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OPtimising Hybrid Energy grids for smart citieS

WP5 Cooperative Control Strategies

Deliverable 5.5

Scalability and applicability of control approach

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Deliverable Description

Abstract: This deliverable discusses the questions of applicability and scalability of the control approaches for hybrid energy networks developed and studied in the OrPHEuS project. The purpose of this discussion is to assess to which extent the results of the project are applicable to cities in various regions of the world and to cities of various sizes.

Key Words: ICT, smart cities, hybrid energy grid, energy saving, demonstrations, smart grid, energy control, monitoring

Document History

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Dissemination Level

Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the Consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Executive Summary

The OrPHEuS project elaborates a Hybrid Energy Network Control System for Smart Cities implementing novel cooperative local grid and inter-grid control strategies for the optimal interactions between multiple energy grids by enabling simultaneous optimization for individual response requirements, energy efficiencies and energy savings as well as coupled operational, economic and social impacts. Starting from existing system setups in two cities, enhanced operational scenarios are demonstrated for today's market setup, as well as for future market visions.

The main scope of the Deliverable D5.5 (Task 5.5) is to discuss the project's control approaches in the context of hybridization scenarios other than the ones studied throughout the project. Applicability to cities in other regions, with different energy networks, different means of energy exchange, and different supply and demand patterns is analyzed. Furthermore, the deliverable also addresses the question of scalability of the control approaches to much larger scenarios, discussing issues like computational constraints, robustness, and communication overhead.

To facilitate a systematic discussion, the deliverable starts with a categorization of grid coupling points and control strategies. The strategies employed in the experiments of WP5 are then classified in terms of these categories, and the subsequent discussion of applicability and scalability makes use of this systematization, analyzing which kinds of control strategies are recommendable in which classes of applications.

Administrative Overview

Task Description

With this deliverable, Task T5.5 draws conclusions for the tested control strategies with regard to the applicability / replicability of the results in similar and different smart city scenarios. With the lessons learnt from Task 5.3, the task has studied scalability and control strategy applicability for various hybrid grid combinations, investigating impacts on scale of size. The task is reporting the results for the assessment of metrics and KPIs in relation to the tested scenarios to WP7.

Relation to the Scientific and Technological Objectives

No.	Objective/expected result	Indicator name	STO	Deliverable	MS	Expected Progress		
						Year 1	Year 2	Year 3
1	Cooperativeness of Control Strategies and sustainability guarantee for Cooperative Control and Operation	Cooperative Control Strategies for cities' Hybrid Energy Networks	STO4	D5.5	MS3			Due: M30 Draft: M27

Relations to activities in the Project

This deliverable reports the results of Task T5.5, addressing the scalability and applicability of the control approach. The input to this analysis consists of most of the results from WP5. The analysis of requirements (T5.1) is here enhanced to further scenarios, and the design of control strategies performed in T5.2 is re-assessed against the aspects of scalability and applicability. T5.3 has evaluated the control approaches in concrete scenarios, while in this deliverable we discuss to what extent the results are generalizable.

This deliverable has been compiled at the end of the OrPHEuS project, and thus any technical usage of its results is out of project scope. WP7 is using this deliverable as part of the input for the overall project results evaluation and conclusion.

Terminologies

Definitions

Control Strategy	Algorithm operating the coupling points in hybrid energy grids.
Coupling Point	Physical element which connects two different energy domains (for instance: combined-heat-and-power plant, electric boiler).
First-order Coupling Pont	Coupling point which consumes energy from one grid and produces energy for another grid.
Hybrid Grid	At least two energy grids that are interconnected by coupling points.
Energy Grid Hybridization	Act of adding coupling points to connect multiple energy grids
Second-order Coupling Point	Coupling point which can either produce energy for multiple grids or can consume energy from multiple grids.
Third-order Coupling Point	An energy producer or consumer which is only connected to one grid in a hybrid grid scenario including first and/or second order coupling points, and which can be operated by a control strategy.

