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Vision of Future Energy Networks (VoFEN)
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Zusammenfassung

Das Projekt "Vision of Future Energy Networks (VoFEN)" beschäftigt sich mit dem Entwurf, der Modellierung und der Analyse zukünftiger Infrastrukturen zur Energieübertragung und -verteilung. Bearbeitet wurden Fragen hinsichtlich Risikomanagement und Investitionsstrategien für nachhaltige Energiesysteme, dezentraler Regelung in Verteilnetzen, optimalem Netzdesign als auch der Netzintegration von Plug-In Hybriden Fahrzeugen. Ziel war es, ein umfassendes Verständnis möglicher zukünftiger Energienetze zu erarbeiten, wobei der Fokus nicht nur auf der Elektrizität lag. Das Projekt verfolgte einen sogenannten Multi-Energieträgeransatz, d.h. die kombinierte Betrachtung von diversen leitungsgebundenen Energieträgern wie z.B. Elektrizität, Gas, Fernwärme, Kälte etc. Zentral für das Projekt waren dabei auch die zwei Fallstudien zur praktischen Verifizierung der theoretischen Ansätze in Anwendung auf die Energienetze in Baden-Dättwil und Bern. Das Projekt VoFEN stellte eine wichtige Basis für thematisch verwandte Forschung am Power Systems Laboratory dar, wie z.B. das von der Europäischen Union finanzierte Projekt "Infrastructure Roadmap for Energy Networks in Europe (IRENE-40)".

Abstract

The energy supply chain from production over transmission and distribution to final consumption generally involves several energy carriers. The project “Vision of Future Energy Networks”' (VoFEN) at ETH Zurich aimed at systematically analyzing multi-carrier energy systems in order to design optimal structures for future sustainable energy systems. Models for the representation of power flow, conversion and storage of multiple energy carriers have been developed within the project. Among them the Energy Hub model was the key concept, which has been used in several other contexts, comprising risk management and investment analysis for multi-energy carrier systems, agent-based control schemes for decentralized generation, a framework to assess the influence of Plug-In Hybrid Electric Vehicles on power systems as well as two exemplary case studies involving Swiss municipalities (Bern and Baden-Dättwil).

1. Introduction

Problem Description

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. 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 co- or tri-generation. Using e.g. CHPs or microturbines it is possible to produce electricity and heat out of natural or bio gas, 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. 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.

Proposed Course of Research

The VoFEN 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.

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 multi-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 subsystems. 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.

In previous years the so-called “energy hub” was developed and identified as major modeling and analysis tool. An energy hub is an integrated system of units that allows the conversion, conditioning and storage of multiple energy carriers. It represents an interface between different energy infrastructures and/or loads. Energy hubs consume power at their input ports connected to e.g. electricity and natural gas infrastructures, and provide certain required energy services such as electricity, heating, cooling, compressed air, etc. at the output ports. Within the hub, energy is converted and conditioned using e.g. combined heat and power technology, transformers, power-electronic devices, compressors, heat exchangers, and other equipment. Existing facilities that can be considered as energy hubs are for example industrial plants (steel works, paper mills), big buildings (airports, hospitals, shopping malls), rural and urban districts, and island energy systems (trains, ships, aircrafts).

The energy hub is the major modeling concept of the VoFEN project, i.e. the underlying theory serves as basis for the currently running working packages described in the respective sections.

2. Objective of the Research Project

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 are 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 uni-directional, "descending down" from higher to lower voltage levels. Due to the increasing penetration of distributed generation the flow may become "bi-directional". 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 networks nodes changes 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. The developed theory to define and describe energy hubs is presented in the next paragraph.

Using the energy hub approach, and thus, relying on a multi-energy carrier perspective the following objectives of the VoFEN project were identified:

- Contributions to identifying future network topologies facilitating the grid integration of small, renewable generation facilities.
- The development of innovative control strategies for decentralized generation units (e.g. in distribution grids) as well as analyzing the prospective economic benefits of certain generation portfolios by means of risk and portfolio management tools.
- Verification of the theoretical concepts by means of case studies in close cooperation with Swiss municipalities (Baden-Dättwil and Bern)

3. Results

The following section summarizes the six work packages of VoFEN. As five of these work packages have already been concluded with a PhD thesis, the sections give a brief introduction to the research work. Details can be found in the theses and the referenced publications, all available from the institute's webpage: www.eeh.ee.ethz.ch (Publications section.)

