Project No. 608930

FP7-SMARTCITIES-2013

OPtimising Hybrid Energy grids
for smart citieS

WP7 Project Results Evaluation and Conclusions

Deliverable 7.1.2

Impact of Cooperative Control Strategies for cities' Hybrid Energy Networks on European scale

(Final version)

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Deliverable Description

Abstract: The report D7.1.2 provides a comprehensive comparison of the results of the technical work packages with the advances to the state of the art reached in the project. The value for advanced technology and its impact for replication will be discussed. Further, the report outlines the recommendations for replication with focus points on technical and economic aspects.

Key Words: ICT, smart cities, hybrid energy grid, energy saving, smart grid, energy control, technical and economic recommendations;

Document History

Version	**Date**	**Authors**	**Description**
0.1	2016-11-15	NEC	D7.1.2 Extension deliverable outlining starting from D7.1.1
0.2	2017-01-05	NEC	D7.1.2 Content definition for extensions
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1.0	2017-01-20	NEC	Final version: polishing and submission for internal review

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 EU 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 objective of this work package is the accumulation of the results of the individual technical work packages (WP2-6) into the conclusions of the overall project results and specifying the lessons learnt throughout the different processes. This work package will comprehend the project results into a comprehensive message addressing technical, economic and social aspects for todays and future energy grid planning and operation within well-defined interactive and smart energy grids.

The report D7.1.2 is the final version to a comprehensive project recommendation report. It aims to provide a comprehensive comparison of the results of the technical work packages with the advances to the state of the art reached in the project and to summarize the gained knowledge in individual technical work packages. From here, the impact of the technology and knowledge extensions is drawn for potential replication. This final report outlines the recommendations for replication with focus points on technical and economic aspects.

Administrative Overview

Task Description

This WP is the final technical WP of the EU OrPHEuS project. The main objective of this work package is the accumulation of the results of the individual technical work packages (WP2-6) into the conclusions of the overall project results and specifying the lessons learnt throughout the different processes. This work package will comprehend the project results into a comprehensive message addressing technical, economic and social aspects for todays and future energy grid planning and operation within well-defined interactive and smart energy grids. The main objectives of this work package are:

- Comprehensive comparison of all aspects of economic, social and technical evaluation drawn across the WPs
- Establishment of the consortium results accumulating over all WP results

Recommendation for the different hybrid energy networks and scenario conditions will be drawn and prepared for dissemination at the European Smart Cities and Communities Stakeholder Platform.

Relation to the Scientific and Technological Objectives

WP7 will comprehend the transfer of all validation results and gathered experiences from all WPs WP2 –WP6) into a holistic set of recommendations highlighting each aspect of the defined STOs addressing the technical replication and transferability potential on wider European scale. Based on the validation results, recommendations for sustainable business development and application area for business models and its impact on Policies Making can be drawn.

This work contributes to:

No.	**Objective/expected result**	**Indicator name**	**STO**	**Deliverable**	**MS**	**Expected Progress**		
						Year 1	**Year 2**	**Year 3**
1	Impact of cooperative Control Strategies for Cities Hybrid Energy Networks	Impact	STO4	D7.1.1 & D7.1.2	MS4			1 Due: M40 Draft M38

Relations to activities in the Project

Input: WP2, WP3, WP4, WP5, WP6, D7.1.1

Output: D7.1.2

Partner contributions and link of WPs: All partners represent their results from the technical work packages WP2, WP3, WP4, WP5 in order to establish the holistic analysis of the WP results. This result is presented as EU OrPHEuS Project results. The achievements of the individual STOs are concluded, and recommendations for replication potential are discussed.

Terminologies

Definitions

All definitions provided in the deliverables of WP2-WP6 apply.

Abbreviations

All abbreviations defined in the deliverables of WP2-WP6 apply.

Table of Contents

1 Introduction

The EU OrPHEuS project aimed to provide new technology and business advances in order to enable a larger impact on utilization of hybrid energy grids. The project aim is:

> **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.** (DOW, Section B1.1)

The objective of this report is to provide a comprehensive comparison of the results of the technical work packages with the advances to the state of the art reached in the project and to summarize the gained knowledge in individual technical work packages. The report analyses the Scientific and Technological Objectives of the project and details which progress has been made with regards to the limitations of the state-of-the-art deployed and operated in the existing energy landscape.

From here, the impact of the technology and knowledge extensions is drawn for potential replication. The result comprehension and its value for advanced technology are summarized such, that the tables for the aimed progress (see DOW section B1.2.1, page 72) which brings together the discussions for the targeted advances with the project results presented as "Gained Knowledge and Impact". This builds the basis for the provided recommendations for replication in Europe beyond the dedicated demonstration sites.

References are made in this report to separate project deliverables, where more details on specific work tasks and results are provided for interested readers. Some of these deliverables are rated as public ("PU", see the Bibilography) and can be freely downloaded on the OrPHEuS project website www.orpheus-project.eu. Deliverables rated other than "PU" are restricted or confidential and are not available on the project website. The project coordinator may be contacted directly to establish access to these deliverables.

2 Gained Knowledge and created Impact

2.1 STO 1: Creation of the concept for new Business Models

The work on STO1 aimed for concept for new business models in order to utilize the technical advantages of cooperating hybrid grids.

"*Based on different consumers' energy service needs, a framework defining the economic interactions between the different market players is developed in a hybrid energy network environment with high shares of renewable resources and sustainable technology penetration. In this context, robust business models and market design is envisaged to ensure high satisfaction and comfort of stakeholders and users across the hybrid energy networks respectively*." (DOW , Section B1.1.1). The creation of the concept for new business models has been based on the following key strategic objectives:

- Techno-economic set-up
- Economic trade-off analyses of default case and alternative business model design:
- Robustness test of business model design
- Business model replication and transferability

These objectives and their application have been explained in detail in [1] and [2]. As result, alternative business models for the project's demonstration sites have been developed and discussed.

The following tables comprehend over the gained knowledge and its impact for replication:

Advances of the OrPHEuS project	**Gained Knowledge and Impact**
1. Integration of hybrid network interactions into the market place	
Business models (technically, economically) are developed to enable *sustainable uptake of hybrid energy network interactions* in delivering energy services for all stakeholders involved.	In the course of hybrid network analysis a comprehensive list of available coupling technologies has been created. Furthermore, the implications of possible technology implementations in terms of energy and revenue flows among different stakeholders along the energy supply chain have been investigated. Based on this knowledge, existing and expected issues and corresponding hybrid business model opportunities have been identified. For the tailor-made business model development it is very important to clearly define the involved market participants, their role and responsibilities, and cost allocations.
Changing economic interactions between the different stakeholders are respected when implementing new innovative technologies (e.g. energy efficiency measures, solar thermal collectors, heat pumps, PV systems) in a hybrid energy network environment.	On the demand side the implementation of new innovative technologies changes the residual load of customers on different energy domains. In the case of energy efficiency measures this implies revenue reduction for both, suppliers and distribution system operators. In the case of hybrid coupling technologies demand and

<table>
<tr><td></td><td>therefore also revenue is shifted from one energy domain to another. On the supply side new hybrid coupling technologies increase flexibility in energy production and, consequently, reduces operational cost. Depending on the type of coupling technology, revenues are shifted among different energy domains or from fossil fuel providers to energy suppliers and distribution system operators. For a power-to-heat technology, for example, heat production may become cheaper. Revenues are definitely shifted from alternative heating fuel providers to electricity distribution system operators and suppliers.</td></tr>
<tr><td colspan="2">Impact:
In order to successfully enable cooperative business models applying to hybrid grid interactions, changing regional characteristics like metrological, demographical, and regulatory conditions as well as current/ future technology portfolios are crucial for the application of the Pareto-Criterion. Especially aspects like investment sharing, operational responsibility, maintenance have to be considered for replication across Europe.</td></tr>
<tr><td colspan="2">2. Alternative business model design</td></tr>
<tr><td>The <i>monetary impact of different alternative business models and cost allocation strategies (compared to a status quo) are investigated</i> on the stakeholders' income and payment balance in the transition phase with increasing share of the new stakeholder type <i>'prosumers'</i>.</td><td>For each investigated business model the effects of new technologies on energy flows have been modeled in detail and the effects on the cash flows of the participating stakeholders have been analyzed comprehensively. In general, investing in new coupling technologies reduces operational cost or avoids alternative investments (e.g. grid reinforcement) for one or more of the considered market participants. By investigating the change of cash flows the net profit of the new business model can be shifted to the remaining market participants by choosing alternative cost allocation strategies. This can be achieved by changing tariffs or sharing investment cost among multiple market participants. This way, win-win situations can be achieved among all participants involved in the business model.
The fulfillment of the Pareto-criterion, however, very much depends on where the system boundaries are drawn: While a new coupling technology could be beneficial for all stakeholders in a hybrid energy network, "external" players like providers of alternative technologies (grid reinforcement) or fuel sources have to deal with reduced turnover compared to the respective status quo business model.</td></tr>
</table>

Economic incentives are incorporated in the *grid regulation process* for investments into ICT and network control devices.	Investments into ICT and network control devices are, in general, less expensive than network reinforcements and enable more efficient grid operation. If the return on investment (ROI) that system operators are granted in the regulation process is too high, they profit more from bigger investments. With a too low ROI, on the other hand, they are incentivized not to invest at all.
The *role, responsibilities and economic implications* for the *different network operators* for enhanced network control and hybrid energy network	Network operators play a key role in the development each business model. Some hybrid business models are directly triggered by the grid operators and network issues in order to avoid alternative expensive grid reinforcement. Many business models require active DSO participation at least to a certain degree for example in the form of providing access to network data or ICT infrastructure. In business models, where the DSO, actively controls energy production, conversion or storage technologies, legal issues concerning the unbundling of the energy supply chain arise. Furthermore, network operators can have a great impact on business models, which they are not actively participating in, as well. The design of network charges significantly affects the profitability of business models and can provide, but also reduce, incentives for customers to change their pattern of energy consumption. Especially business models considering the energy conversion from electricity to heat or to natural gas are very dependent on the network charges design
Impact: In order to successfully enable cooperative hybrid business models, it is very important to analyze existing and changing market interactions among different market participants in detail. The change in cash flows determines economic incentives for various stakeholders to participate in novel business models and is therefore crucial for their deployment. At the same time the regulatory framework, which can be different for different European countries, can be barriers for the implementation of new cooperative business models.	
Fully 'prosumer' oriented advanced business model design in a hybrid energy network environment	
Advanced business models are deployed for fully exploited hybrid energy network control and *active single and aggregated 'prosumer' integration* in the network operation, balancing and cost remuneration process.	Advanced business models have been developed and analyzed for future markets with a high share of active 'prosumers'. On the one hand, an increased share of 'prosumers' results in a lower residual load and, hence, less turnover for both, energy suppliers and distribution system

	operators. At the same time an increased feed-in to the electricity distribution grid by active customers is also challenging the grid, which may therefore require expensive reinforcements. With a hybrid approach and active costumer integration, e.g. with an aggregated cooperative control of certain devices, these issues can be tackled in a way, that most stakeholders can benefit. However, the economic incentives for 'prosumers' to participate in such business models are, in general, very low and depend very much on opportunity costs such as fuel prices, tariffs, network charges, etc.
Robustness test and sensitivity analyses of the key economic parameters determining the *advanced business model* in hybrid energy network environment.	Robustness tests of the key economic parameters have been conducted for the investigated business models. Approaches considering the replacement of one energy carrier by another are naturally very sensitive to different price development scenarios for the respective energy carriers. The profitability of business models revolving around energy efficiency measures and increasing the usage of RES surplus, on the other hand, depends on the relationship of the initial investment cost to the prices or tariffs of the fuel saved.
Impact: The investigated advanced business models for future markets turned out to be very sensitive to key economic input parameters. Hence, it is very important to analyze the effects of a novel business model implementation individually for each use case.	