Abbreviations

CHP	Combined Heat and Power
CP	Coupling Pont
MS	Milestone
STO	Scientific & Technological Objective
PV	Photovoltaic

Table of Contents

1 Introduction

The OrPHEuS project studies a hybrid energy network control systems for smart cities. New interactions between previously isolated energy grids is enabled by the use of coupling points, and these coupling points are operated by novel cooperative local grid and inter-grid control strategies in order to achieve optimal synergies between the grids in terms of energy savings, economic, and social impacts. Starting from existing system setups in two cities, enhanced operational scenarios have been demonstrated by the project for today's market setup as well as for future market visions.

The scope of this Deliverable D5.5 is to discuss the generalizability of the results. More specifically, it is analyzed to which extent the project's control approaches are applicable in hybridization scenarios other than the concrete setups used for design and experimentation in the project. Generalizability includes applicability to cities in other regions, with different energy networks, usability for different means of energy exchange by network coupling points, and different supply and demand patterns. Furthermore, the deliverable also addresses the question of scalability of the control approaches to much larger scenarios, discussing issues like computational constraints, robustness, and communication overhead.

In Chapter 0 a systematic categorization of grid coupling points and of control strategies is developed. These categories facilitate to analyze the specific advantages and disadvantages of particular control approaches in particular scenarios. A first application of these categories is conducted in Chapter 0, where the control strategies and scenarios studied by the project are classified according to this systematization. Chapter 4 addresses the first main question of OrPHEuS Task T5.5: how can the control approaches be expected to perform in other regions and for other grid interaction types. Chapter 5 then addresses the scalability of the control to large-scale cities and regions, discussing various issues that occur during the transition from a small city district to a large city. A summary of the results and conclusions are presented in Chapter 0.

2 Design Space for Control Strategies

Within the scope of the OrPHEuS project, the design goal of control strategies is to coordinate the interaction between cooperating energy grids. To fulfil this goal, the control strategies need to operate all or a subset of the *grid coupling points*, that is, the devices which directly or indirectly transfer energy from one grid on the other, using real-time and predictive data to optimize the control decisions.

In the following paragraphs we describe a number of aspects that help to characterize hybrid grid control strategies. Every decision about a particular control strategy needs to take these main aspects into account.

2.1 Scope of Control Decisions

Direct transfer of energy between the grids is realized by devices which consume energy from one grid (e.g. chemical energy from the gas grid) and convert it into energy in a different form, which is then fed into another grid (e.g. thermal energy for the heating grid). In hybridization scenarios where such devices exist, operating them via intelligent control strategies is a fundamental requirement for the achievement of synergies. The type of devices for direct energy transfer described in this paragraph can be denoted as *primary* or *first-order* coupling points.

There are two additional types of devices connected to multiple energy grids. *Hybrid producers* – like CHP plants – are able to produce energy for multiple grids. Typically the provisioning of energy to one grid is interdependent with the provisioning for the others. For example, a hybrid producer can have a maximum total amount of power it can supply, and it needs to be decided which proportion of the power is supplied to which of the connected grids. It is also a common operational constraint that the amount of power supplied to one grid is proportional to the power supplied to the other.

Hybrid consumers are as well connected to multiple grids; the power they require for operation can be supplied from various forms of energy from various grids. Consider for example an indoor heating system that can utilize gas, electricity, or a district heating network. Such kind of consumers add an interdependence between the grids by the fact that they require a certain total amount of energy, so taking this energy from one grid will relieve the others.

Hybrid producers and consumers can both be denoted as *secondary coupling points.* Hybrid control strategies become more effective by extending the scope of their control to this class of coupling points. There are even hybridization scenarios where no primary coupling points are available, but control over the secondary ones still creates benefits for all involved grids.

