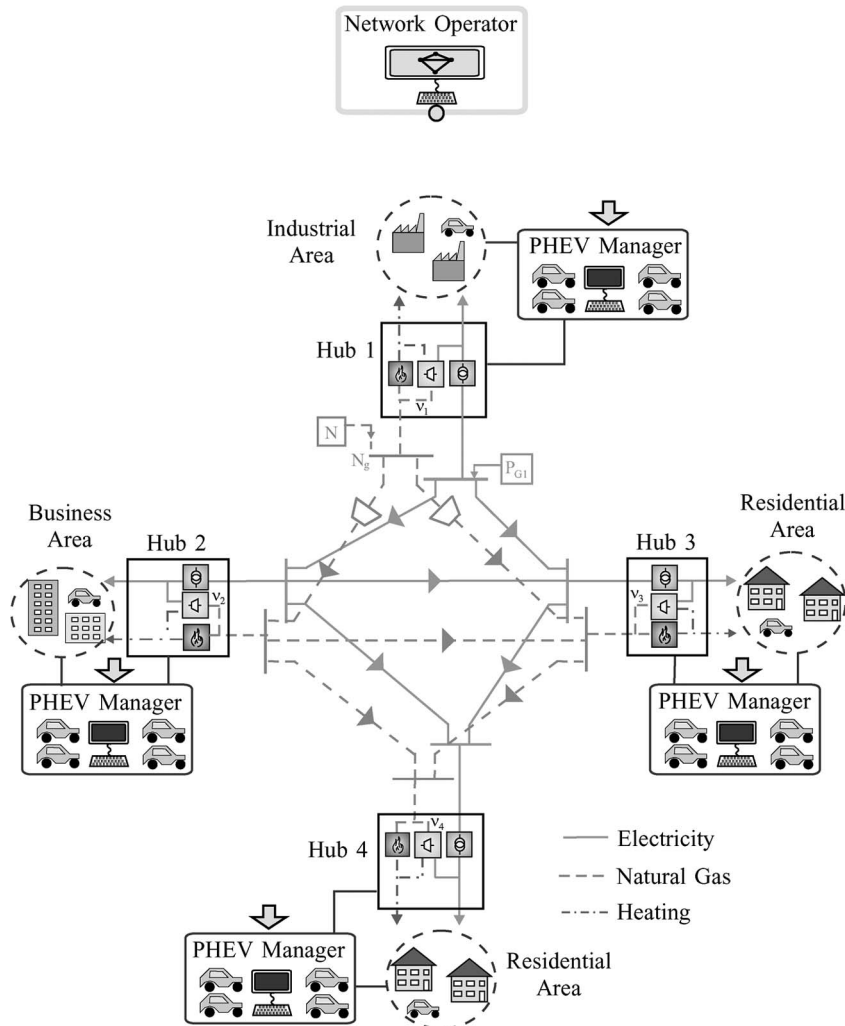


Fig. 9. Network of energy hubs with PHEVs and PHEV managers [33].

was, for instance, addressed in [35]–[43]. Models with special emphasis on system interactions and integrated planning of multiple-carrier energy systems have been presented in [44]–[46]. A Japanese initiative related to the here proposed framework is a project called Flexible, Reliable and Intelligent Energy Delivery System (FRIENDS). The general ideas are presented in [47] and [48].

The energy hub concept as presented in this paper was applied and further developed in [49]–[52].

An extensive overview on distributed multiple generation in general is presented in [53], where also a comparison is made between virtual power plants, microgrids, and the energy hub approach. In short, virtual power plants focus on the market integration of a larger number of distributed generation resources. The energy hub could be used to model the individual DG facilities. This would especially prove useful for cogeneration or trigeneration plants (e.g., CHP devices). In that, it would be possible to optimize the virtual power plant operation

for multiple-energy carriers. The same reasoning applies to the microgrids, where energy hubs could prove useful if multiple-energy carriers as input sources or loads are present in the grid. However, until now, the energy hub concept is an approach that mostly serves modeling, analysis, and planning purposes rather than matching the needs of system operators for real-time operation. Nonetheless, the mathematical formulation of the energy hub relying on an input/output relationship coupled by a conversion matrix can be adopted to diverse applications. The next section details the advantages.