2.2 STO 2: Adaptation of the existing monitoring systems for the fine-granulated energy network control operations

The work for STO2 aimed to look on different aspect of the monitoring systems building the energy as well as the contextual data, and to address it adaptation to support technical advantages of hybrid energy grids:

"*OrPHEuS especially targets the concept of Cooperative Control Strategies by exploiting the interconnected potential of hybrid grids with different spatial and time constrains for grid operation. The basis for a sophisticated level of cooperativeness in the operational strategy is the flexible composition of high level of detailed knowledge from autonomous system measurements as well as common contextual experiences which is brought together into fast variety of synergies to investigate on the combinatorial outcomes with respect to energy efficiency and sustainable replication in similar system configurations*." (DOW Section B1.1.1)

For this purpose, the following key aspects have been investigated:

- Integration of existing independent energy grid ICT systems as subsystems for future Smart City Operation Centers for the energy domain (Section 2.2.1)
- Evaluation of sophisticated level of meteorological information (Section 2.2.2)
- Comprehension of real-life data aggregation with virtual information (Section 2.2.3)

These objectives and their application have been explained in detail in deliverables of WP3. The following sections summarize the main results and discuss their impact related to the project targets.

2.2.1 IoT systems for smart cities

Compared to dedicated, domain-specific monitoring systems (e.g., for the Smart Grid), IoT systems for Smart Cities have the characteristic that they involve heterogeneous and large-scale data flows, which serve various applications that run on top of the collected data. Consequently, the most important new requirements relate to architectures of Smart City-wide IoT deployments (of sensors, GWs, servers etc.) that can satisfy all Use Cases (including hybrid energy control), as well as to efficient data filtering approaches, since the changing requirements of the running applications should now dynamically determine the amount, the quality, and the type of data that are relevant at each point in time.

While [3] has analysed "horizontal IoT platform architectures" with parallel gateways, and discussed how these should be deployed, managed, and used (based on examples from the hybrid energy grid domain), the main technological solutions contributed in this domain were the M2M (Machine-to-Machine) data filtering platform extensions and algorithms, presented in [4]. [5] investigated data filtering in a Smart City context based on data from the Skelleftea demo site, while it provided further ICT recommendations with regard to additional data sources and stream processing techniques that could enhance systems like the OrPHEuS M2M monitoring system.

Our data filtering solution (cf. [4]) was innovative in that it i) considers the reconstructability of the monitored data before it decides how to filter, ii) included real-time versions of data reduction algorithms which were initially developed to work only statically upon complete data sets, and iii) included middleware for fast instantiation of various data handlers close to the data sources.

Figure 1 summarizes both the way of operation and the main achievements of the developed solution:

- Way of operation:
    - Data that comes into the system in the form of a time series is reduced by a data handler which is lightweight, implements a specific reduction algorithm in real-time, and can be dynamically replaced by another handler. Further, "reconstructability" of the original data is taken into account for deciding which data to forward, i.e., which handlers to use and how/when.
- Main achievements:
    - Complex data reduction algorithms (which could previously be used only upon entire data sets) have been modified in order to be executed "per item" without delaying item forwarding more than a few milliseconds (cf. Nr. 1 in Figure 1).
    - Taking reconstructability into account has enabled us to achieve reconstructions of the original data sets achieving a similarity <90% while forwarding only 20-30% of the items (cf. Nr. 2 in Figure 1).
    - Flexibility and adjustability is enhanced by the fact that developers can choose their data handlers among a set of both simple and complex data handlers, which can serve different purposes (cf. Nr. 3 in Figure 1).

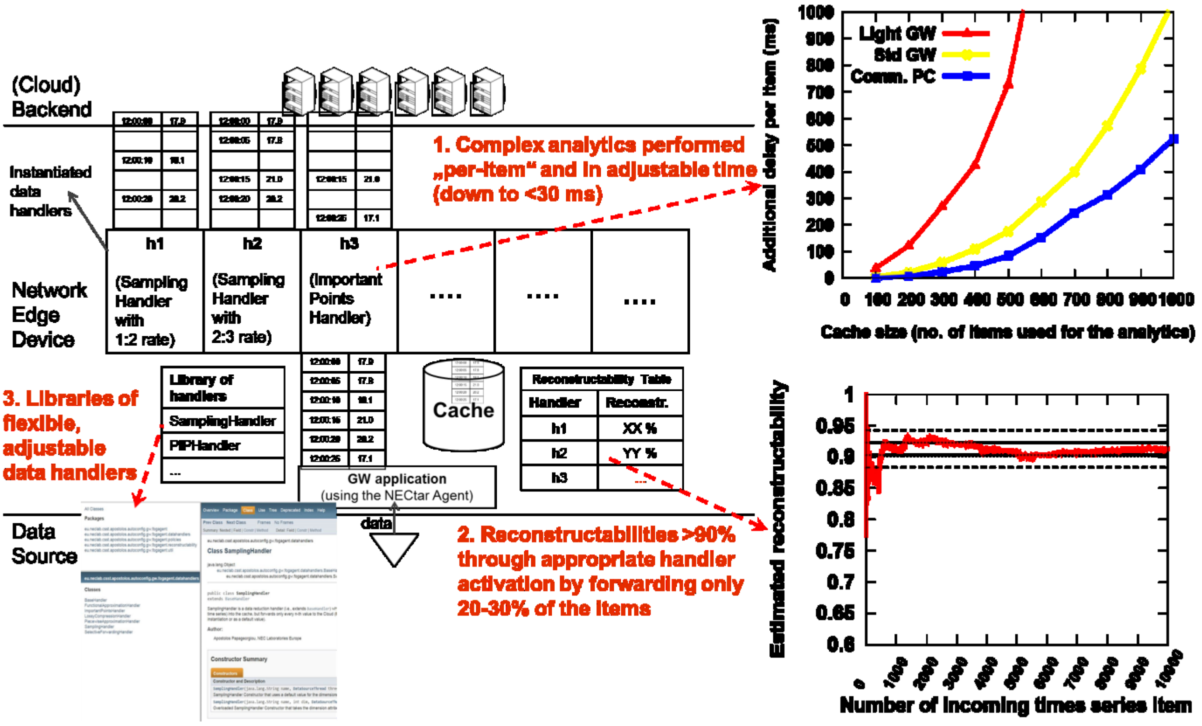

Figure 1: Summary of operation and achievements of the OrPHEuS data filtering solution

The following tables comprehend over the gained knowledge and its impact for replication:

<table>
<tr><th>Advances of the OrPHEuS project</th><th>Gained Knowledge and Impact</th></tr>
<tr><td colspan="2">Intelligent horizontal M2M data management architecture for Smart City</td></tr>
<tr><td>Current research and latest trends suggest a transition towards horizontal solutions, i.e., configurable M2M platforms with extended functionalities and flexible modules, which continuously and proactively maintain knowledge and control of the physical world, providing an API with which various types of new applications can be developed without the need of re-engineering the lower levels, addressing Smart City needs.

With the goal of serving an extensible and sustainable Smart City, architectural extensions <i><u>of horizontal M2M platforms to integrate configurable smart data filters for supporting the data management and control strategy</u></i> needs towards the suitability of different energy networks will be developed in the OrPHEuS project context.</td><td>By analyzing the existing monitoring infrastructure of the OrPHEuS demo sites, and comparing it to standard M2M platform architectures specified by standardization bodies, we have understood how the data required for smart energy control could come from a Smart City-wide IoT platform. This analysis has also given us hints about sensor and gateway deployments that could (as part of a Smart City platform) suffice to serve the needs of our Use Cases. From that point on, all our data filtering solutions have been developed in compliance with and can run on the envisioned “horizontal” architecture that we have described.</td></tr>
<tr><td colspan="2">Impact:

In order to successfully reduce costs by making use of data from other IoT monitoring systems and by re-using existing ICT systems, the “horizontalization” and auto-configuration mechanisms described for the OrPHEuS M2M platform (especially in [3] and [5]) have to be considered for replication across Europe (i.e., in other Smart Grid ICT infrastructures, but also ICT infrastructures of related Smart City domains).</td></tr>
<tr><td colspan="2">Technologies for lightweight M2M data filtering solutions</td></tr>
<tr><td>In OrPHEuS, smart data filtering solutions (in the form of compilation of modules and algorithms) that consider the peculiarities (memory, supported technologies, etc.) of M2M gateways and the architecture of modern horizontal M2M platforms will be developed. OrPHEuS project aims for a solution which, firstly, is more flexible in terms of the memory and processing resources that it consumes on a modern M2M gateway and, secondly, can support the achievement of better filtering results under certain circumstances, e.g., by enabling classes of filtering algorithms that would not be supported otherwise.</td><td>Especially with regard to building data filtering solutions that are “<i>more flexible in terms of the memory and processing resources that it consumes on a modern M2M gateway</i>”, we have developed a solution which - thanks to our <i>cache reduction</i> and <i>cache projection</i> mechanisms- can adjust the “processing time per data item” to the capabilities of the gateway on which the filter runs. Further, based on the concept of <i>reconstructability</i>, we have managed to achieve big load reductions with low information loss. However, “domain-agnostic” data filtering cannot always achieve the desired kind of data reduction, and therefore the limits of our work (e.g., the scenarios of [4]evaluations that do not achieve very high quality in the forwarded data) could work as indicators of when a domain-specific filtering logic is really required (if it is possible to apply it).</td></tr>
<tr><td colspan="2">Impact:

In order to successfully reduce ICT costs and network load along (future) IoT systems, the OrPHEuS reconstructability-based data filtering architecture and algorithms (presented mainly in [4]) have to be considered for replication across Europe.</td></tr>
</table>

Data filtering logic in multi-domain M2M platforms	
In OrPHEuS, solutions that are tailored to the energy application domain and/or to the broader Smart City concept will be investigated. These may be based on new, *Smart City-related classifications* of monitored information or on *domain-specific Quality-of-Information assessment* techniques, which will indicate how important/useful the monitored data can be for the different control systems.	The data filtering solutions discussed in the previous section are inherently built for multi-domain M2M platforms because they are based mainly on data reconstructability and not on domain-specific characteristics. Further, the examples of applying data filtering (and especially pre-aggregation) in data that is a mix of Skelleftea energy data with other Smart City data (cf. [5]) provide a roadmap and recommendations for the further investigation of multi-domain filtering logic.
Impact: In order to successfully keep the Quality-of-Information of energy-related data when it is collected, managed, and filtered by M2M platforms that serve other Smart City domains as well, the OrPHEuS data filtering logic and ICT recommendations (mainly [4]and [5]) have to be considered across Europe.	