I) RISK ASSESSMENT AND INVESTMENT STRATEGIES FOR MULTI-CARRIER ENERGY SYSTEMS (Florian Kienzle)

When evaluating investments in energy supply and generation infrastructure nowadays, one is confronted with multiple sources of uncertainty. Examples for such uncertainties are the liberalization of power markets, regulatory uncertainties regarding carbon dioxide pricing mechanisms or the level of feed-in tariffs for renewable energies, and the volatility of fuel prices. The objective of this thesis is to provide methods that allow for an adequate consideration of uncertainties in the investment evaluation while taking into account the potential benefits from investments involving multiple energy carriers.

The consideration of multiple energy carriers is one of the key aspects of the project "Vision of Future Energy Networks" at ETH Zurich. By regarding different energy infrastructures, e.g. electricity, natural gas and district heating networks, as integrated energy system, the project aims at identifying hidden synergies and at revealing beneficial interactions and conversion possibilities between different energy carriers.

In this thesis, methods from financial economics and financial engineering are applied and adopted in order to evaluate investments in multi-carrier energy systems under uncertainty. This is done from two different points of view. First, assuming a societal perspective, the analysis focusses on finding a portfolio of technologies which provides a certain service area with all required energy carriers in an optimal way. For this problem, mean-variance portfolio theory is applied and extended with a scenario-based analysis of multi-energy portfolios. In the second part of the thesis, it is assumed that an individual investor evaluates a particular investment project consisting of assets for the generation and possibly storage of multiple energy carriers. In this case a profit-maximizing perspective is adopted. Applying a Monte Carlo method, the flexibility of the conversion and storage devices is taken into account when determining the value of the investment.

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II) DISTRIBUTED CONTROL FOR COMBINED ELECTRICITY AND NATURAL GAS SYSTEMS (Michèle Arnold)

The increasing penetration of distributed generation (DG) technologies, such as photovoltaics, wind turbines, micro combined heat and power plants, biomass-fired plants and others, leads to new challenges in operation of power systems. Moreover, the intermittency of local renewable energy sources (RES), e.g., wind and solar power, as well as the uncertainties in their predicted available power output, create the need for storage solutions and appropriate control strategies. For these investigations the energy hub modeling framework is used, which takes into account multiple energy carriers, DG generation, energy storage systems and renewable energy sources.

Figure 1 shows an exemplary system setup, where two hubs, containing micro-CHP, furnace, thermal and electrical storage, and PV, are connected to an electricity and natural gas supply grid. The hubs, representing residential areas, decide when to produce electricity locally via micro-CHP, when to feed electricity back to the grid (gained via micro-CHP or from PV installations), or when to import electricity form grid.

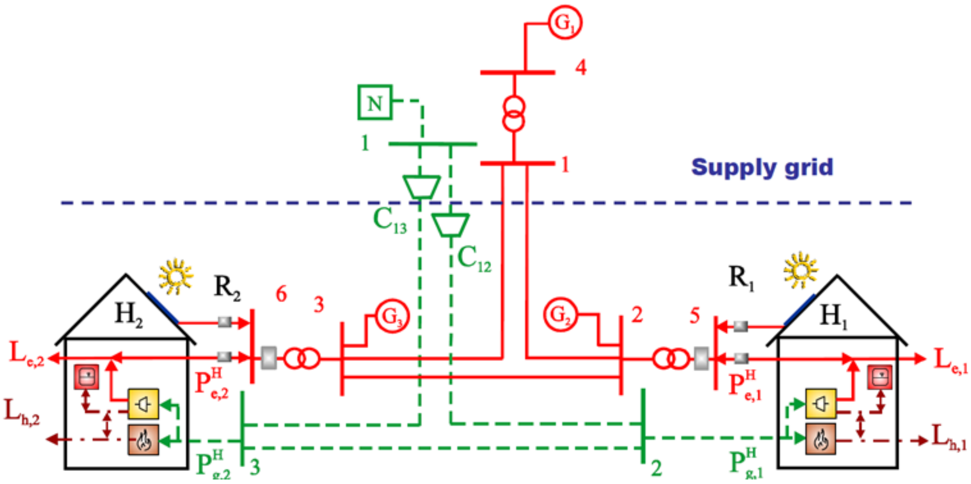

Figure 1: Households (micro-CHP, furnace, heat storage, PV) connected to supply grid.