B. Valuation of the Energy Hub Modeling Approach

The energy hub modeling concept provides the following advantages:

- **Generality.** The previous sections have shown different extensions and applications for the energy hub approach. Examples ranged from the description of network nodes comprising technologies

such as transformers, microturbines, heat exchangers, furnaces, absorption chillers, etc., to plug-in hybrid vehicles and to a portfolio of possible generation investment options. This variety of application examples demonstrates the generality of the energy hub concept.

- **Scalability.** Related to the generality of the approach is its scalability. Energy hubs may describe rather small entities, such as PHEVs. On the other hand, it is possible to describe building complexes (hospitals, shopping malls, etc.) or even subparts of distribution systems, e.g., certain city districts as shown in Section III-G.
- **Modularity.** Usually, the different modeling tools are independent of each other. Although they share the underlying energy hub concept, the different extensions regarding, e.g., OPF, reliability, PHEVs can be used as “standalone applications.” This modularity allows for the combination and transfer of the underlying theory to related research fields such as economics or transportation sciences (see, for instance, Sections III-E and F.)
- **Combining Bottom-Up and Top-Down Modeling Techniques.** When assessing complex, interactive systems like energy networks or markets, different modeling concepts can be applied to describe the system behavior and its properties. Following a simple classification, modeling approaches might be distinguished into bottom-up or top-down concepts. The latter try to formulate analytical models, i.e., an aggregated set of equations describing the relevant phenomena. The multiple-energy carrier OPF may be seen as an example for a top-down modeling approach. On the contrary, bottom-up approaches model the different microentities of the system within a framework of rules, where the different entities can interact with each other. A well-known bottom-up modeling approach are multiple-agent systems [54] as described in Section III-C. In that, the energy hub modeling framework may be used for bottom-up as well as for top-down analysis.

Disadvantages of the energy hub approach origin from the complexity introduced by coupling the different grid-bound and nongrid-bound energy carriers. Even rather small applications (see, e.g., Fig. 2) incorporate a significant number of variables to describe the system sufficiently. Additionally, the optimization problems related to the optimal dispatch and OPF problems are very likely to be nonconvex [11]. The complexity makes it necessary to introduce a certain level of abstraction when it comes to the representation of the different technologies. Hence, there is a risk that the model departs too far away from reality. Another issue of concern with regard to complexity issues are computing times. Especially, the case studies briefly summarized in Section III-G are demanding

in terms of computational power. Simulations are likely to run from several hours to several days.

C. Outlook on Prospective Applications

1) *Topology Optimization:* Currently, there is an ongoing energy policy debate on future generation investment options. Countries like Germany and Switzerland have presented options for prospective generation expansion plans including scenarios relying on “traditional” structures with large thermal or hydro units and, on the other hand, scenarios deploying distributed generation and storage stressing the increasing role of distribution grids. Due to its generality the proposed energy hub modeling approach seems adequate to assess the different generation and network expansion options. The research relies on a multiple-criteria, multiple-level optimization in order to evaluate different investment alternatives considering ecological, economic, and technical indicators. The idea is to evaluate the optimal sizing and placement of components clarifying the question on which network levels generation or storage technologies should be installed. Generally speaking, the research aims at establishing a quantitative framework capable of evaluating “centralized” topology approaches compared with “decentralized” ones. Preliminary results have been reported in [55].

2) *Energy Hubs and National Economies:* As outlined in the preceding paragraph, current policy debates in Europe promote diverse measure in order to cope with the risks of climate change and fossil resource depletion in a sustainable manner. Countries may follow a complex set of policy options, e.g., rely on incentive schemes for the advancement of electricity generation from renewable energy sources, promote energy efficiency, invest into the reinforcement of national and cross-border transmission capacities, promote large-scale wind farms, etc. Despite the coordinating role of the European Union, each country may follow its own set of objectives and measures. In this respect, the energy hub approach offers the possibility to build an interconnected system of hubs representing national economies. Each hub/economy has three loads being an electricity load, a heat load (for private and industry use), and a mobility load. The conversion technologies residing inside the hub describe the national generation portfolios to cover electricity and heat demand; additionally, an aggregated representation of major transportation technologies is present. On the input side, the different primary energy carriers are modeled, such as coal, gas, lignite, etc. The individual hubs/economies are connected with each other by an electricity and gas grid making it possible to study cross-border flows, respectively, energy exports and imports in general. Such a model is to some extent similar to the “classic” input/output models known from economic theory [56]. However, the