2.2.2 Meteorological systems for hybrid energy grids

Meteorological information is a crucial part of a contextual evaluation for control strategies. Existing methods were aimed for investigation with respect to (DOW, section B1.2.2):

- Demand analysis of the multi-utility energy grid operations for specific meteorological data and evaluation of sophisticated level and/or sources of meteorological information for the fine-granulated energy network control operations;
- Definition and assessment of the appropriate weather forecast methods with respect to high temporal and spatial resolution requirements needed. Evaluation of data accuracy increase by using ground station supported calculation methods.

The following tables comprehend over the gained knowledge and its impact for replication:

Advances of the OrPHEuS project	Gained Knowledge and Impact
Demand analysis of the multi-utility energy grid operations for specific meteorological data	
OrPHEuS will increase the understanding of the needs of the energy sectors and invest in respective research and development of new methods, tools and services especially for energy system stakeholders as well as a improved *knowledge of the energy sectors for the background, physics and limits of the delivered meteorological data*.	The meteorological sector got information about: ○ Typical meteorological situations being relevant for the two use cases Ulm and Skelleftea. These were identified based on a stakeholder analysis and a user system description. ○ An overview of meteorological parameters required in various use cases was elaborated. ○ Specifications on temporal and spatial resolutions for various use cases were elaborated. It was found that using advanced meteorological forecasts is blocked by a large gap in understanding of meteorological information and how it is generated. Different languages, unavailability of data handling tools, or without expert knowledge not accessible/understandable information in the meteorological sector turned out to be blocking the uptake of meteorological information more than expected.

During the project, the non-meteorological sector gained specifically prepared

- Knowledge how to perform high quality meteorological measurements was transferred to the utility sector.

Figure 2: Implemented environmental measurement stations for measuring the radiation in a) Alt Plestlin, b) Böken, and c) Sassen.

- Additional information and practical guidance on how to obtain, to use, and to interpret meteorological forecasts. Such 'how-to' knowledge was transferred to both the system simulation developers and to the utility sector.
- Example datasets were provided for the project activities.

This enables the non-meteorological sector to have access to enhanced meteorological forecast products.

Impact:

In order to successfully make use of project results across Europe the following issues have to be taken into account:

- Generally, experts working at the interface of both meteorological and energy system 'worlds' have to be trained. Recently started lectures e.g. on energy meteorology for training meteorology students are a reaction on this need. Such training should be made available in all EC member states both for students and practitioners in both the meteorological and the utility and energy system analysis sector.

Practical guidance with respect to using the ECMWF weather forecast model can be applied across Europe without modification. Knowledge on SMHI based forecasts can be applied in those countries, where the meteorological services are part of the HARMONIE/HIRLAM/ALADIN model developer group. These are countries in Scandinavia, The Netherlands, France, Spain/Portugal, and several countries in Eastern Europe. Knowledge on DWD based forecasts can be applied in the countries participating in the COSMO model developer group. These are mainly Germany, Italy, Austria, and Switzerland. Some Eastern European countries also make use of the COSMO model suite.

Assessment of the appropriate weather forecast methods

OrPHEuS will perform investigation and will conclude recommendations of the today's *weather forecast systems for the*	A gap analysis motivated the following results. A detailed analysis on how to use satellite-based irradiances for the voltage modeling in a distribution grid with large solar shares. Results are published already in an open access journal (Ruf et al., 2016, Solar Energy). HS Ulm has now a system being capable to calculate voltage

issues of hybrid energy grids. This involves the analysis of the *available forecast values, resolution and accuracy from the point of view of a hybrid energy grid stakeholder*.

OrPHEuS will provide the assessment *meteorological data services as input to the contextual observations* as a crucial cornerstone for cooperative control strategies for the hybrid energy grids.

flows at the transformer level based on satellite-based observations or numerical weather predictions.

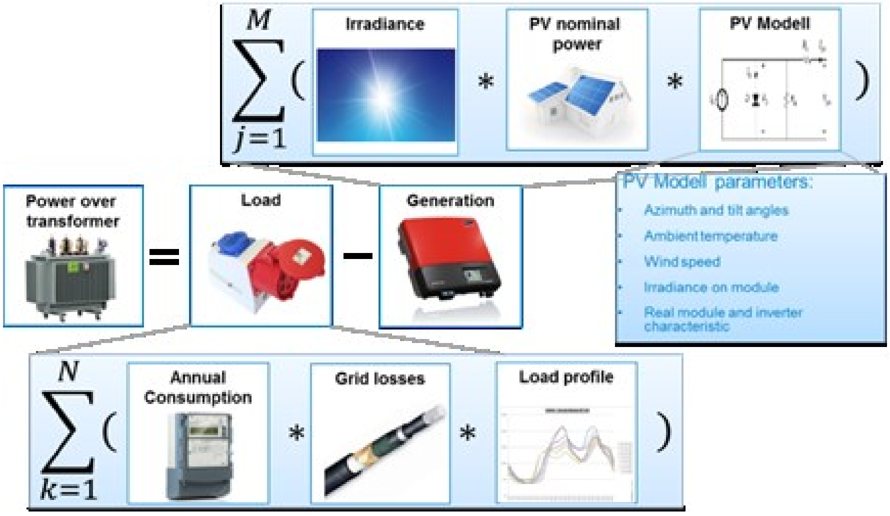

Figure 3: Visualization of the Calculation approach for the power flow calculation over the transformer

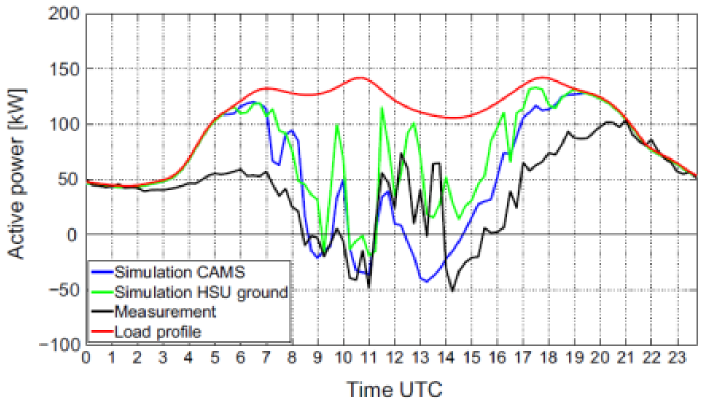

Figure 4: Combination of simulated PV feed-in power and assumed standard load profile on 3rd August 2012 compared with measurements at the transformer. Simulated active power based on satellite-based irradiance observations (blue) and on ground observations (green) and the measurement (black) are shown together with the standard load profile (red).

The satellite-based nowcasting as used for direct irradiances and for large-scale solar power plants could not be successfully transferred yet. The consortium will continue to work on this, but no final solution was found within Orpheus.

Forecast quality assessment with respect to global irradiances as provided by the Deutsche Wetterdienst for Ulm.

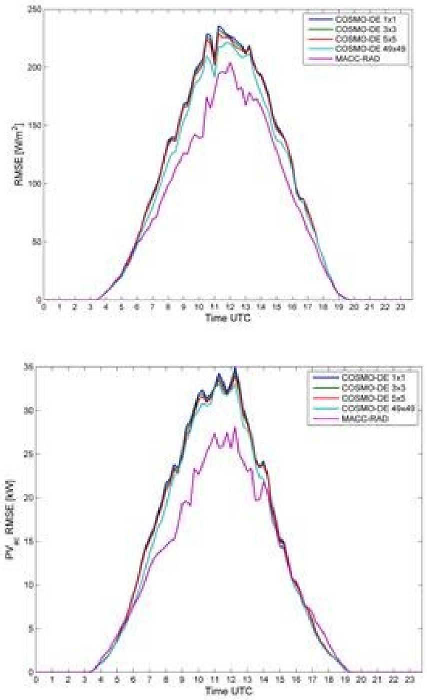

Figure 5: Comparison of COSMO-DE based GHI RMSE vs. measured GHI RMSE at the HS Ulm location (upper) and for the feed-in power (lower panel)

A quantification of variability parameters and temporal distribution of various cloud conditions relevant for a distribution grid with large solar shares.

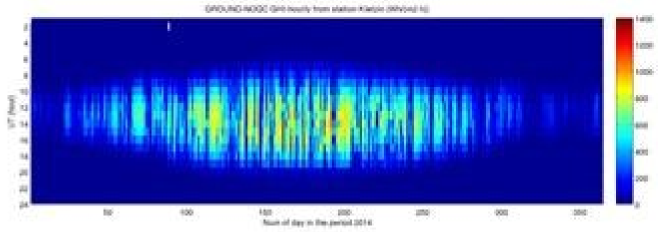

Figure 6: Global horizontal irradiance observations as taken in 2014 at Kletzin (DEMMIN site).

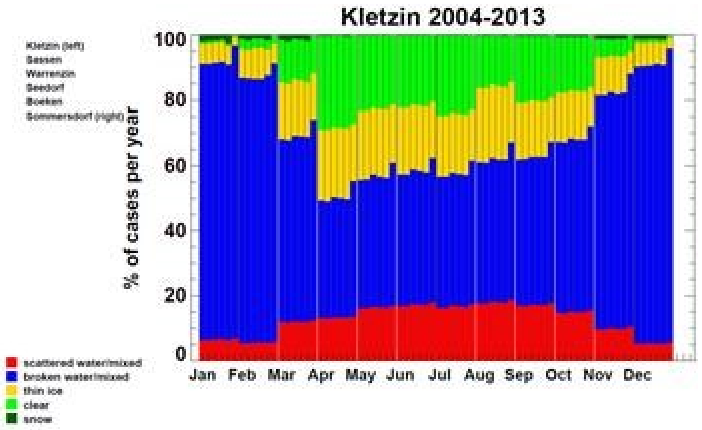

Figure 7: Number distribution of scattered/broken/thin ice/clear and clear+snow conditions at DEMMIN sites Sassen, Warrenzin, Seedorf, Boeken, Sommersdorf with Kletzin as the reference (left) and over the month of the

year.

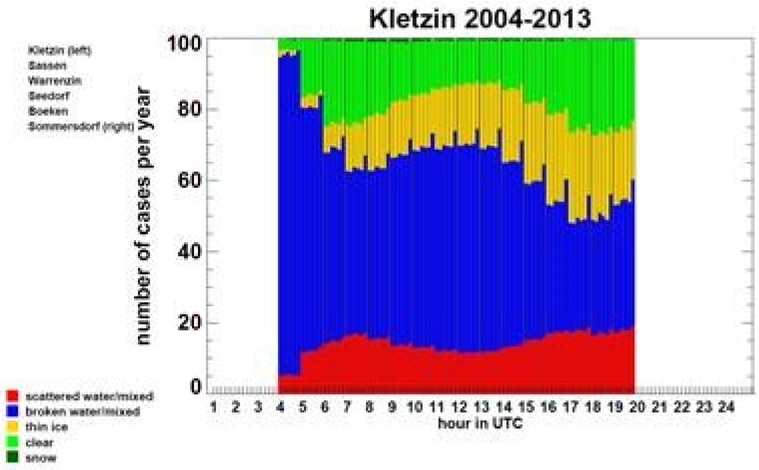

Figure 8: Number distribution of scattered/broken/thin ice/clear and clear+snow conditions at DEMMIN sites Sassen, Warrenzin, Seedorf, Boeken, Sommersdorf with Kletzin as the reference (left) and over the time of the day.

An analysis of temperature weather forecast errors being used for heat demand modeling. Dependencies of heat demand on temperature are certainly dominant and can be used for a control strategy from November to December and again from February to April. In April the dependency has a different structure than in other months. In January, a pure temperature based forecast is not sufficient to explain heat demand - a second strong dependency on relative humidity is found. Relative humidity is used as indicator to identify cloudy and humid conditions (e.g. fog) where the surface is covered like a ‘feather bed’ and the pure temperature forecast is not sufficient for heat demand control.

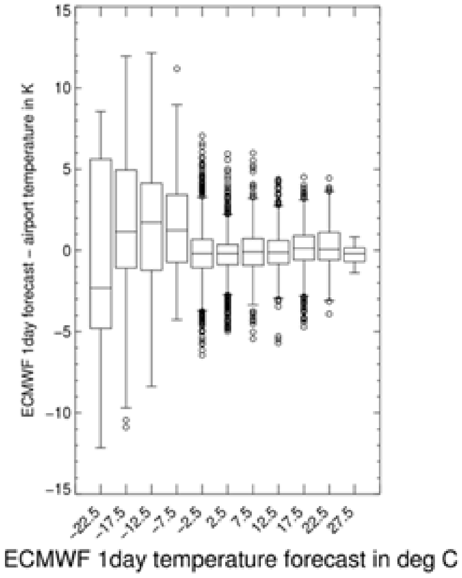

Figure 9. Differences between ECMWF day 1 temperature forecast and measured temperature at Skellefteå airport as function of the forecasted temperature itself.

Recommendations on additional meteorological information needed for different use cases were given based on project results.

Impact:

In order to successfully make use of project results across Europe the following issues have to be taken into account:

- By intention the work in this project used the ECMWF weather forecast widely as it is available on the global scale. Therefore, the used evaluation strategies are applicable worldwide without major modifications. The same applies for the suggested usage strategies in system simulations. Nevertheless, any results concerning the accuracy need to be repeated for the region of interest as the weather has various dominant structures in different regions. Therefore, accuracy findings are not generally transferrable without further local/regional confirmation.

Satellite-based information used in the Ulm case is available up to 60° North. Further in the North, the methods need to be transferred to the evaluation of other, already existing satellite instrumentation on a polar orbit. This is feasible, but an extra effort and the frequency of observations will be still lower than from the geostationary orbit as used in Ulm. On the other hand, the spatial resolution of the observations is higher in this configuration.

2.2.3 Integrating virtual and real-life measurements

With regard to STO, the integration of virtual and real-life measurements investigated on the following aspects:

Assessment of real-life measurements

Grid Planning

For effective grid planning in low voltage grids it is important to know the maximal power of every PV-system. To calculate the maximum PV-power several simulation tools are available. Necessary input parameters for all tools are the nominal power, module efficiency, the solar irradiation and the maximum power of the inverter. The nominal power and efficiency of the PV-module and the maximum power of the inverter are available on the data sheet of the PV-system. Therefore it is important that grid operators collect this information during the registration of a PV-system. For the solar irradiation several sources are available. The investigations during the Orpheus project show that satellite irradiation information are sufficient for grid planning. On cloudless days the calculation models of the meteorological companies are very precise. In Figure 10 for example the results for the validation of CAMS for one weather station located in Lindenberg is shown. A detailed validation of satellite irradiation data was done by HSU. Therefore the data, provided by CAMS radiation services, are used and validated against the values of 34 DWD weather stations located in Germany. The irradiation data at CAMS are available since 2004. So it is possible to figure out the maximal irradiation of the last 12 year for every location in Europe and resultant the maximum power of a PV-system. Opportunities are Heliosat 2, CM SAF and OSI SAF. The irradiation data from this several services are free of charge.

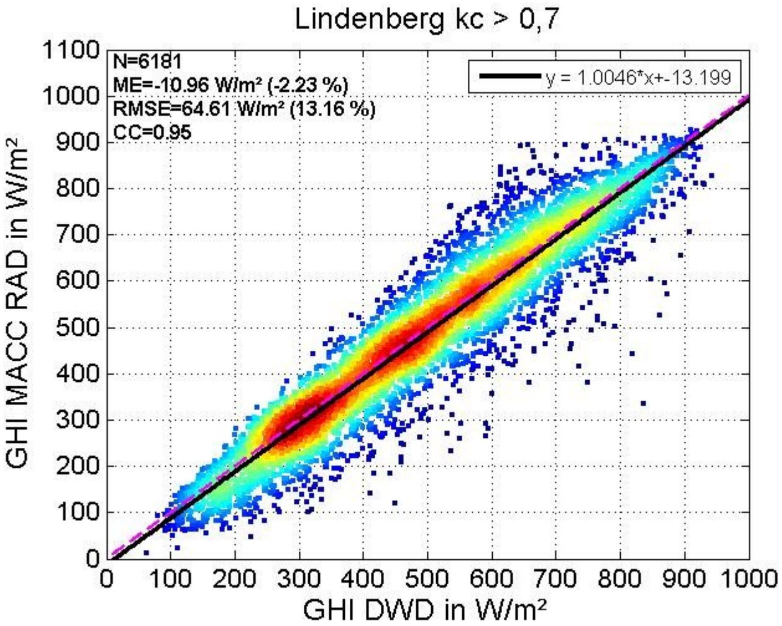

Figure 10. Scatter Plot for satellite GHI against measured GHI for the station located in Lindenberg with a clear sky index higher than 0.7.

Grid operation

In the past grid simulations were not necessary for a distribution grid operator (DSO). Companies with a high demand were bounded to give “demand timetables”. For the households are standard load profiles exist and in combination with the yearly energy demand this procedure is very accurate. Only when new houses were built a load flow calculation was done by hand to figure out the maximum voltage drop inside one feeder for maximum load times. Nowadays with the PV-systems the situation changed and becomes more and more complex. Therefore it is necessary to do detailed grid simulations to know the voltage at all nodes and the utilization of cables and transformers. The satellite based solar irradiation data are not available in real time. The opportunities for the DSO are operation of weather stations by their own or the assignment of weather services. For the operation of own operating weather stations the DSO has installation, operation (data transmission) and maintenance costs. In addition training for the employees is required to work with the new equipment. Also it is necessary to process the data from the weather stations and simulate the PV-systems. For a DSO it makes sense to assign a weather service with this task. They have a lot of experience with the process of weather data and the simulation of PV-systems. Secondary it is helpful for a DSO to buy forecasts of the feed-in from PV-systems. This is helpful for an efficient grid operation because with the knowledge about upcoming surplus the DSO has time to react; for example like for Scenario 2 with a connection to the district heating network. So the DSO can reduce the power production from the CHP for using cheap electric power and save fossil fuels.

Asset Management

In the past the electrical grid was constructed with reserve assets and the normal utilization of transformers and cables were only 20 – 30 % of the nominal power. In areas with high PV-penetration the situation changed. The high PV-surplus on cloudless days raises the utilization of the transformers and cables. This could lead to a decreasing lifetime of the equipment. Therefore it is useful to use temperature simulation models for transformers and cables. In combination with satellite irradiance data it is possible to simulate the PV-influence on the lifetime for more than 10 years in the past (limitation is only the available meteorological data).

The following table comprehends over the gained knowledge and its impact for replication:

Advances of the OrPHEuS project	**Gained Knowledge and Impact**
Assessment of real-life measurements	
OrPHEuS will perform investigation of available measurement systems, reuse of existing measurement systems and stimulate *recommendations of needed values for operating different configurations for hybrid energy systems*. Descriptions of the degree of priority for measurement values in different stages of operation modes depending to the nominal levels are planned. Further the OrPHEuS project will aim for the definition of *necessary parameters, time resolution and accuracy for operating a hybrid energy grid*.	For the OrPHEuS project several measurement systems were analyzed for the electrical, heat and gas network. **Electrical grid**: Satellite based solar irradiation data are suitable for the grid planning and asset management but not for grid operation. For the grid operation weather stations in combination with PV-simulation software are necessary for the actual PV-feed in to the electrical grid. An alternative is to buy weather data from companies like DWD, Meteocontrol, Meteoblue, etc. In addition power measurements at the transformer stations are a good assistance for grid operation. In addition, they required to know the local surplus for a transmission into the other grids like district heat network or the gas grid. **District heating grid**: The operation of a district heating network is quite simple coopered to the electrical grid. There it is only necessary to measure the temperature and volume flow at the CHPs. But if distributed energy transmission from the electrical grid is done, the temperature and volume flow at the feed in point have to be measured also for the control unit. A simulation model help to plan and operate a district heating network using decentral power to heat feed-in because conventional planning an operation approaches getting more and more unprecise. **Gas grid**: For the operation of a gas grid it is necessary to measure the pressure and the volume flow at all transmission stations. If a power to gas system is used also a measurement of pressure and volume flow at the feed in point is necessary. In addition the hydrogen concentration after the conditioning process is required. This information is important for the control unit. In the field of gas is a simulation model also (like the district heating network) an important tool to retract on the chancing conditions on operation and planning.
Impact: In order to successfully operate hybrid energy grids, planning and operation need different aspects of virtual and real-life measurements. For the power grid details, satellite-based data enhance the grid planning and asset management. Operation however gains detailed transformer grid measurements comprehended with PV-simulation models. Building up for the hybrid energy grid, the Power-to X attached grid operation can be fully based on intrinsic system data of the attached grid (X: heat or gas).However for the planning, the usage of simulation models greatly helps in the definition of the hybrid coupling and its interaction with the power grid. Therefore, for successfully applying hybrid grids, the combination of virtual and real-life measurements -- carefully adapted to the regional conditions (e.g. availability of renewable energies, its penetration distribution) and link to existing grid infrastructure -- has to be considered for replication across Europe.	

Cost efficiency through combination of measurements and simulated values

Decentral energy generation causes new details of technical parameter of energy grids in cities. OrPHEuS covers hybrid grid approaches paired with new business models. To evaluate the cost efficiency of the combination of measured and simulated values a cost baseline is necessary. This baseline will be delivered by the costs for state-of-the-art measurement devices in distribution grids which are necessary to deliver the same density of data like the OrPHEuS approach. The validation of the simulated results delivers the needed backbone to evaluate the utility of the resulting data.

Real measurements can deliver more precise data than simulation. However, this is difficult to quantify in money in the context of cost efficiency. Therefore, this point will be excluded for investigate the cost efficiency. All costs calculated for 15 years, because that time is the DSO assumed average lifetime of a smart meter device. Ongoing costs over the 15 years period for all cost factors are also considered.