Since storage dynamics and forecast uncertainties have to be coped with, a multi-time step optimization, which is operated in a receding horizon fashion, is required. Model predictive control (MPC) provides an appropriate control approach for taking into account system dynamics, future price and load profiles, and forecast uncertainties. By operating the system in a receding horizon fashion, the consequences of forecast uncertainties can be kept at acceptable levels. At every time step updated system measurements and forecasts are used to predict the future behavior of the system. Instead of compensating forecast uncertainties with fast acting backup generators or balancing energy, as it is often done in current practice, the imbalances can be compensated with storage devices, placed close to locations where uncertainties arise.

The controller can either be implemented in a centralized or distributed way. A centralized, supervisory controller measures all variables in the network and determines actions for all actuators. Due to practical and computational issues implementing such a centralized controller may not be feasible. Therefore, a distributed MPC scheme, in which the control is spread over the individual hubs is implemented. Each controller solves its own local MPC problem using the local model of its hub. However, this local MPC problem depends on the MPC problems of the other controllers, since the electricity and gas networks interconnect the hubs. Therefore, the MPC optimization problems of the controllers have to be solved in a cooperative way.

This work package has been concluded in the summer of 2011 with a PhD thesis. All relevant publications can be found in the following references section. The PhD thesis was not publicly available while this report was written.

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III) INTEGRATED ANALYSIS OF POWER AND TRANSPORTATION SYSTEMS (Matthias Galus)

In order to analyze the impacts of wide scale electric mobility, this project combines vehicle fleet, vehicle energy demand and large scale transportation simulations. This approach provides detailed data on temporal and spatial vehicular energy demand, used as input for power system simulations. The power system model incorporates a predictive, distributed, hierarchical control scheme in order to avoid local overloads through electric vehicles thereby shifting the excessive electric vehicle demand to low-demand times.

Vehicle-to-Grid (V2G) schemes can be integrated into the charging control scheme and are also investigated. Case studies are performed for the entire electricity distribution system of Zurich, Switzerland, comprising multiple voltage levels and detailed temporal and spatial load data.

Modelling Framework. Three independent models, the Vehicle Technology Assessment Model (VTAM), the Multi Agent Transportation Simulation (MATSim) and the PHEV Management and Power System Simulation (PMPSS) are combined. The models are linked and rely on outputs of each other.

The VTAM comprises two features. Firstly, the evolution of the future vehicle fleet can be simulated and secondly, it constitutes the models of the respective powertrains, which, when fed with real world drive cycles, provide energy consumption data of the vehicles within the fleet. The output data is handed over to MATsim.

MATSim simulates vast numbers of agents utilizing different traveling modes, such as mass transportation and individual vehicles in order to determine and analyze transportation flows with high spatial and temporal resolution. The information on temporal and spatial energy demand as well as vehicle type is handed over to PMPSS. The PMPSS assesses the impact of the energy demand from electric vehicles on the utilized electricity distribution network. It uses a predictive, distributed, hierarchical charging control scheme to avoid asset overload and and voltage stability violations. The scheme determines nodal control price signals which, in a sequential setup are used to shift demand to low-load times. In the iterative setup, the control price signals are provided to MATSim which reschedules charging behavior while giving full consideration to constraints on spatial and temporal daily activities (work, shop, etc.) of the agents. This means that charging can be rescheduled between different activity locations through this iterative scheme.

The integrated approach has been tested on the power system of Zurich comprising ca. 1600 nodes and ca. 1800 lines. A fleet of 250'000 PHEVs has been simulated and managed by PHEV managers in the power system. The managers incorporate a framework that allows to control them for vehicle-to-grid purposes for which they are clustered and controlled as a large aggregated storage, physically distributed over the whole power system.

Future work will include voltage- and line system state constraints in the PHEV-Manager scheme. Application of the scheme to dynamic pricing will be performed. Further, considerations will be given to balancing stochastic, renewable generation with PHEVs using potential vehicle to grid services. The individual transportation demands will as well be integrated in these services. Finally, case studies will be performed for the area of Zurich investigating system limitations due to increasing power demand by electrified mobility.