energy-hub-based approach offers the functionality to link technological and economic system properties. It is possible to study the influence of, e.g., different national generation mixes, a possible increase in cross-border transmission capacities, the deployment of technologies such as high-voltage-direct-current (HVDC) transmission, the influence of national energy efficiency programs, etc., on a Pan-European level. Such a modeling framework provides the degree of detail of a bottom-up approach allowing evaluations on a macroperspective. A similar approach has been developed with focus on the United States in [57].

V. CONCLUSION

This paper presented a framework for the comprehensive modeling of energy systems deploying multiple-energy carriers, such as electricity, heat, cooling, gas, etc. The modeling framework is based on the so-called energy hub approach. Section II described the underlying assumptions as well as the mathematical modeling details. Due to the generic formulation of the energy hub approach, it is possible to apply and/or extend the concept to a broad spectrum of topics related to questions of production, delivery, and consumption in multiple-carrier energy systems. Section III presented specific modeling applications related to multiple-energy carrier OPF, risk management and investment strategies, agent-based control of

energy hubs, reliability and markets assessments as well as a framework for the modeling of PHEVs. The paper was concluded with a section presenting the key benefits of the energy hub modeling framework, including the possibility to either follow top-down or bottom-up modeling approaches.

Considering the stronger integration of different energy carriers driven by the use of cogeneration and trigeneration technologies, the energy hub approach together with its specific extensions provides a comprehensive modeling basis. Major benefits of the framework derive from its generality, scalability, and modularity. It is expected that the energy hub approach can be adopted also to upcoming challenges in order to contribute to the various modeling and analysis tasks related to future energy systems. ■

Acknowledgment

The material presented in this paper is to a large extent based on the research works by P. Favre-Perrod, M. Geidl, B. Klöckl, and G. Koeppel as well as F. Adamek, P. Ahcin, M. Arnold, M. Galus, F. Kienzle, and M. Schulze. The individual contributions are referenced in the paper. Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, would also like to thank all previous and current members of the “Vision of Future Energy Networks” research team.