Following cost factors considered for the OrPHEuS approach:

- Measurement devices: Developed measurement boxes (HSU), weather station, several smart meter at PV-systems
- Software: PowerFactory (electrical grid), STANET (gas grid), Dymola (district heating network)
- Commercial data: Weather data

Following cost factors considered for the baseline (measurement) approach

- Smart meter for each household
- Smart meter gateway for each house
- BSI[1] conform data transmission channel for each household
- Updates in the grid operation center (data base, communication, transmission)

The following table comprehends over the gained knowledge and its impact for replication:

<table>
<tr><th colspan="2">Cost efficiency through combination of measurements and simulated values</th></tr>
<tr><td>OrPHEuS will provide a novel means for addressing cost efficiency with respect to installations of distributed measurement devices (limitations in quantitative rollout and qualitative rollout (esp. spatial resolution) by the combination of real measurements with simulated “virtual” measurements. High-accuracy simulations are performed in order to conclude the definition of critical grid nodes in hybrid energy grids which shall measure in real-file mode and which shall be comprehended by accompanied virtual measurements through system modelling and simulation.</td><td>Cost efficiency was evaluated based on a funded database. For the cost baseline as well as the OrPHEuS approach cost efficiency is given. However, the cost efficiency was high enough (232% at Einsingen and 125% at Hittistetten) to deductive reasoning that there are high potential for cost reduction.</td></tr>
<tr><td colspan="2">Impact:
Replication on cost efficiency is rather difficult. Reasons are that prices for smart meter are still under development and under pressure from the e.g. German governance. In addition, ongoing prototyping or research solutions (computing and hardware) still make any cost estimation difficult to assume.</td></tr>
</table>

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[1] BSI - Bundesamt für Sicherheit in der Informationstechnik (engl. German Federal Office for Information Security)

2.3 STO 3: Fine-grain hybrid energy network modeling of cities' Hybrid Energy Networks

Extended simulation capabilities have been a crucial point for the evaluation of the Cooperative Control Strategies and the investigations of requirements and suitability of technology combinations for future investments in today's and future energy system landscape.

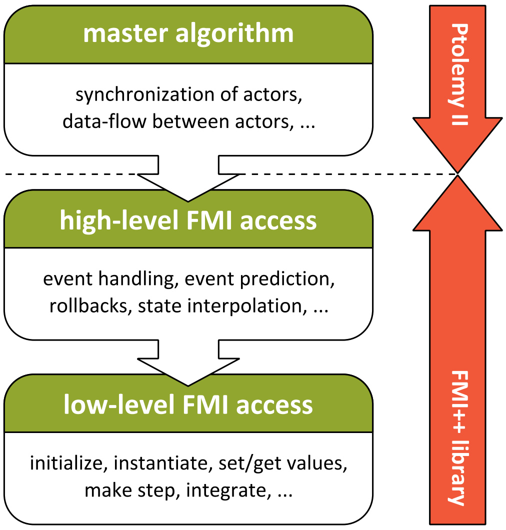
The prerequisite for a wholesale model-based evaluation of hybrid system solutions is the detailed simulation of not only the individual subsystems but also their dynamic interactions. Beyond the state-of-the-art simulation tools have been developed well suited for modeling and simulating hybrid energy systems that integrate subsystems across the borders of traditional engineering domains. The chosen solution to this challenge is co-simulation, coupling the existing domain-specific state-of-the-art tools (Modelica for the thermal domain and DIgSILENT PowerFactory for the electrical domain) in a way that enables a dynamic multi-physics simulation of the hybrid system.

By basing the co-simulation framework on the de-facto standard introduced by the *Functional Mock-up Interface* (FMI) specification, the corresponding software developed within the OrPHEuS project is highly re-usable for follow-up projects, ensuring a sustainable development.

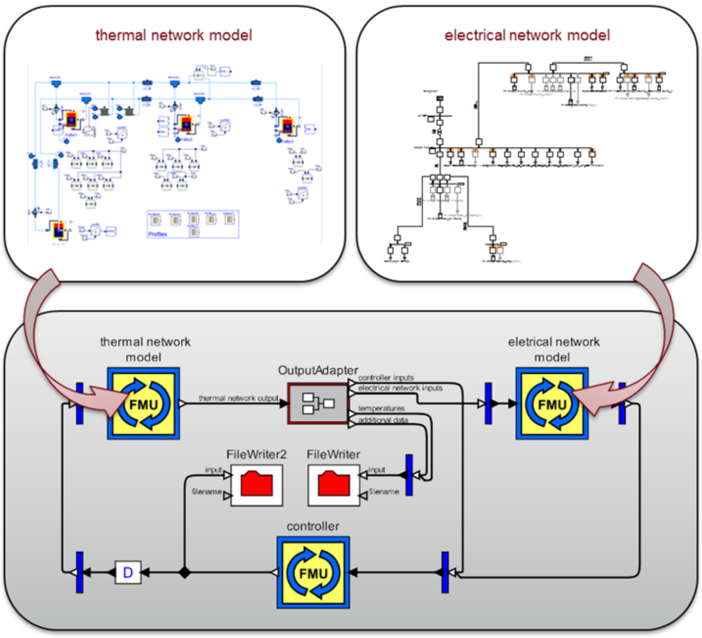
For the effective and convenient handling of FMI-conformant simulation components the *FMI++ library* (an open-source software utility library developed at the AIT) has been further developed, builds upon the FMI specification and implements high-level features that facilitate the integration of both models and tools as standalone components within a simulation framework.

A crucial functionality of each co-simulation environment is its capability to orchestrate the execution and data flow of the individual components. The framework used for the purpose of the OrPHEuS project is developed on top of *Ptolemy II* and the *FMI++ library*.

The concurrent processes are represented by *actors*, while their interaction, i.e. their data exchange and order of execution, is governed by *directors*. For the purpose of the co-simulation framework presented here, Ptolemy II is used to coordinate the execution of FMI-compliant models and tools and the data flow between them:



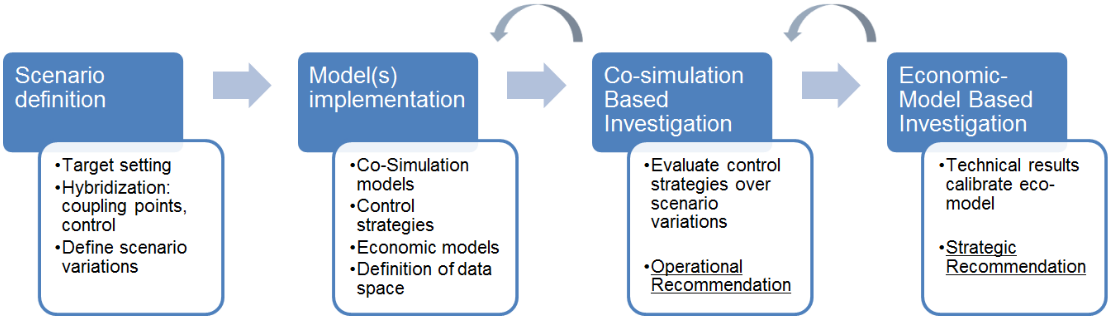
The following table comprehends over the gained knowledge and its impact for replication:

<table>
<tr><th>Advances of the OrPHEuS project</th><th>Gained Knowledge and Impact</th></tr>
<tr><td colspan="2">**Advanced fine-granulated level of multi-domain system modelling**</td></tr>
<tr><td>OrPHEuS will *extend and advance the use of existing energy grid simulation environments with fine-granulated level of multi domain system modeling* (e.g. electricity, heat, gas), breaking off system abstractions to a defined accuracy level in order to enable the *development and validation of grained control strategies on grid coupling points and important grid nodes*.</td><td>The integrated deployment of state-of-the-art modeling approaches for the individual domains (electricity, heat, gas) with the help of a co-simulation approach facilitates the assessment of dynamic interactions in hybrid energy systems. As such it provides a handle on investigating the potential synergies of hybrid grid operation approaches in detail.</td></tr>
<tr><td colspan="2">**Impact:**
In order to successfully overcome technical challenges related to the implementation of control strategies for multi-carrier energy systems, more emphasis has to be put on introducing methods and tools for the evaluation of multi-domain energy systems (including controls). Approaches like co-simulation are already today mature enough to provide useful results. However, more development and dissemination of these tools and methods is needed to reach the technology readiness level required to be usable in the context of industrial applications. The methods and tools used and developed in the OrPHEuS project are a good basis in this context.

</td></tr>
<tr><td colspan="2">**Advanced consideration of different time horizons and time operational needs**</td></tr>
<tr><td>OrPHEuS will *enhance the simulation granularity levels for the investigation of different time horizons and time operational needs* through prediction technologies and</td><td>The simulation-based evaluation of control strategies in the OrPHEuS project relies on two complementary approaches:</td></tr>
</table>

simulation of energy network systems by integrating multi domain energy supply and demand technologies, network technologies and infrastructure means (various energy domains, network levels, network topologies and time resolution), *enabling the simulation for planning and operation of interactive energy networks.*	1. detailed technical simulations (electricity, heat, gas) of the hybrid energy networks with high time resolution, enabling an assessment of control strategies regarding operational aspects (e.g., network stability, energy savings) 2. economical simulations with coarser time-resolution but over longer periods, enabling an assessment of control strategies regarding planning aspects (e.g., business models, return of investment) This complementary approach gives an elaborate overview of the impact of innovative control strategies, both from an operational and a planning perspective. When assessing the feasibility of a potential implementation, this allows addressing a broad spectrum of stakeholders and facilitates the decision process.

Impact:

For the successful implementation of multi-carrier energy systems a holistic assessment process is needed, which goes beyond the limits of traditional engineering domains. Like for the case of the technical evaluation, this needs more development and dissemination of the corresponding tools and methods in order to reach the required technology readiness level. The methods and tools used and developed in the OrPHEuS project are a good basis in this context.



2.4 STO 4: Cooperative Control Strategies for cities' Hybrid Energy Networks

In order to investigate control strategies for hybrid grids, several scenarios have been discussed and analyzed. In the course of the project, basic and advanced scenarios for city of Skellefteå and Ulm have been described and deployed over the simulation environment. The holistic investigation process employed within the project is a highly interactive activity between WP5 (control strategy development), WP4 (hybrid grid simulation development), and WP2 (economic and business modeling).

Concepts considered included e.g. studies for replacement of energy sources (e.g. replacement of oil boilers), modifications to current infrastructure (e.g. location of additional boilers and/or storages), addition and/or modifications to space heating opportunities, up to further future concepts for modifications to the ensemble of the producers and consumers to an extended hybrid grid. Details to the scenarios are provided in [6] and [7].