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IV) HUB TECHNOLOGY (Franziska Adamek)

Renewable energy generation has been increasing for years, and is likely to increase even more in the future. Private households contribute to the renewable boom, e.g. with the installation of roof-mounted photovoltaic plants. Owners are interested in making the most out of their local resources to keep energy costs as low as possible. To reach this aim, a household can apply energy storage and the change of load demand, also called demand response, or cooperate with other houses in the vicinity by sharing renewable generation and coordinating load demand to minimize the collective energy costs.

The aim of the research package was to examine the influence of energy storage and demand response on domestic energy costs in the residential sector. Special focus is put on the influence of both on the energy supply strategy and the resulting energy costs. It is also examined whether additional benefits arise from a combination of demand response and energy storage, and if a cooperation between a group of houses can increase the overall welfare compared to individual energy supply.

The application of demand response and energy storage to make use of price variations and intermittent renewable generation has been widely treated in literature. First research has been carried out with respect to a cooperation of several residential customers. However, the benefits of demand response and energy storage for a private household have not been investigated in detail yet. Also, advantages and limits of combining both possibilities have not been studied. The combined effort of a group of houses has been subject of few studies, but no analysis of potential benefits for the individual actors has been carried out.

The research package considers a single-family house in moderate climate and one in hot climate as well as a group of houses in moderate climate to examine the topics presented above. Heat exchange between the interior and the ambient due to temperature differences and artificial ventilation, and heat gain by solar irradiation cause a temperature change in the house. Space heating or cooling have to compensate this change to keep the inner temperature at a comfortable level. The required heating or cooling power and energy as well as warm water and electricity have to be provided by a number of conversion and storage technologies. The devices are aggregated in a multienergy hub and coordinated such that they best exploit the available renewable resources and variable energy prices to minimize the household's energy costs. An energy hub is a device that models the processing (conversion and storage) of various energy carriers, both conventional and renewable, to determine the optimal power supply for a given load demand. The energy hub is extended with demand response to be suitable for the study at hand. A sensitivity analysis is carried out to determine the impacts of the system parameters. The storage parameters cycle efficiency and storage capacity, the demand response parameters maximum shiftable power and maximum shiftable energy, and the amount of local renewable electricity generation are varied. Also, the cases without/with energy storage and without/with demand response are examined to assess their respective impacts and the benefits of a combination of both. As frame conditions, seven price constellations for gas and electricity price are evaluated.

For a group of six houses, a multiple-level approach is proposed to model the interdependencies and the cooperation of the actors. The two cases of coexistence and coop-eration are compared for the group of houses. In the first case, each actor defines its own energy supply strategy, in the latter case the houses share excess electricity and information about demand response and energy storage use to increase common benefits.

The results show that in moderate climate electric demand response is without large influence on energy costs. Also, an electrical domestic hot water tank allows larger cost savings than an electric storage device. In hot climate, it is the other way round. Electric demand response is well suited to decrease costs, as well as an electric storage device. In both climate zones, the combination of demand response and energy storage is only beneficial if sufficient renewable excess electricity is available and load demand is high enough. A cooperation of a number of households is only beneficial and expedient if the renewable generation sites are concentrated in few places. As a consequence of the obtained results, single-family houses in moderate climate are recommended to use excess electricity for thermal load demand, while houses in hot climate should invest in small electric storage devices. In a group of houses, energy storage is best installed such that it supplies a number of houses, while renewable resources should be exploited individually.

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V) CASE STUDY ENERGY HUB BADEN (Matthias Schulze)

The case study has started in September 2007 and was concluded in August 2010. Dättwil, a district in the city of Baden (Switzerland), was chosen as the study object. The district contains about 3,500 inhabitants with industrial, commercial and residential area. A decomposition of the area into dependant energy hubs and the network topology used in the calculations, where nodes and corresponding hubs represent the essence of the present grid, can be seen in Figure 2. The hubs are interconnected with a grid for natural gas, district heating and of course electricity. The heating plant of a large hospital there is the supplier for the district heating network. There are four boilers fired with either natural gas or fuel oil to produce heat and steam. This facility will be substituted within the next few years by a biomass power plant. The new plant uses wood gas from the gasification of woodchips and could produce electricity and heat via a CHP, heat via a boiler and synthetic natural gas and heat via a purification process. For each individual hub measurements for the electricity consumption were taken. The measurements took place at the transformers, about three of them supply one hub's area. From weekly data and the annual curve of the near substation synthetic load curves for seven hubs are available, showing the typical behavior of e.g. industrial sites. Heat load is either feed from the district heating network, from natural gas or from fuel oil. The data of the network is already available. For the measurements of chemical feed heating probes are going to be used counting the flow rate. Because measurements can only show today's consumption scenarios are needed to provide an outlook into the Dättwil of 2060. Additionally future energy produced by distributed generation, from solar-thermal, photovoltaic or wind energy, was estimated. Both, the present data and the scenarios for future changes will allow an overall simulation of the energy infrastructure in Dättwil.