REFERENCES

- [1] M. Vignolo and R. Zeballos, “Transmission networks or distributed generation?” in *Proc. 1st Int. Symp. Distrib. Generat., Power Syst. Market Aspects*, T. Ackermann and V. Knyazkin, Eds., Stockholm, 2001.
- [2] D. Hinrichs, “Cogeneration,” in *Encyclopedia of Energy*. New York: Elsevier, 2004, p. 581.
- [3] J. Hernandez-Santoyo and A. Sanchez-Cifuentes, “Trigeneration: An alternative for energy savings,” *Appl. Energy*, vol. 76, no. 1–3, pp. 219–227, 2003.
- [4] W. Kempton and J. Tomic, “Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy,” *J. Power Sources*, vol. 144, no. 1, pp. 280–294, 2005.
- [5] J. Tomic and W. Kempton, “Using fleets of electric-drive vehicles for grid support,” *J. Power Sources*, vol. 168, no. 2, pp. 459–469, 2007.
- [6] *Vision of Future Energy Networks—Project Website*. [Online]. Available: <http://www.future-energy.ethz.ch>
- [7] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klöckl, G. Andersson, and K. Fröhlich, “Energy hubs for the future,” *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 24–30, 2007.
- [8] J. C. Willens, “The behavioral approach to open and interconnected systems,” *IEEE Control Syst. Mag.*, vol. 27, no. 6, pp. 46–99, Dec. 2007.
- [9] M. D. Ilić, L. Xie, U. A. Khan, and J. M. F. Moura, “Modeling, sensing and control of future cyber-physical energy systems,” *IEEE Trans. Syst. Man Cybern. Special Issue on Engineering Cyber-Physical Ecosystems*, 2010.
- [10] P. Favre-Perrod, “A vision of future energy networks,” in *Proc. Power Eng. Soc. Inaugural IEEE Conf. Expo. Africa*, Durban, South Africa, 2005, pp. 13–17.
- [11] M. Geidl and G. Andersson, “Optimal power flow of multiple energy carriers,” *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 145–155, Feb. 2007.
- [12] F. Kienzle, P. Favre-Perrod, M. Arnold, and G. Andersson, “Multi-energy delivery infrastructures for the future,” in *Proc. Int. Conf. Infrastructure Syst. Services*, Rotterdam, The Netherlands, 2008, DOI: 10.1109/INFRA.2008.5439681.
- [13] M. Geidl and G. Andersson, “Optimal coupling of energy infrastructures,” in *Proc. PowerTech Conf.*, Lausanne, Switzerland, 2007, pp. 1398–1403.
- [14] M. Geidl, “Integrated modeling and optimization of multi-carrier energy systems,” Ph.D. dissertation, Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2007, ETH No. 17141.
- [15] P. Favre-Perrod, “Hybrid energy transmission for multi-energy networks,” Ph.D. dissertation, Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2008, ETH No. 17905.
- [16] G. Koeppel and M. Korpås, “Improving the network infeed accuracy of non-dispatchable generators with energy storage devices,” *Electric Power Syst. Res.*, vol. 78, pp. 2024–2036, 2008.
- [17] M. Geidl and G. Andersson, “A modeling and optimization approach for multiple energy carrier power flow,” in *Proc. IEEE PES PowerTech*, St. Petersburg, Russia, 2005, DOI: 10.1109/PTC.2005.4524640.
- [18] M. Arnold, R. R. Negenborn, G. Andersson, and B. De Schutter, “Model-based predictive control applied to multi-carrier energy systems,” in *Proc. 16th Power Syst. Comput. Conf.*, Glasgow, Scotland, 2008, DOI: 10.1109/PES.2009.5275230.
- [19] M. Arnold, R. R. Negenborn, G. Andersson, and B. De Schutter, “Model-based predictive control applied to multi-carrier energy systems,” in *Proc. IEEE Power Energy Soc. General Meeting*, Calgary, AB, Canada, 2009, DOI: 10.1109/PES.2009.5275230.
- [20] M. Arnold, R. Negenborn, G. Andersson, and B. De Schutter, “Distributed control applied to combined electricity and natural gas infrastructures,” in *Proc. Int. Conf. Infrastructure Syst. Services*, Rotterdam, The Netherlands, 2008, DOI: 10.1109/INFRA.2008.5439653.
- [21] G. Koeppel and G. Andersson, “Reliability modeling of multi-carrier energy systems,” *Energy*, vol. 34, no. 3, pp. 235–244, 2009.
- [22] G. Koeppel and G. Andersson, “The influence of combined power, gas, and thermal networks on the reliability of supply,” in *Proc. 6th Int. World Energy Syst. Conf.*, Torino, Italy, 2006.
- [23] G. Koeppel, “Reliability considerations of future energy systems: Multi-carrier systems and the effect of energy storage,”