The following table comprehends over the gained knowledge and its impact for replication:

Advances of the OrPHEuS project	**Gained Knowledge and Impact**
Leveraging sophisticated ICT for efficient control by utilizing the knowledge across multiple linked energy systems	
Respecting the value but also limits of the grid-coupling points (e.g. CHP), the autonomous, self-driven system control strategies of each *independent energy system will be reconsidered*, and a *synergetic approach utilizing the interaction potential will be built into the control strategies*. This will result in a holistic view of the full energy landscape for a given geographical location and allow planning perspective for the region. Domain specific topologies, operational requirements, and data handling will be lead together into a *holistically managed data provisioning for the OrPHEuS Control Strategy Design layer*. Crucial parts addressed in this data aggregation process is the sophisticated metering via M2M ICT system, it's comprehension with simulation based virtual measurements, and integration with contextual observations (specifically meteorological information). Via the continuously designed knowledge enhancement process, OrPHEuS will *define the requirements on the ICT systems (metering as well as context)* and *on the simulation environment* in order to enable the deployment on the Cooperative Control Strategies targets.	The control strategies realized for all studied scenarios use control not only over the direct coupling point, but also include the energy generation and storage facilities in order to achieve a holistic optimization. In the case of the Ulm target site, the control is directing the electric boilers (coupling points) and thermal storages (see [6], chapter 2.1), while for the Skellefteå target site all thermal generation resources as well as the thermal storage are controlled in addition to the coupling points (electric heater, CHP; see [6], chapter 4.2) A regional planning perspective has been taken into account by running simulations for several alternative coupling point configurations, determining the optimal ones (see [6], chapter 5.3.2). Various sources of context data have been taken into account, including both sensor information about the electricity network state and forecasts about energy demands in the future. In a range of experiments it has been investigated to which extent such additional data improves the quality of the control; see e.g. [6], chapter 5.4, where the results indicate that limited local sensors information is often enough.

<table>
<tr><td colspan="2">Impact:
In order to successfully deploy hybrid energy solutions, a careful consideration of the tradeoffs between cost and benefit of the necessary sensor installations is advisable. More data does not automatically mean better control, although certain context data has shown to be helpful in determining the right control at any moment. These trade-offs have to be considered for replication across Europe.</td></tr>
<tr><td colspan="2">De-centralized Control Strategies respecting specifics of individual energy systems and their coupling points</td></tr>
<tr><td>While utilizing a more fine-granulated measurement scheme in the individual energy grids and the observations of the grid-coupling points, <i>de-centralized control strategies</i> can be built upon <i>the interconnection topologies</i> of physically linked energy systems. By accessing this knowledge, OrPHEuS will develop new control strategies providing synergy controllability for the emerging clusters around the nodes of installed grid coupling points, and will enable a new level of energy efficiency across energy systems. Local specific situation in the grids as well as contextual environment can by synergistically approached and taken to local advantage.</td><td>On the target site of ULM every building has been realizing an individual coupling point between the electricity domain and the heating domain. Within the OrPHEuS project several degrees of centralization have been experimented with, ranging from greedy self-usage paradigms to completely centralized control. The experiments demonstrate that a certain degree of centralization is helpful to improve the overall efficiency, but a loose coordination is sufficient; see e.g. [6] (chapter 5.3.4, Figure 50) for details.</td></tr>
<tr><td colspan="2">Impact:
In order to successfully deploy hybrid energy solutions with multiple coupling points, a certain degree of coordination and mutual support has turned out beneficial for all involved stakeholders. But also the fact that complete centralized control does not guarantee the highest efficiencies has to be considered for replication across Europe.</td></tr>
<tr><td colspan="2">Optimal simultaneous control for multiple grid</td></tr>
<tr><td>OrPHEuS will define novel algorithms for fine-grain control decisions capable of load balancing by optimizing multiple utilities demand and supply across multiple grids, <i>respecting independent operational needs and interactive operational control</i> and energy storage opportunities (e.g. CHP, electrical and thermal storage, buildings as storage and thermal operational mass) . Especially, characteristics in advantages and boundaries of the grid coupling points link to high variety of control opportunities that need to be considered by novel control algorithms.</td><td>The benefits and limits of hybridization in several scenarios with multiple utilities demand and supply have been studied in extensive simulation-based experiments. More specifically, the main findings are
o Connecting domestic hot water systems with the local electricity grid has the potential to decrease the usage of heating oil by up to 90%, replacing it by electricity locally generated during peak generation hours.
o Conversely, for areas with high penetration with photovoltaics, the energy needs of domestic hot water systems are not sufficient to consume all local surplus.
o In district heating networks, the usage of oil heating for covering peak demands can be nearly</td></tr>
</table>

	completely avoided by making use of the electricity network, saving cost during operation. Saving cost has turned out to be economically compatible with the objective to reduce oil usage; see [6] (chapter 4.3.2, questions 3 and 4). o With regard to storage facilities, our studies show that a careful dimensioning, taking into account a trade-off between economic and ecologic considerations, is necessary. In particular, the experiments show for the scenario under consideration that, while a larger storage increases flexibility and thus decreases the peak loads to be served using oil heating, economic considerations suggest using smaller storages.
Impact: In order to successfully deploy hybrid energy grids, the dimensioning of devices for coupling needs to be studied in order to make the correct selection. In the selection process also the relative priorities with regard to economic aspects and ecologic ones have to be considered for replication across Europe.	
Cooperativeness of Control Strategies	
Bringing together the intelligence gathered in the M2M infrastructure utilizing “Smart Energy Grid systems” with the new contextual experiences, OrPHEuS allows a new level of collateral observations simultaneously in different energy systems. Exploiting this accumulated wisdom, *Cooperativeness of the new control strategies* will be introduced into the control schemes of previously un-linked or independently operated systems. Especially, OrPHEuS will challenge the methods of cooperative control addressing novel schemes needed to provide *cooperativeness to non-identical system segments* and addressing spatially fixed but possibly time—varying interconnection topology. These strategies will then naturally *turn into control design aimed for the targeted outcome of the strategy* rather than the procedural strategies. This is the base concept for a *cooperative control* strategy concept.	All control strategies developed by the project are cooperative in the sense that they target mutual benefits of the involved grids. The interconnection points are operated in a controlled manner, making the inter-grid energy exchange dependent on the supply and demand patterns of both grids and taking into account sensor and meteorological data. Economic studies have been conducted to verify that these technical benefits are economically sustainable and have viable business models.
Impact: In order to successfully deploy energy network hybridization, both technical viability – using the right control strategies - and economic sustainability for all involved stakeholders have to be considered for replication across Europe.	

3 Recommendations

3.1 Focus point: Technical replication and transferability potential on wider European scale

3.1.1 Recommendations for Cooperative Control Strategies for cities' Hybrid Energy Networks across Demo sites and on European scale

The OrPHEuS project has studied five main energy hybridization scenarios for two target sites, each with a range of variations in terms of energy demand, supply, prices, and device configurations. Control strategies have been designed in a way that each control strategy would be applicable to all variations of one particular scenario. In the following paragraphs we summarize the experiences from control strategy design and evaluation in the form of recommendations.

When designing control strategies for a particular scenario, a number of **aspects of the scenario** have to be taken into account. The first question is:

> *What are the controllable coupling points?*

In [8] we have given a categorization of coupling points (CP). First-order CPs directly transfer energy from one grid to another. Second-order CPs are devices which indirectly transfer energy by being able to supply energy to multiple grids, or by being able to satisfy their energy demand from multiple grids. Finally, third-order coupling points are energy producers or consumers that are connected to only one grid but still offer some amount of controllability, and so operating them in combination with a first- or second-order CP can still influence other grids. Coupling points of each of these categories should be considered to be included into the control approach for a given scenario. As shown in [8], we have experimented with coupling points of all categories in the OrPHEuS project.

Having identified the coupling points, the next question is:

> *What level of control do the coupling points offer?*

Some coupling points only admit on/off control, while others expose one or more continuous control variables that enables the controller to realize fine-grained control over how much energy is transferred between the grids, or how much energy from which grid is produced or consumed. Coupling points often also have some dynamicity constraints, restricting the velocity of changing the input and output. Typically – and this was also the case in the OrPHEuS scenarios – large-scale devices offer more fine-grained control than smaller devices. In situations like the Ulm present-day scenarios, where the coupling points were small-scale devices on the consumer side, the required fine grained control was not on these individual devices. However, due to the large numbers of such devices the control strategies were able to carefully switch on or off some smaller or larger subset of coupling points, thus still having fine-grained control with regard to the aggregated behavior and the overall effects on the electricity grid.

The next question regarding the coupling points is:

> *What are stateful parts of the setup?*

Stateful system parts are those where control actions conducted at some time have an effect not only on the immediate future state, but on a whole time horizon in the future. Stateful system parts need the control strategy to plan ahead; possibly not only acting to optimize the current state, but also to consider the future. In the OrPHEuS scenarios stateful system parts were storages and large coupling points with limited dynamicity like e.g. a biomass boiler having a long ramp-up time.

Another relevant question is related to the quantities of coupling points:

How large and complex is the hybrid setup?

The scale and complexity of the system has an impact on the applicable control strategies. For example, centralized controller modules can become a bottleneck or even a single-point-of-failure in very large systems. In the OrPHEuS project the scale of the systems addressed has not been prohibitively large, but [8] contains an analysis and recommendations regarding the scalability of the applied control approaches.

The final question to analyze is:

What are the control targets?

The main selling point for hybridization is that multiple grids will experience a benefit from the interconnection. This already hints at the fact that typically there is more than a single control target. In some cases – especially when a single stakeholder owns the entire infrastructure – a single target like cost minimization or CO2 reduction can be applied. The other extreme are cases where hybridization takes place at the consumer side, and then each individual consumer needs to have a benefit of some sort. In OrPHEuS we had both extremes occurring in our scenarios. In the technical simulations we have in many cases simply assumed a cooperative behavior of the coupling points, leaving the design of suitable incentive models to business development and analysis. However, we have also experimented with control strategies with self-optimizing coupling points (see below for a discussion), and each of the control strategies had several KPIs that were taken into account in the design phase and which were evaluated in the experiments.

Having analyzed the scenario at hand according to the above questions, the designer of the control strategies is able to take decisions regarding a number of control aspects. In [8] these aspects have been identified as controller architecture, cooperativeness, and data usage.

Cooperativeness of control strategies have been proposed by the OrPHEuS project from the very beginning. Indeed, our hybridization setups with consumer-side coupling points have shown that the cooperative strategies Control-2 and Control-3 had a clear advantage over the strategy Control-1, where the individual households targeted at consuming only their own energy surplus from PV production (see [6] for details).

The **controller architecture** aspect relates to the individual control modules and their interconnection. On one extreme end of the spectrum there is *centralized control* where a single control module receives all relevant real-time and predictive data, takes decisions for each of the coupling points, and communicates these control decisions to the coupling points which only execute them. This approach has the advantage of a global view and the (theoretical) possibility to take globally optimal decisions, but this comes at the price of a lacking scalability and the risk of a single point of failure. On the other extreme, completely *decentralized* controllers define an own control module for each individual coupling point, which might receive data from nearby sensors and other coupling points, but takes any decision autonomously. This kind of architecture is more robust and scalable, but control decisions tend to be suboptimal, e.g. overreacting to situations. In most practical situations with a large-scale system a hybrid setup is recommendable, where important strategic decisions are centralized, but the execution is left to local controllers. An example of such a strategy is Control-2 in the first Ulm present-day scenario presented in [6], whereas Control-1 and Control-3 in that scenario is a completely decentralized and a completely centralized controller, respectively. In the OrPHEuS, due to the simulation environments and the limited scale of the scenarios, the disadvantages of centralized controllers were not directly visible; thus there is a tendency towards centralized controllers in most scenarios.

