Recent developments in simulation-based assessments of integrated urban energy systems

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RECENT DEVELOPMENTS IN SIMULATION-BASED ASSESSMENTS OF INTEGRATED URBAN ENERGY SYSTEMS

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ABSTRACT

Simulation-based assessments are a cost- and time-effective way of evaluating various aspects of large energy systems. For instance, they can help in the design process of energy systems, where they provide insights into technical or economic questions. Or they can be used for developing operational strategies and controllers to increase the efficiency of energy systems.

In the case of integrated urban energy systems, simulation-based assessments still remain challenging due to their complex requirements, from both a methodological as well as a technical perspective. This is not only due to the size of the considered systems but also due to the fact that they comprise and integrate subsystems that are related to different engineering domains (e.g., electric grids and heat networks) and different stakeholders. Nevertheless, recent work has demonstrated how innovative simulation approaches can be successfully utilized in this context, enabling detailed multi-domain assessments for urban energy systems.

However, not only models and tools are necessary for such complex simulation-based assessments. Issues related to data availability and reproducibility are of equal importance, in order to set up simulations and compare results. And, with the help of proper methodologies, it is possible to exploit synergies between complementary simulation approaches for holistic assessments. Within this context, this paper highlights recent developments from research projects that target these issues. The examples demonstrate how these new approaches help in understanding the associated risks and potentials, paving the way for early adopters to implement innovative concepts in the context of integrated urban energy systems.

Key words: energy system integration; co-simulation; data harmonization; model harmonization; methodology development;

INTRODUCTION

The integrated planning and operation of traditionally separated energy systems is considered to be an important aspect of making cities more sustainable in the future. This means that urban energy systems are supposed to evolve into complex multi-network structures, in contrast to the classical silo-like approach of separated energy carriers today. This concept has been investigated from different and complementary perspectives, focusing for instance on the electrical (Ilic, Xie, Khan, & Moura, 2018) or the thermal (Lund, et al., 2014) point of view.

This proposed paradigm shift for the planning and operation of urban energy systems towards multi-carrier energy networks also implies a growing number of intricate interactions between previously separated systems and stakeholders. Within this context, simulation-based approaches provide the most viable way of assessing such systems in terms of cost- and time-effectiveness. However, energy-

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related simulation tools traditionally focus on just one specific engineering domain, such as power grids, heating networks or buildings. From a historical perspective, this approach is quite natural, given that these tools are typically either the result of long-term academic research efforts from specific fields of engineering or have been developed by industry with a specific aim and audience in mind. But even though these tools have been very successful in delivering valuable insights in the past, they are as such not suited to address issues in multi-carrier energy systems (Palensky, Widl, & Elsheikh, 2014).

In order to overcome the challenges of modelling and simulating multi-carrier energy systems, a lot of research and development has been carried out in recent years. For instance, in the context of technical assessments, which target primarily issues related to the operation and closed-loop control of such systems, two approaches have received particular attention. Multi-domain modelling languages, such as Modelica (Fritzson, 2011) and MATLAB/Simulink, on the one hand, and co-simulation approaches, especially based on the FMI specification (Blochwitz, Otter, Arnold, Bausch, & Clauß, 2011) and the HLA standard (IEEE Computer Society, 2010), on the other hand, have gained a lot of popularity. And, as a matter of fact, both approaches have been successful in showing their potential regarding the assessment of complex energy systems on the scale of neighbourhoods, districts and cities, see for instance (Wetter, Bonvini, & Nouidui, 2016) or (Jacobs, et al., 2018).

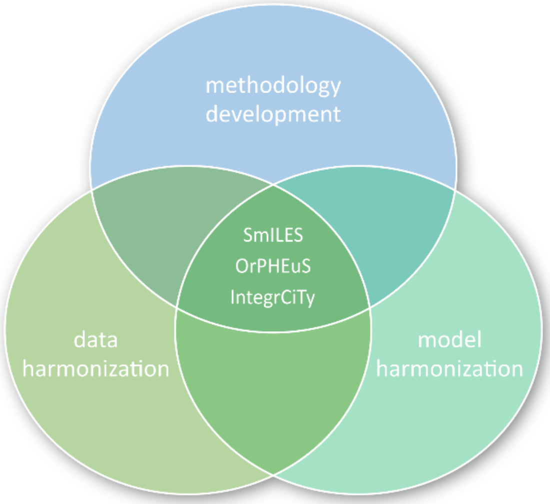

Figure 1: Overview of recent research trends (and selected research projects) to improve the applicability of simulation approaches in the context of integrated energy system assessments.

However, models and tools are not the only pre-requisite for successful simulation-based assessments. As the considered systems grow larger and more complex, several other challenges arise. Recent developments regarding three of these challenges are specifically addressed in this paper, providing a short overview and putting them into a larger context. The considered challenges are:

- *Data harmonization*: The availability of high-quality, well-formatted and semantically structured data is a crucial prerequisite for the simulation-based assessment of urban energy systems. Unfortunately, best practices for data modelling are rarely utilized in the context of energy-related simulations, such that data management and data access often become tedious and cumbersome tasks. However, with the steady progress of digitization, also more and more geographical and semantic city data become available and accessible. In the context of urban energy system simulations, the challenge is to represent the required data in a way that simulation tools can make use of it.
- *Model harmonization*: Depending on the type of application, different types of models for the same physical entity may be required. For instance, optimization models used for network planning may look considerably different than simulation models used for assessing the operation of the same network. However, in many cases it would be advantageous to be able to compare or link these models. