An Investigation Process for Hybrid Energy Grid Optimization

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Abstract: A hybrid energy network is an energy system operated across different domains of energy grids, where energy can be transformed between energy carriers. It is regarded as one good solution for managing volatile renewable energy sources in a better way. The paper introduces an investigation process that is designed to develop and evaluate co-operative hybrid energy network control strategies. The proposed investigation process consists of two-step holistic investigation with simulation-based and economic-model based analysis. The process is designed to enable multi-aspect investigation on the range of flexibility provided by evolution of hybrid energy grids.

1 INTRODUCTION

The electricity grid model is evolving from a hierarchic centralized architecture towards a decentralized one. One of the main challenges in this course is the lack of flexibility to integrate high penetrations of volatile renewable energy sources in the existing power grids. The challenge is about how a temporary energy surplus can be managed. It can be either saved for the grid at low-generation times (e.g. storage), or utilized more efficiently in a time- and location-effective manner (e.g. local consumption, local transformation). Hybrid energy networks can be regarded as one of the opportunities to provide solutions for managing this imbalance (Appelrath et al., 2012) (Lehnhoff et al., 2013). A hybrid energy network is an energy system operated across different domains (such as gas, district heating, and electricity) whereby energy can be transformed between energy carriers: the energy can be consumed, stored, transported within a grid in its specific form or transformed into other forms of energy between different grids for different times and locations. The advantages of this are including the increase in reliability, flexibility and the synergy effect (Arnold, 2011).

The development of smart grids on each independent energy grid has progressed with extensive research for many years. One prominent next step for the energy network evolution path will be the connection and integration of different energy grids, and realizing hybrid energy networks efficiently operated through coupling points (e.g. Combined Heat and Power (CHP) and power to gas plants) and cooperative managements. The energy operators can take advantage of the characteristics of each energy carrier and exploit, for example, the possibility of transmitting energy as electricity and storing energy as gas or as warm water in accumulators.

Investigation of this hybrid evolution path is still in its infancy. There has been some investigation of individual components (Keirstead et al., 2012) (Derksen et al., 2012), or possible control strategies (Arnold et al., 2009), but they generally lack the full investigation on the impact of hybridization in real-world environment. A thorough investigation, which includes major stakeholders that are modeled from a real-world city, will open more convincing and exciting new possibilities for the energy network evolution.

The paper introduces an investigation process that is designed to develop and evaluate co-operative, coexisting hybrid grid control strategies. The process starts with a set of hybridization setups observed from two European cities. The setups represent hybridization chances that are identified from the target sites. A concrete hybridization scenario can be identified from the setups, by adding specific technological and economic goals of the stakeholders. Each identified scenario is then implemented and investigated via two-step investigation process based on co-simulation and

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economic model. The simulation investigation focuses on technological and operational impacts, while the economic model examines social and economic aspects in the long-term. The proposed process enables researchers to investigate hybrid networks in detail, with which one can provide concrete recommendations for stakeholders in both technological (operational) and economic (strategic) aspects.

2 STATE OF THE ART

With the unbundling of the energy supply chain, technological advancements of renewables, support mechanisms to promote their installation, increasing environmental awareness and more active participation of customers, the amount of distributed (small-scale) generation plants and de-centralized feed-in of electricity has considerably increased in recent years. Thus, energy distribution system operators (DSO) have to cope with bidirectional load flows in their networks and both, DSOs and energy supply companies, have to deal with decreasing turnover. Furthermore, fluctuating energy production from renewable energy sources (RES) - from large-scale to household level - is de-coupled from energy demand, which is causing a lack of storage in the electricity network (Trebolle et al., 2010).

In general, this issue can be partially tackled by shedding renewables during hours of high production, increasing transmission capacity of the electricity network, installing additional capacities of energy storages and/or increasing the flexibility of demand. However, the challenge will probably not be solved by one of these options alone and the storage and flexibility potentials on the electricity domain are limited.