In addition to primary and secondary coupling points, the behavior of every other producer and consumer in hybrid grids can have an influence on all interconnected grids, even when the device is connected to only a single grid. Once the grids are interconnected by primary and/or secondary coupling points, the amount of power produced and consumed in any grid has an influence on the power supply and demand in the others. For example, when a fuel boiler is set to produce enough thermal energy for a district heating network, then an e-boiler coupling point does not need to convert electricity into heat, and thus less power needs to be generated for the electricity network.

Of course not all producers and consumers admit to be operated by control decisions. Wind and solar power do only enable curtailing, and typical energy consumers at most admit some very limited time shifting of their demand. The class of non-hybrid producers and consumers which admit some control can be denoted as *tertiary* or *third-order coupling points.* Also energy storages, which sometimes act as a producer and sometimes as a consumer, fall into the category of third-order coupling points. It is important to note that there are no hybrid grids containing only third-order coupling points; hybridization always needs to include at least one first-order or second-order point, as otherwise the grids are mutually independent.

As a summary, any hybrid grid setup includes one or more first-order and/or second-order coupling points, and hybrid control strategies operate a set of coupling points falling into any of the three categories described.

In theory, the more coupling points are operated by a control strategy, the more effective is the control. Practical considerations (like ownership, liabilities, regulations, communication infrastructure) are limiting the amount of control over the coupling points in practice, but in the experiments conducted by the OrPHEuS project it is generally the case that all coupling points are operated by the control module.

2.2 Control Input

The preceding paragraphs describe the output of control strategies: real time control signals for all or a subset of the coupling points of the hybrid grid setup. In what follows the other side of the control logic, the input, is categorized. Any control strategy requires some information based on which the control decisions are then made. We distinguish between static, real-time, and predictive input.

Static input is information which does not change during the runtime of the control strategy. It is the fundamental information which determines the design of the control strategy, including the involved energy networks, the available coupling points and their operational constraints, network topologies, statistical information about supply and demand patterns, and the KPIs to optimize.

Static input can be provided with little effort, as it is information the network operators typically have available and no measurement infrastructure needs to be installed. Statistical information can be collected offline, and thus the required communication infrastructure is simple or non-existing..

Real-time input includes all information that is dynamically changing during runtime of the control strategies. It includes the current demand and supply in all networks, the status of the network elements and coupling points, the status of storage devices, as well as context information like weather conditions or external events.

Real-time information is generated by a multitude of sensors installed at various points in the energy networks. It requires communication infrastructure to collect the data and provide it to the control logic fast enough that the next rounds of control decisions can take the new data into account. In some cases real-time processing of the raw data needs to be performed in addition before the control can use it. All of these steps lead to extra costs in terms of energy, maintenance, and procurement, and thus the right tradeoff between cost and control accuracy needs to be found.

However, the costs and effort of installing sensor infrastructure with communication capabilities has enormously decreased in the recent years, and emerging standard protocols for M2M communication further lower the barrier for the wide adoption of such technologies.

Predictive input is information about the future. Such information almost always comes with some degree of uncertainty, but nevertheless it is often essential to have such information. Especially predictions of the energy demand are required to plan the operation of storages and coupling points with dynamicity constraints. Demand predictions are mostly based on historical information as well as weather forecasts. Other predictions include short- and medium-term energy market trends. The quality of prediction methods is steadily improving, and thus control strategies can rely more and more on the accuracy of forecasts.

In the simulations conducted by the OrPHEuS project, various control strategies with various levels of dependence on information have been experimented with. Some strategies have used all three types of information as input, while others have shown to produce good results with only little information available.

2.3 Degree of Centralization

Whenever control strategies operate more than one coupling point, there are two opposing design paradigms: centralized and decentralized. In centralized strategies the control logic runs in a single dedicated component. All required information is transmitted to this central controller, and the control decisions are communicated back to the coupling points to be executed. In decentralized strategies every coupling point runs a separate control logic. Only a subset of the network information is available to each controller, and communication between the controllers is limited or does not take place at all.