- Ph.D. dissertation, Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2007, ETH No. 17058.
- [24] H. M. Markowitz, "Portfolio selection," *J. Finance*, vol. 7, no. 1, pp. 77–91, 1952.
- [25] F. Kienzle and G. Andersson, "A greenfield approach to the future supply of multiple energy carriers," in *Proc. IEEE Power Energy Soc. General Meeting*, Calgary, AB, Canada, 2009, DOI: 10.1109/PES.2009.5275692.
- [26] F. Kienzle and G. Andersson, "Efficient multi-energy generation portfolios for the future," in *Proc. 4th Annu. Carnegie Mellon Conf. Electr. Ind.*, Pittsburgh, PA, 2008.
- [27] F. Kienzle and G. Andersson, "Comprehensive performance and uncertainty analysis of multi-energy portfolio," in *Proc. PowerTech*, Bucharest, Romania, 2009, DOI: 10.1109/PTC.2009.5281853.
- [28] B. D. Williams and K. S. Kurani, "Commercializing light-duty plug-in/plug-out hydrogen-fuel-cell vehicles: "mobile electricity" technologies and opportunities," *J. Power Sources*, vol. 166, no. 2, pp. 549–566, 2007.
- [29] W. Kempton, A. Dhanju, and S. E. Letendre, "Electric vehicles as a new power source for electric utilities," *Transp. Res. D, Transp. Environment*, vol. 2, no. 3, pp. 157–175, 1997.
- [30] R. Sioshansi and P. Denholm, "The value of plug-in hybrid electric vehicles as grid resources," *Energy J.*, vol. 31, no. 3, pp. 1–22, 2010.
- [31] M. Galus, R. Waraich, M. Balmer, G. Andersson, and K. W. Axhausen, "A framework for investigating the impact of PHEVs," in *Proc. Int. Adv. Mobility Forum*, Geneva, Switzerland, 2009.
- [32] M. Galus and G. Andersson, "Power system considerations of plug-in hybrid electric vehicles based on a multi energy carrier model," in *Proc. IEEE Power Energy Soc. General Meeting*, Calgary, AB, Canada, 2009, DOI: 10.1109/PES.2009.5275574.
- [33] M. Galus and G. Andersson, "Integration of plug-in hybrid electric vehicles into energy networks," presented at the PowerTech Conf., Bucharest, Romania, 2009.
- [34] M. Galus and G. Andersson, "Demand management of grid connected plug-in hybrid electric vehicles (PHEV)," presented at the IEEE Energy 2030 Conf., Atlanta, GA, 2008.
- [35] H. M. Groscurth, T. Bruckner, and R. Kümmel, "Modeling of energy-services supply systems," *Energy*, vol. 20, no. 9, pp. 941–958, 1995.
- [36] I. Bouwmans and K. Hemmes, "Optimising energy systems—Hydrogen and distributed generation," in *Proc. 2nd Int. Symp. Distrib. Generat., Power Syst. Market Aspects*, Stockholm, Sweden, 2002.
- [37] S. An, Q. Li, and T. W. Gedra, "Natural gas and electricity optimal power flow," in *Proc. IEEE PES Transm. Distrib. Conf.*, Dallas, TX, 2003, vol. 1, pp. 138–143.
- [38] E. M. Gil, A. M. Quelhas, J. D. McCalley, and T. van Voorhis, "Modeling integrated energy transportation networks for analysis of economic efficiency and network interdependencies," in *Proc. North Amer. Power Symp.*, Rolla, MO, 2003.
- [39] O. D. de Mello and T. Ohishi, "An integrated dispatch model of gas supply and thermoelectric systems," in *Proc. 15th Power Syst. Comput. Conf.*, Liège, Belgium, 2005.
- [40] C. Unsuhay, J. Lima, and A. de Souza, "Modeling the integrated natural gas and electricity optimal power flow," in *Proc. Power Eng. Soc. General Meeting*, 2007, DOI: 10.1109/PES.2007.386124.
- [41] M. Chaudry, N. Jenkins, and G. Strbac, "Multi-time period combined gas and electricity network optimization," *Electr. Power Syst. Res.*, vol. 78, no. 7, pp. 1265–1279, 2008.
- [42] C. Liu, M. Shahidehpour, Y. Fu, and Z. Li, "Security-constrained unit commitment with natural gas transmission constraints," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1523–1536, Aug. 2009.
- [43] H. Chen and R. Baldick, "Optimizing short term natural gas supply portfolio for electric utility company," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 232–239, Feb. 2007.
- [44] M. S. Morais and J. W. M. Lima, "Natural gas network pricing and its influence on electricity and gas markets," in *Proc. IEEE PowerTech Conf.*, Bologna, Italy, 2003, vol. 3, DOI: 10.1109/PTC.2003.1304386.
- [45] M. Shahidehpour, Y. Fu, and T. Wiedman, "Impact of natural gas infrastructure on electric power systems," *Proc. IEEE*, vol. 93, no. 5, pp. 1042–1056, May 2005.
- [46] B. Bakken, M. M. Belsnes, and J. Roynstrand, "Energy distribution systems with multiple energy carriers," in *Proc. Symp. Gas Electr. Netw.*, Brasilia, Brasil, 2002.
- [47] K. Nara and J. Hasegawa, "Future flexible power delivery system and its intelligent functions," in *Proc. Intell. Syst. Appl. Power Syst.*, 1996, pp. 261–265.
- [48] K. Nara, "A least cost planning method of friends," in *Proc. IEEE PES Power Syst. Conf. Expo.*, 2004, vol. 3, pp. 1687–1691.
- [49] M. Houwing, P. Heijnen, and I. Bouwmans, "Deciding on micro-chp, a multi-level decision-making approach," in *Proc. IEEE Int. Conf. Netw. Sens. Control*, 2006, pp. 302–307.
- [50] M. Houwing, P. Heijnen, and I. Bouwmans, "Socio-technical complexity in energy infrastructures," in *Proc. IEEE Int. Conf. Syst. Man Cybern.*, 2006, pp. 8–11.
- [51] A. del Real, A. Arcea, and C. Bordonsa, "Optimization strategy for element sizing in hybrid power systems," *J. Power Sources*, vol. 193, no. 1, pp. 314–321, 2009.
- [52] A. Hajimiragha, C. Canizares, M. Fowler, M. Geidl, and G. Andersson, "Optimal energy flow of integrated energy systems with hydrogen economy considerations," in *Proc. IREP Symp., Bulk Power Syst. Dyn. Control VII*, Charleston, SC, Aug. 2007, DOI: 10.1109/IREP.2007.4410517.
- [53] G. Chicco and P. Mancarella, "Distributed multi-generation: A comprehensive view," *Renewable Sustainable Energy Rev.*, vol. 13, pp. 535–551, 2009.
- [54] T. Krause, "Evaluating congestion management schemes in liberalized electricity markets applying agent-based computational economics," Diss., Swiss Fed. Inst. Technol. (ETH), Zürich, Switzerland, 2006, ETH No. 16928.
- [55] F. Adamek, "Optimal multi-energy supply for regions with increasing use of renewable resources," presented at the IEEE Energy 2030 Conf., Atlanta, GA, 2008.
- [56] W. W. Leontief, *Input-Output Economics*, 2nd ed. New York: Oxford Univ. Press, 1986.
- [57] A. Quelhas and J. McCalley, "A multiperiod generalized network flow model of the us integrated energy system," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 829–836, May 2007.