Considering other energy domains and networks (gas, district heating) as well can significantly increase the storage capacity and demand flexibility potentials. Conversely, these domains can benefit from a closer interaction with the electricity domain too. Converting electric energy when production from renewables is high and electricity demand is low, e.g., can reduce the usage of fossil fuels for heat production. Though these synergies are becoming increasingly apparent, the full potential of cooperation among different energy domains is not yet fully exploited. There are several reasons for this: For one thing, different energy domains are, in fact, competing for the customers energy demand. Space heating, e.g., can be provided by district heating, or by a gas or electricity network using e.g. heat pumps or boilers. Thus, different market participants (DSOs, supply companies) operating on different energy domains are rather interested in maximizing their own turnover and profit than in finding cooperative strategies to increase total efficiency. Furthermore, there are some structural and regulatory issues complicating a connection and cooperation between different energy networks. It is possible, e.g., that using cheap excess electricity from RES production for heating is not economical compared to using other fuels due to electricity network charges, even though an increased electricity demand could support network operation.

The topic of hybrid energy grid is getting more interests recently. Behavior of individual components (Keirstead et al., 2012), optimizing local controls (Bakken et al., 2006)(Arnold et al., 2009), or infrastructural planning (Hinterberger and Kleimaier, 2013) have been investigated before. Compared to previous work, the proposed process of this paper is more holistic and aims to deliver the whole picture, and focuses on the evolutionary path of the existing energy networks. One special focus here is exploiting the synergies among different energy domains and, hence, increasing the flexibility of energy networks and facilitating the integration of RES. The approach emphasizes a multi-agent perspective by taking into account the individual objectives of different market participants and aiming to develop cooperative strategies among competitors resulting in win-win situations. Moreover, this process aims to identify barriers in todays regulations and go beyond current market rules to examine possible future hybrid control strategies and business models.

3 HYBRID-GRID INVESTIGATION: SETUPS AND REQUIREMENTS

3.1 Identifying Hybrid Setups from the Two European Cities

The investigation process is first initialized by spotting possible hybrid chances from two actual European sites. Our target sites are the city of Skelleteå, Sweden, and two districts of Ulm, Germany.

Skellefteå is a city in mid-northern Sweden, in a subarctic climate region. Population of the city is over 32,000, and served by district heating (DH) grid with around 4200 heating substations. For a typical year, the DH grid provides about 343,000 MWh of heat to the city. Base heat load is being served by a CHP, which uses bio-mass fuel to generate heat and power. Districts of Einsingen and Hittistetten are located in the suburb of Ulm, Germany. They are small residen-

Table 1: Three Hybrid Setups from the Two Cities.

Name	Involved Stakeholders	Hybrid Means	Target Site
Co-operative suppliers	Energy providers, DSO	Co-operative District & Power grids	Skellefteå
Prosumer community	Consumers with RES, and DSO	Consumers with RES, and DSO	Ulm
Interacting providers & consumers	All of the above	All of the above with higher ICT connectivity	Both

tial districts with some commercial and public spaces, and have registered population of 400 and 300 respectively. Both are characterized by relatively high-level of PV penetration: 21 panels and 233kWp in Einsingen, 58 panels and 1.16MWp in Hittistetten. In addition to power grid, they have gas-grids that serve as the most common means of heating.

With close support from the energy providers and the DSOs in Skellefteå and Ulm, we have identified three *hybrid control setups*, which form the starting point of hybrid-investigations. Table 1 summarizes the three setups. *Co-operative suppliers* is a hybrid setup that focuses on the supplier side hybridization. Here, the participants are energy providers and DSOs of power and DH grids. The tools for hybridization are devices that connect DH and electricity grids on supplier side, such as CHP (as generation to both grids), and e-boilers (convert electricity to heat grid). In this setup, the synergy comes from operating both power and heat supply in co-operation. On the contrast, the second setup *Prosumer Community* focuses on consumer side. The participants of this setup are consumers and DSO, where the consumers have RES. The hybrid nature of this setup comes from the consumers side, where each consumer is connected to multiple grids with various devices. The hybrid synergy can be realized by co-operative control of various house hold devices (such as domestic hot water, space heating), in connection to their RES and surplus energy. The final setup, *Interacting providers and consumers*, targets both Ulm and Skellefteå. This setup aims at a more distant future situation on both sites, such as introducing new grids or new business models. It assumes tighter level of ICT connections of both sites, which will enable far higher level of interactions between consumers, providers and the devices, both in resolution and data amount.