Both paradigms have their specific set of advantages and disadvantages. Centralized control strategies, due to their global view, can optimize across the whole network. This global view comes at the price of a higher complexity of the central controller, where errors potentially have a system-wide impact. Furthermore, communication infrastructure is necessary to feed the controller with information and to forward control decisions to the coupling points. Finally, the reaction time to unforeseen events is higher when there is a single global controller.

Decentralized control strategies in contrast are better scalable and more flexible. The controller at each individual coupling point is less complex and can react faster to events. The downside of the missing global view is that the reactions are not coordinated and thus the overall system is more likely to overreact to events of behave suboptimally in some other way. Furthermore, the limited information available to each controller can potentially prevent optimal operation of the whole set of coupling points.

Many control strategies follow a tradeoff between centralized and decentralized control. Typically, the centralized component sets one or more parameters according to which the local controllers then operate the coupling points.

In the OrPHEuS project we have experimented with control strategies ranging between all extremes of the spectrum, including fully decentralized strategies, hybrid ones, and fully centralized methods.

3 Overview of Control Strategies in OrPHEuS

In this section we give an overview of the hybrid grid control strategies that have been employed in the technical simulations of the OrPHEuS project. We categorize them in terms of the aspects described in the section above, and we present the lessons learnt from the experimental results.

Table 1 and Table 2 show the categorization of the scenarios and control strategies in terms of algorithm input and output as well as the degree of centralization. We remark that the set of controlled coupling points are entirely determined by the particular scenario under consideration. Within OrPHEuS the controllers always take control over all available coupling points. Thus, different strategies for the same scenario differ only in terms of the control input they use and their degree of centralization.

In the column for the control input the table lists only real-time and predictive inputs, omitting the static inputs for the sake of clarity. Only Table 2, which represents the Skellefteå scenarios, contains predictive input as for the scenarios of Ulm (Table 1) a reactive control approach was chosen.

The category of centralization only plays a major role in the Ulm present-day scenarios, as in the other scenarios there is only a single coupling point of each type. These coupling points of different types are controlled centrally by all strategies for the particular Skellefteå scenarios.

<table>
<tr><th>Scenario</th><th>1st order coupling points</th><th>2nd order coupling points</th><th>3rd order coupling points</th><th>Control strategy</th><th>Real-time control input</th><th>Centralization</th></tr>
<tr><td rowspan="3">Ulm present-day</td><td rowspan="3">-</td><td rowspan="3">domestic hot water operated from gas or electricity</td><td rowspan="3">-</td><td>Control-1</td><td>PV surplus of each house, storage temperatures</td><td>de-centralized</td></tr>
<tr><td>Control-2</td><td>local node voltage, transformer flowback, storage temperatures</td><td>semi-centralized</td></tr>
<tr><td>Control-3</td><td>node voltages, line loads, transformer status, storage temperatures</td><td>centralized</td></tr>
<tr><td rowspan="3">Ulm present-day with space heating</td><td rowspan="3">-</td><td rowspan="3">DHW and space heaters operated from gas or electricity</td><td rowspan="3">-</td><td>Control-1</td><td>PV surplus of each house, storage and indoor temperatures</td><td>decentralized</td></tr>
<tr><td>Control-3</td><td>storage and indoor temperatures, transformer flowback</td><td rowspan="2">centralized</td></tr>
<tr><td>Control-4</td><td>same as Control-3 and daytime</td></tr>
<tr><td rowspan="2">Ulm future</td><td rowspan="2">Electric boiler</td><td rowspan="2">-</td><td rowspan="2">Thermal storage</td><td>Control-A</td><td rowspan="2">PV surplus, storage status, heat demand</td><td rowspan="2">n/a
(only two CP)</td></tr>
<tr><td>Control-B</td></tr>
</table>

Table 1: Characterization of scenarios and control strategies for the target site of Ulm-Einsingen