ABOUT THE AUTHORS

Thilo Krause (Member, IEEE) received the Diplom-Wirtschafts-Ingenieur degree in economics and electrical engineering from the Dresden University of Technology, Dresden, Germany, in 2002 and the Ph.D. degree from the Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, in 2006.

During 2007 and 2008, he was with the Swiss Federal Office of Energy managing the national research programs on electricity networks and hydro power. Currently, he is a Senior Research Associate at the Power Systems Laboratory, ETH Zürich.



Göran Andersson (Fellow, IEEE) was born in Malmö, Sweden. He received the M.Sc. and Ph.D. degrees from the University of Lund, Lund, Sweden, in 1975 and 1980, respectively.

In 1980, he joined ASEA, now ABB, HVDC division in Ludvika, Sweden, and in 1986, he was appointed a Full Professor in Electric Power Systems, Royal Institute of Technology (KTH), Stockholm, Sweden. Since 2000, he has been a Full Professor in Electric Power Systems at Swiss Federal Institute of Technology (ETH), Zürich, Switzerland, where he heads the Power Systems Laboratory. His research interests are in power system analysis and control, in particular power system dynamics and issues involving HVDC and other power-electronics-based equipment.

Prof. Andersson is a member of the Royal Swedish Academy of Engineering Sciences and the Royal Swedish Academy of Sciences.



Klaus Fröhlich (Fellow, IEEE) received the M.Eng. and Ph.D. degrees in technical science from the Vienna University of Technology, Vienna, 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 (ETH), Zürich, Switzerland.

Dr. Fröhlich chairs the Cigre Technical Committee.



Alfredo Vaccaro (Senior Member, IEEE) was born in Vico Equense, Italy, on June 5, 1974. He received the M.Sc. degree with honors in electronic engineering from the University of Salerno, Salerno, Italy, in 1998.

From 1999 to 2002, he was an Assistant Researcher at the Department of Electrical and Electronic Engineering, University of Salerno. Since March 2002, he has been a Research Scientist and Aggregate Professor in Electric Power Systems at the Department of Engineering, University of Sannio, Benevento, Italy. His special fields of interest include soft computing and interval-based method applied to power system analysis and advanced control architectures for diagnostic and protection of distribution networks.

Mr. Vaccaro is an Associate Editor/member of the Editorial Board of IET Renewable Power Generation, the *International Journal of Electrical and Power Engineering*, the *International Journal of Reliability and Safety*, and the *International Journal of Soft Computing*.