Each hybrid setup represents a class of hybridization potential applicable to typical European cities, where it is assumed that the target sites are instances of such a co-operative hybridization setup. The idea is to identify and investigate hybrid scenarios that can be repeated at other European cities. Note that each setup only provides a general direction, which is still without specific tools or goals. To form an actual investigation question, *control goals* and *hybrid-means* should be added (Section 6).

3.2 Requirements for Hybrid-grid Investigation

Before designing actual investigation process, the requirements of the two target sites had been surveyed first. It is not possible to list all of them due to space, but the identified requirements can be summarized into the following three groups.

Impact of Co-operative Control on Technological Aspects. The investigation must enable us the observation of impacts of varying degrees of hybridization and different co-operative controls. For example, usual evaluation metrics on power grids and heat grids, such as voltage quality of LV-grid or heat-losses of DH-grid, should be measurable and comparable with and without co-operative hybrid strategies.

Impact of Co-operative Control on Social-economic Aspects. The investigation process should be able to clarify and show social and economic impacts of the co-operative control. This not only includes basic cost analysis, but also has to process more sophisticated issues such as guaranteeing mutual benefits (Pareto-criteria), regulatory aspects, and conditions for new business models.

Impact of Data on Co-operative Control. Synergy of co-operative control strategy depends a lot on data. This includes prediction (price, demand) data, meteorological data, and finally sensor data and their supporting ICT infrastructures. Impact of various data accuracy and resolution levels on the performance of co-operative hybrid energy grid should be explored.

The identified requirements affect the investigation in two folds: first, they provide basis for the evaluation metrics. Second, they directly and indirectly affect the design of the investigation process.

4 ECONOMIC MODELING FOR HYBRID GRIDS

Before novel cooperative control strategies can be implemented in real life, their economic feasibility has to be validated for each of the involved stakeholders. This means that the long-term monetary benefits for the actors participating in new control strategies need to be verified. Thus, it is important to first get a basic understanding of the general structure of hybrid energy retail markets.

4.1 Market Structure

The most important market participants in energy retail markets are customers (pro-/consumers), supply companies, and DSOs. Their major interactions, roles and typical objectives are illustrated in Fig 1. Starting from the right-hand side, the customers try to minimize their cost for meeting their demand for energy services, like e.g. lighting, heating, cooling etc. Depending on their available technology portfolio they can satisfy parts of their demand with self-generation, and the remaining residual load has to be purchased from a supply company via distribution networks. Supply companies retail energy in form of electricity, gas or heat to their customers and try to maximize their profit. They can procure this energy either by operating generation plants, by buying energy from wholesale markets or with long-term contracts (e.g. long-term gas delivery contracts). Of course they can also increase their profit by selling energy on wholesale markets. DSOs are providing the necessary infrastructure for energy delivery. They are responsible for (re-)investments in their distribution networks and for the maintenance of the network components. Network operation is characterized by economies of scale, subadditivity of cost and sunk cost, which makes it a natural monopoly (Auer, 2011). Thus, DSOs have to be regulated by a public authority in order to ensure economic efficiency, security of supply and non-discriminatory third-party access to the grids.