The experimental results for the first Ulm present-day scenarios have shown that the semi-centralized control strategy could well compete with the centralized one. The completely decentralized strategy (Control-1), both in the scenario with and without space heating, had an inferior performance in terms of the KPIs. However, we doubt that this observation applies to the decentralized approach in general. The reason for the low performance of Control-1 in the case of the Ulm scenario is that each individual building was operated to optimize its own benefits without regard to the overall system. Thus, the problem was rather a lack of social or *collaborative* behavior than a lack of centralization. Control-2, which still operates all coupling points independently from each other to a large extent, but programs them to operate cooperatively (consuming surplus when detecting an overvoltage), showed much better results.

<table>
<tr><th>Scenario</th><th>1st order coupling points</th><th>2nd order coupling points</th><th>3rd order coupling points</th><th>Control Strategy</th><th>Real-time and predictive control input</th><th>Centralization</th></tr>
<tr><td rowspan="2">Skellefteå present-day</td><td rowspan="2">electric boiler</td><td rowspan="2">CHP</td><td rowspan="2">Biomass boiler, oil boilers, thermal storage</td><td>Phase-out-oil</td><td>heat demand predictions, storage status</td><td rowspan="2">centralized</td></tr>
<tr><td>Cost-best</td><td>heat demand predictions, heat demand, storage status, price information</td></tr>
<tr><td>Skellefteå future</td><td>electric boiler, heat pump</td><td>CHP</td><td>Biomass boiler, oil boilers, thermal storage, electric storage</td><td>Cost-best</td><td>heat demand predictions, heat demand, thermal and electric storage status, price information</td><td>centralized</td></tr>
</table>

Table 2: Characterization of scenarios and control strategies for the target site of Skellefteå

Predictions were only employed by the control strategies for the Skellefteå scenarios. The predictions of the heat demand in the near future (next three days) are essentially required here, because the charging policy of a large-scale thermal storage needs to be decided on, and some of the heat suppliers have a long ramp-up time.

From the experiments with various control strategies there is no clear indication that more data always leads to better results. For example Control-2 and Control-3 in the Ulm present-day scenario vastly differ in the amount of information they take into account, but the performance of these two strategies turned out to be comparable. From these observations we would recommend a conservative approach, first experimenting with control strategies using only little data before gradually switching to more data-rich strategies.

4 Applicability of Control Approach

In this section we discuss the applicability of the control approaches, studied in the context of the OrPHEuS scenarios, to energy network hybridization setups in general. Hybrid energy networks is a very broad concept and thus one-to-one mapping of control algorithms from one deployment to another is hardly possible. Nevertheless, the lessons learnt from the project's studies can to a large extent be applied elsewhere, and control principles have broad applicability.

The OrPHEuS scenarios and control strategies were selected so as to cover a broad range of hybrid energy network setups. As Table 1 and Table 2 show, all principal categories of coupling points were covered by the scenarios. Regarding 2^{nd}-order coupling points, both hybrid producers (CHP) and hybrid consumers (hybrid heating) were part of the studies. Independent from the category, coupling points both on the consumer side and on the producer-side occur in the scenarios. The consumer-side hybridization setup involved a large number of small coupling points, while the hybridization on the producer side was realized by a smaller number of large-scale coupling points.

The expected benefit of hybrid energy networks is to mitigate the effects of fluctuations in demand and supply. Both types of fluctuations were part of the studies, and additionally price fluctuations and problems in the electricity network due to overproduction of solar energy were considered.

In the following paragraphs we discuss the applicability of our results for the specific scenarios of Ulm and Skellefteå to other classes of scenarios.

4.1 Applicability to Other Geographic Regions

The Ulm scenarios with solar panels in individual households find applicability in all regions where there is enough solar irradiation for photovoltaic energy to be effective. The applicability is however limited to residential areas with small-scale PV systems installed on individual houses, because this is where the PV surplus is causing problems in the low voltage grid and where there is heating demand making this particular type of hybridization sensible. Larger solar farms are a fundamentally different producer, as these are designed to feed electricity directly into the medium or high voltage network.