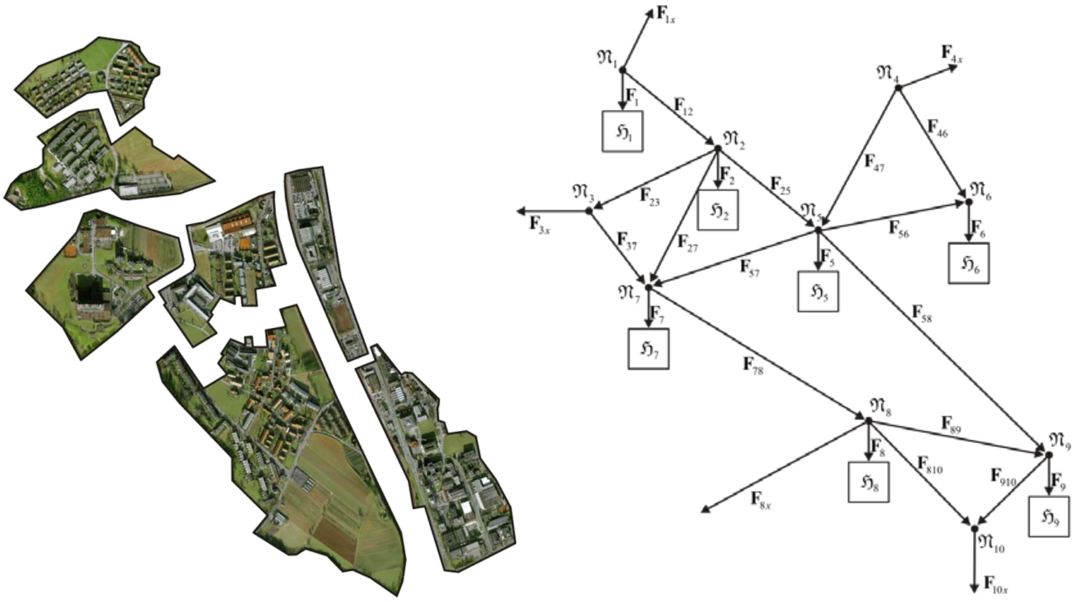

Figure 2: Decomposition of the investigation area into Hubs and configuration of Hubs and Nodes

In the last phase of this work package the previously gathered data has been used to produce an entire model of Dättwil. The study of more accumulative or synergetic effects was the goal. The technological settings, as they appear within the model's coupling matrix, were selected in cooperation with the project partners from the Regionalwerke AG Baden (the local utility) and the Energiekommission der Stadt Baden (the advisory board for energy in Baden). In order to open the prices as weight factors, multiple optimization were run, with alternating prices for the energy carrier. This procedure yields in higher computational effort, so some work has been carried out to speed-up the hard- and software. Finally, a Matlab-independent program has been created, which is able to run without limits to processor cores on local workstations, servers or even clusters. The optimization is now, depending on the hardware, more than 103 times faster. For the project partners, it's now possible to bring in their knowledge about future markets and price developments.

Two different procedures are applied in order to simulate Dättwil's infrastructure: quarter-hourly values for analyzing time-based phenomena, e.g. the influence of photovoltaic's and intraday storage; annual energy consumption for sensitivity studies on costs and feasibility studies for alternative energy carriers. In Figure 8 an example network for the integration of multiple storages in a network of three hubs is shown. Here is the quarter-hourly dataset useful to evaluate the relevance of storage size and position, and of course to study the advantages depending on the kind of storage used.