4.2 Methodology

In most cases, novel cooperative control strategies require clearly defined business models. Here it has to be specified which market participants are involved and how their role and responsibilities in these new business models are allocated. It has to be described which technology portfolio is considered in the business model and which technologies are controlled by the control strategy in which way. Furthermore, it is important to clearly define the ownership of the technology portfolio and to decide who operates the controller. In addition, if the controller reacts on price signals, the tariff design has to be specified.

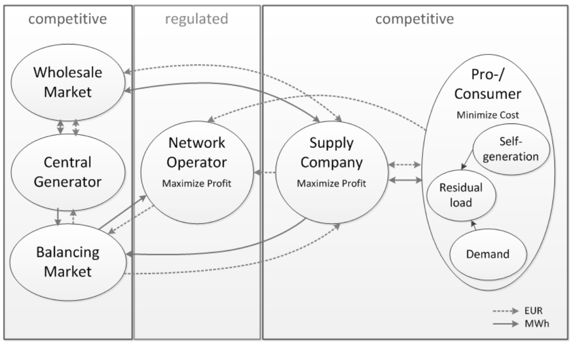

Figure 1: Simplified Illustration of the Structure of Energy Retail Market.

Once the control strategy and the corresponding business model are clearly defined, an economic trade-off analysis has to be conducted. In order to fulfill the cooperative concept, a crucial condition here is a Pareto-criterion. This requires that no market participant has higher cost (or lower profit) with the new business model than with the status quo. Thus, the formal framework for economic modeling consists of individual optimization problems for all involved market participants.

4.3 Economic Models

Since different hybrid control strategies and business models for different market participants are analyzed, the economic models have to be capable of considering various technology portfolios, several tariff designs and multiple energy domains. To incorporate the hybrid point-of-view, all quantities $\mathbf{q} = (q^E, q^G, q^H)^T$ and prices $\mathbf{p} = (p^E, p^G, p^H)^T$ are written as three-dimensional vectors, with each component representing one energy domain: electricity, gas and heat. Depending on the research question, control strategy and business model, the optimization problems have different time periods, time resolutions and are either formulated as Linear Programmings (LPs) or Mixed Integer Linear Programmings (MILPs), if investment decisions are considered. In the following, the considered time period in years is written as N, the number of time steps per year is denoted by n and r is the personal interest rate of each market participant.

4.3.1 Customers

To minimize their cost for meeting their energy demand, customers generally have several possibilities.

They can either procure all the energy from a supply company via the energy distribution networks at a certain tariff or they can invest in different technologies for energy self-generation, conversion and storing. If the demand of a standard passive customer is denoted by $\mathbf{d}$, and the tariff by $\mathbf{p}$, then the cost is given by

$$C = \sum_{y=1}^{N} (1+r)^{-y} \cdot \sum_{t=1}^{n} \mathbf{p}(y,t)^T \cdot \mathbf{d}(y,t) \qquad (1)$$

If a prosumer is considered, this cost function can be gradually extended to an optimization model by adding new terms and constraints, describing additional technologies. Consider, e.g., a customer with a heat pump and let the energy input vector of the heat pump be denoted by $\mathbf{q}_{in}^{HP}$, the output by $\mathbf{q}_{out}^{HP}$ and the matrix, describing the coefficient of performance, $\mathbf{COP}^{HP}$. Furthermore, $\mathbf{q}$ describes the energy purchased from a supply company and the investment cost of the heat pump are given by I^{HP}. Then the optimization problem of this customer can be written as:

$$\min \sum_{y=1}^{N} (1+r)^{-y} \cdot \sum_{t=1}^{n} \mathbf{p}(y,t)^T \cdot \mathbf{q}(y,t) - I^{HP}, \qquad (2)$$

$$\text{s.t. } \mathbf{q}(y,t) + \mathbf{q}_{out}^{HP}(y,t) = \mathbf{d}(y,t) + \mathbf{q}_{in}^{HP}(y,t), \qquad (3)$$

$$\mathbf{q}_{out}^{HP}(y,t) = \mathbf{COP}^{HP} \cdot \mathbf{q}_{in}^{HP}(y,t), \qquad (4)$$

$$\mathbf{q}(y,t), \mathbf{q}_{out}^{HP}(y,t), \mathbf{q}_{in}^{HP}(y,t) \geq 0. \qquad (5)$$

In a similar way other energy conversion technologies as well as energy generation and storage systems can be added to the model.