The first-order coupling points employed in the Skellefteå scenario turn electricity into heat on a large scale, and this is type of coupling is applicable in any region having heating demand. The same observation holds for the second-order coupling point, the CHP. Heating grids are getting increasingly common throughout the world, and the potential to link them with the electricity network via heat pumps or electric boilers is not limited to specific areas. The second and third-order coupling points producing heat in Skellefteå are operated with Biomass and Oil, but this does not limit the applicability of the control approaches to other energy sources as well. Renewable energy sources like wind or solar energy pose further challenges due to their lack of controllability, but this is to some extend already taken into account in the Skellefteå scenarios with the fluctuating electricity market prices.

4.2 Applicability to Other Coupling Points

The energy domains studied in the OrPHEuS project are mainly heat and electricity. The gas network is formally included by the Ulm present-day scenario, but it is only considered as a fallback source of heating energy without own demand and supply patterns taken into account.

The focus on heat and electricity represents one of the limitations of the OrPHEuS results; other networks that remain to be studied are gas grids, cooling networks, and electricity networks on varying voltage levels. However, some of the observations can be assumed to apply to other energy domains as well. For example, heat pumps like in the Skellefteå future scenario can be used for cooling networks as well, and the cooling demand has comparable characteristics. Surplus PV energy can also be used for space cooling, similarly to heating. This is in particular interesting in summer, when space heating is no a relevant usage possibility for local PV surplus.

Another limitation of the OrPHEuS studies is on the types of first-order coupling points studied. All included coupling points of that category convert electricity into heat. Devices like power2gas or micro-CHPs operated from the gas grid remain to be studied in future work. Studying power2gas would require modelling of gas grids with their own supply and demand characteristics. Micro-CHPs, on the other hand, have again both electricity and heat as output, but, unlike in the Skellefteå scenario, they are highly distributed. There is certain similarity to the Ulm present-day scenarios, only with the hybrid consumers replaced with hybrid producers.

The energy storages considered by the project were rather short-term storages which could influence the energy demand and supply over the time horizon of a few days or even a few hours. Seasonal storages require a different handling, because their storage capability reaches beyond planning horizon of the control strategies we have employed in our studies.

5 Scalability of Control Approach

This section discusses the potential of the OrPHEuS control approaches to be applied in energy network hybridization setups on different scales from small villages to large cities. It is a well-known fact that the infrastructure requirements do not simply grow linearly with the size of cities, but cities of different sizes have fundamentally different requirements. Control of energy network hybridization is no exception, and thus each aspect of making the network hybrid has to be discussed in the context of various city sizes.

The relevant infrastructure for hybrid energy grids consists of (a) the existing individual grids, (b) the coupling points, (c) the data sources like sensors, (d) the communication infrastructure for control to be executed, and (e) the architecture and algorithms of the control modules.

When considering cities of growing size, the individual grids do not only become larger, but also increase in complexity of topology. The redundancy is increased by having multiple connections between two points instead of a tree topology, and the fact that the network has grown over time makes its structure more difficult to analyze than a centrally planned and then built network.

The amount of coupling points also grows with the network size, and at some point it becomes impossible to have large centralized coupling points like e.g. in the Skellefteå scenarios studied by the OrPHEuS project. With the size of the cities under consideration, the amount of data produced by the sensor infrastructure is also increasing and begins to require dedicated network capacity for transmitting, and massive processing capabilities in data centers to be made use of.

Finally, control modules in large-scale setups need to have an architecture taking more consciously into account reliability of operations and possible limitations of the communication and computation infrastructure.