The influence of mobility in Dättwil was another emphasized point. Since this topic is implemented with far less details as in the work package "Integrated Analysis of Power and Transportation Systems", the addressed questions are more energy-related than questions of grid stability or control. Therefore, qualitative assumptions were taken, where charging load profiles for uncontrolled public and home charging exist. Applied on the Dättwil-model only the number of inhabitants, the car usage per-capita and the amount of public parking slot has to be determined. Assuming a 100% penetration with electric vehicles, as the worst or far future case, answers about additional load within the hub's areas and the medium voltage grid (22 kV) can be given. It has been show that home charging is possible without limits due to the already high capacity of the PCC from houses to the MV-grid. The opposite behavior results for public charging, where actions must be taken. Otherwise, at begin of a shift the electric load would more than double. It is advised again that stability questions are not addressed with this kind of investigation.

Four alternative energy sources and (partial) carrier were study within the case study. As an energy carrier, hydrogen, synthetic natural gas and ethanol were proved, whereas as sources we considered mainly biomass, and for the case of hydrogen, solar radiation. For the feasibility the energy conversion efficiency (from the source to the carrier) as well as the necessary land for the production are taken into account during the calculations. Consequences on the scarce good land displayed doubts in terms of sustainability issues. However, the physical and chemical integration has been demonstrated, and due to changing general conditions it might become reality in future.

On the theoretical side the energy hub model, in the version used for Dättwil, was extended to network related aspects. A nodal matrix for the energy exchange in between nodes and the surrounding environment (or higher grid level) has been developed. Grid-based prices were considered as well, enabling the integration of fees for grid usage and cross-border capacities into the model.

All in all the envisaged results were achieved, especially from the understanding of Dättwil's energy infrastructure, energy conversion and future trends point of view.

The work package was concluded with a PhD thesis. However, it was not publicly available while this report was written.

VI) CASE STUDY BERN (Peter Ahcin)

Main objectives of the project:

- Identify configurations of the energy distribution system that generate acceptable levels of greenhouse gas emissions.
- Develop a roadmap to a desired energy distribution system configuration.

After the theoretical part of the Vision of Future Energy Networks had been outlined, two case studies were started. The aim of this project was to identify possible very low greenhouse gas emitting energy distribution system solutions for the year 2060 and provide a roadmap from today's system to the desired future system.

In the first phase an energy distribution system model was developed, that allowed the simulation of different electricity and heat supply strategies, more specifically, different heat and electricity generating technologies, energy storage and demand side management. On the energy generation side, focus was put on improving the representation of technologies with variable efficiencies and thermal losses in the district heating networks. On the consumption side building renovation, heat load management as well as management of some household electric appliances were added as new features to the original Energy Hub model.

In the second part of 2010 the project entered the second phase where a procedure to develop a roadmap to the desired future system is being developed. The procedure treats different energy distribution systems as portfolios of different levels of costs, risk, greenhouse gas emissions and self-sufficiency. An example of two measures that featured as investment options in the investment portfolio. With the help of dynamic programming an optimal long term investment policy based on allowed portfolios and different fuel price paths is then generated.

The work package was concluded with a PhD thesis. However, it was not publicly available while this report was written.

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4. Discussion

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 sub-parts of distribution systems, e.g. certain city districts.

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. optimal power flow, reliability, plug-in hybrid electric vehicles can be used as “stand-alone applications”. This modularity allows for the combination and transfer of the underlying theory to related research fields such as economics or transportation sciences.

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-enery carrier optimal power flow may be seen as an example for a top-down modeling approach. On the contrary, bottom-up approaches model the different micro-entities 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 multi-agent systems. 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 non-grid-bound energy carriers. Even rather small applications incorporate a significant number of variables to describe the system sufficiently. Additionally, the optimization problems related to the optimal dispatch and optimal power flow problems are very likely to be non-convex. 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 are demanding in terms of computational power. Simulations are likely to run from several hours to several days.

5. Conclusion

Within the project a framework for the comprehensive modeling of energy systems deploying multiple energy carriers, such as electricity, heat, cooling, gas etc was developed. The modeling framework is based on the so-called energy hub approach. Due to the generic formulation of the energy hub approach, it is possible to apply and/or extent the concept to a broad spectrum of topics related to questions of production, delivery and consumption in multi-carrier energy systems. Several applications were presented related to risk management and investment strategies, agent-based control of energy hubs, reliability and markets assessments as well as a framework for the modeling of Plug-In Hybrid Electric Vehicles.

Considering the stronger integration of different energy carriers driven by the use of co- 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.