In the controller design there is a degree of influence on the **input data** that is used. Thanks to the latest Internet-of-Things technology and Big Data analytics, there is an abundance of possible data sources to be taken into account by the controllers. Although the current trend is to use as much data as possible, not all data is equally relevant, and from our discussions with stakeholders we learnt that the deployment of sensing infrastructure is far from being trivial and cheap. This might change in the future with the further advance of machine-to-machine communication, but still the lesson learnt is that a conservative approach first trying to achieve good control results with as little dependence on real-time data as possible is recommendable.

A question regarding the internal algorithms of the controllers is that of **greediness vs. conservativeness**. Greedy algorithms try to maximize the benefit in each time step with no or only little regard of the future. While this approach sounds naïve, it often turns out a valuable solution in practice because of its robustness. Greedy strategies are not dependent on models of how the system will look like in the future; they only react to the current system state at any moment. Therefore they are robust against model changes and model inaccuracies, and this is also confirmed in our experiments. On the other hand, some degree of taking the future into account still has to be applied when there are devices involved where the dependency of present and future is over a long period of time, which is true e.g. for seasonal storages. In some of the OrPHEuS scenarios we have applied rule-based policies to prepare e.g. for demand peaks in the near future.

3.1.2 Recommendations for the underlying M2M ICT system

Considering the impact from the underlying ICT platforms the following conclusions (as mentioned above already) can be summarized:

- The "horizontalization" and auto-configuration mechanisms as described for the OrPHEuS M2M platform are a crucial aspect for making use of data from other IoT monitoring systems and by re-using existing ICT systems (i.e., in other Smart Grid ICT infrastructures, but also ICT infrastructures of related Smart City domains).
- The OrPHEuS reconstructability-based data filtering architecture and algorithms (presented mainly in [4]) will greatly help to reduce ICT costs and network loads of future IoT systems and their linking platforms.
- OrPHEuS data filtering logic and ICT recommendations (mainly [4] and [5]) will be helpful to ensure the Quality-of-Information of energy-related data when it is collected, managed, and filtered by M2M platforms that serve the energy as well as other Smart City domains.

3.1.3 Recommendations for the meteorological information

As mentioned above already, we observed however also, that there is a need for training for the experts working at the interface of both meteorological and energy system ‘worlds’. By intention the work in this project used the ECMWF weather forecast widely as it is available on the global scale. It has however also be found that accuracy of forecasts would be subject of the region of interest and are generally not transferrable between regions.

With respect to the impact on control strategies as applied in the OrPHEuS project, a somewhat surprising outcome of the project has been that greedy strategies (i.e. strategies that do not take into account past data or future predictions) are almost always performing better or nearly-as-good as prediction-informed strategies ([7], chapter 3). In regard to this learnt fact, meteorological information does not seem as critical as previously envisaged to hybrid grids control strategies, as long as sensory data is readily available in real time.

We did still simulate non-greedy control strategies, notably at the Skellefteå site where we decide whether to switch the biomass boiler depending on the predicted presence of a consumption peak during the day. Such a use-case does not need to use extremely accurate fine-grained meteorological information. Adding a large amount of noise to the data did not seem to heavily degrade the performance of the control strategy either.

Additionally we found out that inaccuracies and simplifications of the control strategy’s internal models (heat storage, CHP, etc.) are responsible for a much larger performance impact than prediction inaccuracies. We therefore concentrated mostly on refining these models and tuning the control strategies, rather than analyzing effects of missing/erroneous meteorological data.

3.2 Focus Point: Sustainable business development and application area for business models and its impact on Policies Making

The major objective of this section is to decouple from the demo-site specific framework in the OrPHEuS project in terms of business model development and to derive an overall synthesis of the project outcomes to enable sustainable business model design and future applications in a wider European scale. This includes also recommendations for replication and transferability of the demo-site specific framework for general policy making in hybrid energy systems. Here it is also important to note, that sustainable business model development also expects transparent and robust legislation/regulations as well as non-discriminatory treatment of several market participants involved along the entire energy supply chain in a hybrid energy system. Therefore, this task is a highly interdisciplinary one, considering also socio-economic and behavioral aspects of consumers/prosumers.

First and foremost, it is important to note that any energy sector-coupling – finally resulting in a more advanced hybrid energy infrastructure (compared to the status quo) – is built upon an existing energy infrastructure. And this existing energy infrastructure usually is characterized by sunk cost; meaning that at least parts of this existing energy infrastructure also build the backbone for an advanced hybrid energy infrastructure in the future with more coupling points across the different energy domains. Against this background, the two different demo-sites in the OrPHEuS project build an excellent foundation to derive recommendations on sustainable business model design in a more electricity-dominated initial energy infrastructure (Ulm), on the one hand, and a more heat-dominated system (Skellefteå), on the other hand. A further important aspect for sustainable business model development is – regardless of the anatomy of the existing energy system – the ambition in terms of future energy efficiency implementation, because energy efficiency standards finally determine the absolute level of energy demand having to be covered. And varying energy demand, ultimately, is a very sensitive parameter resulting in uneven distribution of individual economic positions across the different market participants involved in energy service provision and thus oppose in many cases the ultimate goal of the implementation of cooperative strategies across several players involved.

The first set of recommendations below addresses the direct economic relationship between the different market participants involved in energy service provision along a hybrid energy supply chain. This means that recommendations for sustainable revenue streams of several market participants involved (i.e. supplier/retailers, distribution grid operators, consumers/prosumers, aggregators) are derived, building upon robustness tests of varying economic parameters (like investment/operational cost relationship of new coupling technologies, changes of relationship of different grid tariff components, etc.).

The second set of recommendations below addresses social/socio-economic and regulatory relationships in sustainable business model development. This includes – among others – varying needs and behavioral aspects of different groups of customers/prosumers (e.g. those with versus without PV self-generation), non-technical and regulatory barriers having to be overcome to enable implementation of sustainable business models.

Here it is also important to note, that the general recommendations derived in this section are not only the synthesis of the direct OrPHEuS project outcomes, but also incorporates the essence of the several OrPHEuS stakeholder and dissemination events.

3.2.1 Economic relationships

In the following Table 1 & Table 2 a synthesis of the direct economic relationship of the business models derived in the Orpheus project is presented in qualitative terms. This means, that these relationships finally can be used for sustainable business model development in hybrid energy systems in general. Whereas Table 1 focuses on a predominantly electricity-based initial energy infrastructure (i.e. synthesis of recommendations of the Ulm demo-site), Table 2 focuses on a predominantly heat-based initial energy infrastructure (reference in the synthesis to the Skellefteå demo-site).

Both Table 1 and Table 2 are split into separate columns for high versus low energy efficiency, on the one hand, and combinations of high versus low operational/investment cost (and vice versa) of new coupling technologies to be implemented into an initial energy infrastructure, on the other hand:

- Although future business model design shall automatically expect the implementation of high energy efficiency standards (and thus lower specific energy demand compared to the status quo), this can’t be guaranteed. Therefore, both cases in terms of future energy efficiency ambitions are considered in future business model design.
- In addition, several possible hybrid coupling technologies are described by couples of high versus low operational/investment cost (and vice versa). This generalization enables decoupling from the specific hybrid energy technology portfolios analyzed in the Orpheus project and guarantees the recommendations of general business models in hybrid energy systems.

The interpretation of Table 1 (electricity-dominated initial energy system) is as follows: it describes – in qualitative terms compared to the status quo – the development of the revenue streams / cost positions of each market participant (existing as well as potential new entrants) when assuming already a certain share of decentralized PV penetration in the system as well as further integration of hybrid coupling technologies ("Power-to-X") into the system. The following overall effects can be observed:

- Market entry of new market participants, as there are e.g. distribution grid operators for heat and/or gas as well as suppliers/retailers for heat and/or gas is virtually impossible. There are no market shares as well as no sustainable business models visible for these potential new entrants. Aggregators only might be rewarded – in a high energy efficiency case and low investment cost for Power-to-X technologies – with entry and sustainable revenue streams in this particular case.
- The aggregator in this special case could enter and sustain in the market if corresponding pooling of PV feed-in to the electricity grid and/or aggregation of Power-to-X services is more profitable on aggregated than individual level (higher transaction cost and no economies of scale). In addition, the aggregator can offer invoicing/billing services for several of the remaining market participants. This is most probable in a hybrid energy system characterized by high energy efficiency implementation.
- The economic framework is most sensitive for customers without PV self-generation. This means that a Pareto-optimum – an economic setting where none of the market participants loses (compared to the status quo) if several others win – is difficult to reach. This is mainly due to the fact that in electricity-dominated systems with further prosumer-motivated PV self-generation several residential energy services (also heating, cooling, and hot water) are increasingly covered by electricity. This can lead to the effect, that consumers without PV self-generation increasingly cross-subsidies this development e.g. in case the variable component of the grid tariff (or the relationship between the fixed and variable component of the grid tariff) remains unchanged. Moreover, this effect is even worse for the customer without PV self-generation in case of low energy efficiency implementation and thus higher electricity demand (see also corresponding row in Table 1). A more dominant fixed grid tariff component (on the expense of the variable component) can relief this relative disadvantage for the customer without PV-self generation. In case of high energy efficiency implementation the economic situation of this customer group can be locked-in in the initial situation again. Therefore, this is the most promising situation for a cooperative strategy among several market participants and customer groups and thus the implementation of sustainable business models.

Concluding, a Pareto-optimal cooperative strategy among existing market participants (and a potential new aggregator as an entrant) is possible only in a high energy efficiency scenario and low investment cost of a Power-to-X coupling technology.

Table 1: Sustainability of Revenue-Streams / Cost Position per Market Participant in an electricity-dominated hybrid energy system

De-centralized PV + Power-to-X		**Low Energy Efficiency**		**High Energy Efficiency (1)**	
		High Operational Cost/ Low Investment Cost of Power-to-X	**High Investment Cost/ Low Operational Cost of Power-to-X**	**High Operational Cost/ Low Investment Cost of Power-to-X**	**High Investment Cost/ Low Operational Cost of Power-to-X**
DSO	**Power**	+	+	+	+
	X (2)	-	--	-	--
Supplier/Retailer	**Power (3)**	+/++	+/++	o/+	o/+
	X (2)	-	--	-	--
Consumer/Prosumer	**with PV (Prosumer)**	++	+	+	+/o
	without PV (Consumer) (4)	-	--	o	-
Aggregator		-	--	o	-

Footnotes:

(1) Having in mind the targets of the *European Energy Efficiency Directive* and the fact that the CO_2 abatement cost of energy efficiency are negative, the adaption of consumers/prosumers to high energy efficiency standards in the future is supposed to be rational. However, decision making of consumers/prosumers on large-scale is not necessarily purely rational in practice.