The customer tariff consists of three parts, namely, (i) the energy tariff, which is paid to the supply company, (ii) network charges, which are paid to the distribution system operator, and (iii) fees and taxes. Each of these parts, in general, can have several components: (i) a one-time initial payment or connection cost, (ii) an annual lump sum, (iii) a quantitative component, which can be flat, time-of-use (TOU) or real-time-pricing (RTP), and (iv) a peak-load-pricing component; in order to incorporate these different tariff types in the models, various objective terms and constraints have to be added, which will not be further elaborated here.

4.3.2 Supply Companies

The supply company model has a very similar structure to the customer model. The objective is given by the firms profit. The revenue is determined by the quantities, retailed to the customers at a certain tariff and possible sales on wholesale markets. The total cost consists of the investment cost and operational cost for generation plants, coupling technologies and energy storage devices. Additionally, if the supply company is buying energy from wholesale markets or via long-term contracts, these expenses have to be considered. If the purchased energy is transmitted via a network and if it is used by a device at the supply companys site, e.g. a gas-fired CHP , network charges have to be paid as well. Otherwise, the network charges are applied to the customers, consuming the energy.

Furthermore, supply companies have to predict their generation and their customers demand and report the respective schedules to a clearing and settlement agency. If balancing energy is required to uphold smooth network operation, they have to pay a share of the resulting cost ex post, based on their deviations from the announced schedule.

Though the models for customers and supply companies presented here are strictly cost-optimizing, they are adapted to match the operation mode of the respective control strategy for business model evaluation.

4.3.3 Distribution System Operators

It has already been mentioned that DSOs are regulated. Within the regulatory constraints, however, they try to maximize their profit. Their revenue is given by the network charges of their customers, also including supply companies, and their cost consist of investment cost and operational (maintenance) cost for the network components. The DSO model is formulated as a mixed-integer investment-planning problem, where the annual decision options comprise reinvesting, repairing or doing nothing per component. The realized choices affect the expected failure rate, the cost and the total asset value, which could be subject to regulatory constraints.

Different regulatory frameworks provide incentives for different investment and maintenance strategies. Price- or revenue-cap regulations limit the annual revenue and typically facilitate under-investments. Cost-of-service or rate-of-return regulations limit the profit by a percentage of the investments and, thus, rather promote over-investments (Auer, 2011).

5 CO-OPERATIVE CONTROL MODEL AS OPTIMIZATION OVER PLANNING HORIZON

The scope of hybrid grid control strategy includes major elements of the participating grids. It not only

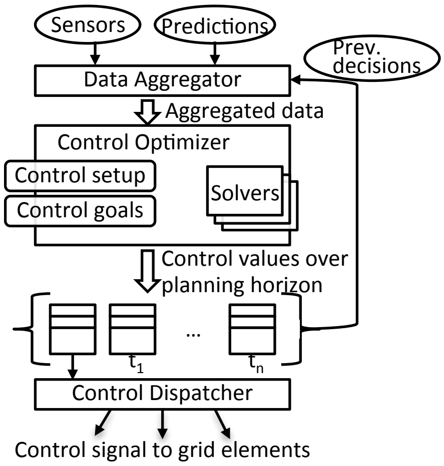

Figure 2: Conceptual Data Flow of Control Model.

includes grid coupling devices such as CHP or heat-pump, but also traditional elements such as fuel-based boilers or fuel-based generators. The control also optimizes market side decisions (e.g. when to generate electricity and sell for CHP), and provides signals for consumer side (e.g. when to store PV surplus). For the investigation, the control strategy is implemented as one central module that can observe and signal all participating elements.

This central module observes all relevant information over the hybrid grid, and plans best co-operative, co-beneficial decisions over the planning horizon. An essential role of the control is to optimize multiple grids together to gain benefits that were not realized before in isolated grids.

Fig. 2 shows the conceptual data flow. The flow starts with the data aggregator. It collects data over various data sources such as sensors, market prices, and demand prediction data. The aggregator provides a coherent view over the grids. The data are then fed into the control optimizer. The optimizer processes the data to derive best control decisions. The optimizer has two pre-set inputs. One input is pre-defined models of the hybrid-grid elements and the grid structure (control setup), and the other is the target for optimization (control target). The two inputs formulate constraints and objectives for mathematical optimization, and present the control problem as an optimization problem. To resolve this optimization problem, the control module employs multiple solvers (mathematical optimizers) to search and optimize. This includes various mathematical programming methods (linear programming, quadratic programming) as well as heuristic optimization methods (such as genetic algorithm). Once the solvers resolve the problem, the optimizer outputs the best control values for the planning horizon. The next step is dispatching of the control values. The dispatcher sends currently needed control values to actuators, and stores planned values to ease and reduce future problem spaces. The optimization process is repeated, as data from sensors and prediction are updated. For the investigation, the control is initially implemented to repeat planning for each 15 minutes. The planning horizon is currently fixed to 24 hours.

Control strategy modeling is similar to modeling of actors in economic model, in the sense that it frames the problem with an optimization framework. However, components in the control model are generally more detailed and complex (e.g. non-linear) since the control deals with actual devices. Control's optimization behavior is thus heavily affected by technical constraints of grid elements, and the control's problem space is limited to short-term horizons.

6 HOLISTIC INVESTIGATION ON THE IMPACT OF HYBRID GRIDS AND CO-OPERATIVE CONTROL STRATEGY

The investigation process as whole can be now explored, with the two introduced components of economic and control models.

Defining Scenario. The investigation starts by designing a specific hybrid evolution scenario. In this paper, a *scenario* means a hybrid setup of Table 1 instantiated into a concrete situation, bounded by specific control goals and hybrid devices. For example, *Co-operative suppliers* setup of Skellefteå can be turned into a scenario of "providing better peak-boiler with hybrid strategy", by adding electric boilers in addition to existing CHP and oil peak boilers. The control goal for the scenario can be: a) best cost peak-heat supply by tapping into fluctuating electricity price, and b) reduce total green-house gases. Finally, attaining the goals would require new control strategies. This would form a concrete investigation scenario that can be clearly evaluated and compared with current state-of-the-art.

Scenario Implementation. Once a scenario is given, the next step is *Scenario Implementation*. This includes building the simulation models for the target site, implementing the control model that meets the control goal, and the instantiation of the economic model that can describe the major actors of the scenario. If we follow the example of "better peak-boiler” scenario, simulation models to be implemented are district heat grid simulation and electricity grid simulation of the target site, where the two simulations are to be run by a co-simulation tool. A control model is implemented to control the simulated components on the simulation; such as CHP, added electric boilers, oil boilers, heat storage, power grid switches and so on. The economic model incorporates major contributors of the scenario, including major devices (above mentioned CHP and boiler behaviors, simplified), and stakeholders' behavior (the expected long-term behavior of power and heat providers).

Simulation-based Investigation. The next step is *Co-simulation-based investigation*. This step is characterized by many simulation runs for testing the control strategies. Each competing control strategy (including baseline) is being evaluated over the target grids in various relevant situations. Continuing the example of peak-boiler scenario, a set of control strategies will be evaluated across various demand conditions (e.g. cold, not-so-cold winter), price conditions (high/low price ratio of oil to electricity), various boiler sizes (adding single to multiple electricity to heat devices), for many simulated winter months. The investigation step systemically covers as many combinations as possible to make fair comparisons.