5.1 Scalability in Computational and Communication Terms

Deliverable D3.1.3 describes recommendations for interactions in energy control systems, and such recommendations become more relevant with application areas that grow in size. Hybrid Grid controllers need both to work with a growing number of inputs from sensors, and they need to operate a growing number of coupling points. Low-latency interaction is crucial in both directions, and thus a robust and high-performance communication infrastructure is required when applying control strategies to large-scale scenarios.

Processing and filtering of the streams of input data has been recommended in D3.1.3 to be done close to the data sources in order to save bandwidth, energy, and storage costs. A mechanism to deploy such tasks among the path between the data source and sink has been presented, reaching beyond state-of-the-art stream processors, and generalizing it to the situation in control, where the data flow between controller and devices is bidirectional.

Thus, the project has successfully addressed the issues of scalability in communication infrastructure. What is remaining is the discussion of the computational scalability. Here there is again the fundamental distinction between centralized and decentralized control. Centralized control can become a bottleneck in computational terms. The control decisions have to be computed fast enough, so that their execution does not happen later than admissible. In the simulations the hard deadline for any control decision has corresponded to the time step length of 15 minutes, but in other scenario the admissible computation time should be close to real-time. Flexibly configurable trade-offs between runtime and solution quality help to make sure the hard computation deadlines are met, but this comes at the cost of deteriorating solution quality when the scenarios grow larger. Parallelization of computation in datacenters is another approach, but due to the mutual interdependence of most control decisions the potential for parallelization is limited. Introducing some degree of decentralization is helping to preserve scalability in terms of computational restrictions, but requiring a careful design of the individual controllers in order for the overall system to react appropriately to the environment.

It should however be mentioned that, despite the potential computational problems that unavoidably occur when the scenario exceeds a certain size, that critical size is really large. State-of-the-art optimization tools are able to handle problem sizes four to six orders of magnitude larger than the scenarios we have studied in the OrPHEuS project.

5.2 Scalability in Terms of Control Architecture

In the present-day scenario for Ulm the control strategies have operated a number of coupling points in the order of magnitude of hundreds. We have considered decentralized, semi-centralized, and completely decentralized control strategies. In the simulation environment the degree of centralization only has an effect on the control decision; issues regarding computational time, communication costs, or reliability are not directly visible as such simulations are not real-time.

Centralized control strategies with a single control module for large numbers of coupling points have their limitations due to computational and communication bandwidth constraints. The number of variables and constraints of the optimization problems to solve become larger, and more data has to go into and out of the control modules. Furthermore, larger setups have a higher probability that components fail to work, thus robustness against such failures has to be addressed by the control architecture.

Decentralized strategies where each coupling point is controlled by an independent module represent one solution approach. When this is not possible because some global coordination is needed, a layered architecture which includes some redundancy in the upper layers is the recommended architecture. A simple example of this is Control-2 in the Ulm present-day scenario, were the global controller sets a threshold for the local ones. However, the detailed study of such larger-scale control architectures has been out of scope of the OrPHEuS project due to the limited size of the hybridization scenarios under consideration and the simulation setup where this class of issues is not directly visible.

6 Summary and Conclusion

This deliverable has presented an analysis of the generalizability of the OrPHEuS control approaches, focusing on applicability and scalability. In the discussions we have considered cities of various sizes and various locations, as well as various energy network combinations that are made hybrid.

Summarizing our findings, there is a wide applicability of the particular hybridization approaches that have been studied in the project, and for these applications the proposed control approaches can be adopted. When dealing with scenarios which are by two or more orders of magnitude larger, additional computational and robustness issues have to be addressed by the control infrastructure. In this and other project deliverables we have given recommendations on how to deal with the communication and computation scalability.

Other energy network combinations to be made hybrid by coupling points are more challenging to apply the OrPHEuS results to. We have learned in the project that the specific supply and demand patterns of the different networks play a major role in the control design, and thus applying the controllers to other forms of energy has to be done with special care. We are however optimistic that the most important finding of the project also holds here: Network hybridization has the potential to create synergies all interconnected networks benefit from.

Disclaimer

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