(2) X describes energy domains heating/cooling and gas. Market entry for distribution grid operators and suppliers/retails for heating/cooling and gas is virtually impossible in electricity-dominated energy systems.

(3) Supplier/retails benefit from increasing sales of electricity covering also remaining residential energy services as there are heating, cooling, hot water, etc.

(4) Whereas consumers with PV systems for self-generation (and feed-in of excess generation) are called prosumers, those without PV systems are still called consumers.

Similar to the interpretation of Table 1, Table 2 is discussed in terms of sustainable business model development in heat-dominated initial energy systems with additional Power-to-X technology implementation. Again, the development of the revenue streams / cost positions of each market participant (existing as well as potential new entrants) is presented in qualitative terms (compared to the status quo). The following overall effects can be observed:

- Market entry for new players like aggregators is virtually impossible. There is no convincing business case recommending this (see Table 2).
- Although a high energy efficiency scenario for the future is preferable, also in a low energy efficiency scenario there exists a similar case representing a sustainable economic framework (notably the case with high investment cost and low operational cost of additional Power-to-X technologies). Therefore, both scenarios enable the implementation of cooperative strategies among several players involved and thus sustainable business model design. In the high efficiency scenario hosted by an initially heat-dominated system low investment cost of additional Power-to-X technologies are recommended to maintain corresponding revenue streams and cost positions of the different market participants involved. There is only one small negative aspect for customers preferring stand-alone co-firing in addition to grid-connected heating supply: this option is expected to be highly uneconomic. However, overall also in heat-dominated systems the high energy efficiency case combined with low investment cost of Power-to-X technologies is qualified for sustainable business model implementation across several market participants and customer groups.

Table 2: Sustainability of Revenue-Streams / Cost Position per Market Participant in a heat-dominated hybrid energy system

Central CHP + Power-to-X		Low Energy Efficiency		High Energy Efficiency	
		High Operational Cost/ Low Investment Cost of Power-to-X	High Investment Cost/ Low Operational Cost of Power-to-X	High Operational Cost/ Low Investment Cost of Power-to-X	High Investment Cost/ Low Operational Cost of Power-to-X
DSO	Power	+	+	+	+
	X	+	+	o/-	o/-
Supplier/Retailer	Power	o/+	o/+	o/+	o/+
	X	o/+	o/-	o	-
Consumer/Prosumer	with stand-alone co-firing	o/-	-	--	--
	without stand-alone co-firing	o/+	o/+	o	o
Aggregator		-	-	-	-

3.2.2 Social/socio-economic and regulatory relationships

In an overall synthesis and thus generalization of the outcomes of the Orpheus project in terms of social/socio-economic and regulatory considerations for sustainable business model development in a hybrid energy system environment, the following aspects are supposed to be the most important:

- Consideration of different customer groups, notably the low income versus high income segments.
- Varying consumer behavior in terms of desired energy service levels.
- Flexibility of consumers/prosumers offered to the market/aggregator.
- Grid (end-user) tariff regulation, notably in terms of ratio of fixed versus variable component.
- Consideration of data protection and privacy concerns.

In the following, each of these aspects is discussed more comprehensively, referring also to the qualitative assessment in Table 3:

- Customer groups: Mainly depending on the income, different consumer groups have different degrees of freedom to invest in high energy efficiency as well as Power-to-X technologies characterized by high investment cost. Therefore, low income customers are rather locked-in to the status quo; meaning that they are at least not negatively affected (in economic terms) by any investments of remaining customer groups into novel, sophisticated Power-to-X technologies.
- Consumer behavior: The key indicator measuring consumer behavior is energy service level variation. In general, both directions of energy service level variation are possible. However, in low energy efficiency scenarios increasing energy service levels negatively affects the cost position of customers. Therefore, energy service level (comfort) increase is most beneficial (least costly) in a high energy efficiency scenario accompanied with further novel, sophisticated hybrid energy coupling technologies.
- Flexibility offered: In many cases, customers can offer flexibilities to the electricity and/or heat market (or an aggregator) without negative implications in terms of convenience/comfort. This is possible due to the inertia of some of the customer applications (e.g. heat pump, freezer, refrigerator, grid connected heating and cooling systems, etc.).

Typical market segments for the provision of short-term flexibilities taking advantage of inertia of hybrid energy systems are balancing electricity markets. From the economic point-of-view it is a win-win situation for both customer and market agent. Moreover, this could be a key factor for a sustainable business case of an aggregator.

- Grid tariff regulation: Regulatory issues in general, and grid tariff regulation in particular, is one of the most sensitive factors in hybrid energy systems at the presence of high shares of local self-generation and feed-in of local excess generation. This can negatively affect revenue streams of distribution grid operators. In order to mitigate this challenge, usually the ratio of fixed/variable grid component is increased. This guarantees more independent revenue streams for distribution grid operators in distributed hybrid energy systems. However, a higher share of fixed tariff component also negatively affects price elasticity of energy demand; meaning that energy saving and thus energy efficiency implementation is less attractive from the customers' point-of-view. So there is a feedback loop having to be taken into account in this respect in order not to open another "problem field" (i.e. undermining energy efficiency implementation).
- Data protection/privacy: Finally, also data protection/privacy issues need to be considered, notably in hybrid energy systems with high shares of novel, sophisticated Power-to-X technologies. Because here the time resolution and the amount of individual data of customers is very high and, therefore, need to be treated with care. Aggregator could find a business case also here to aggregate, maintain, and further process data (e.g. for billing and invoicing purposes). Moreover, this could bring additional services to the hybrid energy market where several of the incumbent players benefit.

Table 3: Social/socio-economic and regulatory relationships feeding into sustainable business model development in hybrid energy systems

Electricity&Heat System + Power-to-X		Low Energy Efficiency		High Energy Efficiency	
		High Operational Cost/ Low Investment Cost of Power-to-X	High Investment Cost/ Low Operational Cost of Power-to-X	High Operational Cost/ Low Investment Cost of Power-to-X	High Investment Cost/ Low Operational Cost of Power-to-X
Customer Groups	Low Income Group	o	-	o	-
	High Income Group	o	+	o	+
Consumer Behavior	Desired Energy Service Level increase	--	-	+	++
Consumers offering flexibility to Market/ Aggregator	Energy Service level increase	-	+	-	+
	Energy Service level decrease	+	-	+	-
Grid Tariff Regulation (End-User Bill)	Ratio Fixed/Variable Component high	++	-	+	--
	Ratio Fixed/Variable Component low	--	+	-	++
Data Protection / Privacy Concerns		low / less sensitive	high / sensitive	low / less sensitive	high / sensitive

4 Customer Feedback

Within the effort to evaluate the EU OrPHEuS project's motivation, and approach, the consortium organized special workshops to disseminate the results and make an in-depth discussion with local stakeholders holding a diversity of technical and business backgrounds and serving as potential customers [9]. This section summarizes their feedback and the conclusions taken.

Ulm

The workshop participants agreed on the one hand that the cooperative hybrid concept seems like a promising approach to foster the transition of the energy system and to reach renewable integration targets. On the other hand, however, there has also been a consensus among the attendants that there are obstacles for distribution system operators to implement such a business model. The regulatory incentives to rather invest in grid reinforcement and the need of a significant share of customers or prosumers participating and cooperating voluntarily have been identified as major barriers. In addition, not all heating systems in houses of prosumers are suitable for power-to-heat and it could be a lot of work to acquire all necessary data of the variating heating systems. The regulations currently in effect in Germany make it difficult to handle the additional costs and taxes which would be introduced in business cases between the DSO and prosumers. The overarching challenge is that all prosumers in a given area would have to concur in order for power-to-heat to become a viable alternative to grid reinforcement by the local DSO.

The workshop was concluded with a survey circulated to the workshop participants. The questions focused on the major points remaining to be cleared to implement power-to-heat as a common tool in grid operation. The results show that the participants of the survey are very well informed about power-to-heat and power-to-gas and the associated benefits for the electrical grid operation. However, they also have doubts regarding the gas grid operation and see some challenges. They have no practical experience yet of how to handle such approaches and have not done a lot to reach hybrid grids as a common planning alternative. Therefore, SWU and HSU see the need to pilot projects and develop results that are very closely oriented toward practical conditions. With such results, decision-makers can be more easily persuaded to use company resources for hybrid grid approaches in their common workflow.

Skellefteå

One of the main issues for Skellefteå Kraft as the local Distribution System Operator (DSO) is the balancing of the grid. In that sense the solutions investigated by the EU OrPHEuS project can be helpful as the hybrid approach emphasizes energy storage and conversion, which can assist in stabilizing the grid and making use of more locally produced electricity. Participants agreed that Transmission System Operators (TSOs) could also benefit from local hybrid grids at the national level since the scheme would reduce the needs for long-distance power transmission and centralized energy storage capacities, especially with high penetration of intermittent renewable energy (e.g. wind, solar). It was suggested that a new business model remains to be devised in order to be beneficial to both DSOs and TSOs with a long-term perspective. This effort could be fostered by a relevant national platform such as the Swedish Smart Grid forum.

Representatives from Skellefteå Kraft pointed out that one of the major obstacles they see to the immediate implementation of hybrid grids in Skellefteå is the current energy tax of 193 SEK/MWh (20€/MWh) for power-to-heat conversion, be it for electric boilers or heat pumps. This energy tax makes energy conversion economically unviable and limits the present efforts of Skellefteå Kraft towards energy flexibility to an optimization of the CHP production with the hot water storage. Skellefteå Kraft expressed their preference for a regulatory change reducing or removing the energy tax if it serves to improve overall energy efficiency, or for other financial incentives serving a similar purpose.

Finally, as an outlook to possible extensions of the project work, it was suggested to consider increasing the optimization range from two to four different grids: the electrical grid, district heating grid, district cooling grid and gas grid. This would be especially relevant for larger cities such as Stockholm, in the Swedish context.

Conclusion

While the operational benefits of hybrid energy grids is evident in both Germany and Sweden in terms of flexibility and increased penetration of renewables, in practice more developments are required on the regulatory side to clearly define how responsibilities would have to be shared between the different cooperating energy actors, as well as to offer more economic visibility with clear benefits for all involved parties. More applied pilot projects are also deemed necessary to clearly highlight the feasibility and benefits of the hybrid grid approach for utilities. These important considerations are likely to be taken to the national level by participating organizations (VKU in Germany and SKR/Swedish Smart Grid in Sweden) to be further debated.

5 Summary

This report – given as final summary of the EU OrPHEuS project - is focused on the comprehension of the results of the technical work including business model design, ICT aspects (IoT, virtual and real-life measurements, and meteorological data), simulation frameworks and the control strategy evaluation.

The result comprehension and its value for advanced technology bring together the discussions for the targeted advances with the project results presented as “Gained Knowledge and Impact”. This builds the basis for the provided recommendations for replication in Europe beyond the dedicated demonstration sites. During the last months of the project, the consortium organized workshops with potential customers of the project results, provided in customer feedback section.

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