Note that it is a co-simulation environment. In a co-simulation, each simulation (e.g. heat grid and power grid simulation) runs together and exchange information at the same time, bounded by a co-simulation tool. For our investigation, PowerFactory[1] was used as power grid simulation, Dymola[2] for district heat simulation, and FMI++[3] as the co-simulation driver. Detailed description of the co-simulation environment is outside of the scope of this paper. Interested readers are kindly asked to refer to (Widl et al., 2015) for the environment we have adopted.

Direct result of the simulation investigation is all values that are observed and saved from a simulation run. The observed values can be processed further by technical evaluation measures, and can be compared between different strategies and/or hybrid configurations. This enables investigators to form concrete conclusions with supporting numbers and measures. In this paper, this conclusion out of simulation investigation is called *Operational recommendation*. It includes the modeled control strategy itself (the best control strategy among tested), and evaluated performance differences and lessons learned from the simulation runs.

[1]http://www.digsilent.de/

[2]http://www.3ds.com/products-services/catia/products/dymola

[3]http://sourceforge.net/projects/fmipp/

Economic-model-based Investigation. The last step of the investigation is *Economic-model-based investigation*. The simulation-based model alone cannot answer all important questions. Long-term effects and indicators like the internal rate-of-return (IRR) of investments need to be evaluated by an additional economic model. This also includes competing interests of stakeholders. The economic investigation comprises an analysis of currently existing structural barriers and the design of novel business models that enable a distribution of benefits, where all stakeholders can profit.

The economic model uses simulation results of the previous step to calibrate various parameters within the model. By doing this calibration, it can describe realistic long term effect of a hybrid grid strategy (such as total energy saved by a specific control scheme, or the behavior of a specific hybrid elements in different conditions) without explicitly modeling all technological details of the simulation. On the other hand, the economic model explicitly models and provides all major economic values and their stakeholders' interest, which are absent in the simulation. The values observable in economic model are processed further by social and economic evaluation measures, which can compare the proposed scenario with baselines. This enables the investigators to draw concrete conclusions for each proposed hybrid scenario. This conclusion, supported by projected values and measures of economic model, is called *Strategic Recommendation*. This provides the best perceived way of investments for the given scenario, and their expected return, and possible (or needed) price-scheme and business models.

7 OUTLOOK AND CONCLUSION

Currently there are two investigations on-going with the proposed process. One scenario is about providing better peak heating for the DH grid of Skellefteå, in a manner both economically and environmentally beneficial (“better peak boiler” example of Section 6). For the operational recommendation, it is expected to show the optimal size and type of the added boilers, the best co-operative control strategy over two grids, and cost and green house gas footprints of competing control strategies. For the strategic recommendation, the economic model will provide 20-years view of cost and investment analysis, with respect to various possible future fuel / electricity price changes.

For Ulm site, the first investigation is about "storing surplus PV as heat in households", where the control goals are to maximize local PV consumption, to minimize loads over critical grid elements, and to maximize subscribers' benefits on using surplus power. Operational analysis will provide impacts of various heating devices (e-boiler, heat pump) and control strategies, with their impacts on storing PV surplus power. Economic analysis will present on what condition the strategies will make sense (such as adoption of new feed-in tariff), and comparison to alternatives such as network reinforcement. There are also plans for more advanced hybrid investigations: such as investigating ideal heat/power cosupply in Skellefteå for the expected 20% more population in 2030, how to take benefit of hybridization with demand side management, and investigation of new business chances in Ulm site with a new hybrid electricity-DH grid, etc.

The paper proposed two-step investigation process that enables concrete and thorough checking of hybrid energy grid scenarios. The competitive edge of the proposed process comes from the approach's ability to check and sample details on both operational (short-term, technical) and strategic (long-term, economic and social) aspects of the given setup. It provides a set of holistic recommendations for stakeholders of the investigated grids. It is our belief that the holistic recommendations will provide valuable insights for the possible future energy grid evolution.

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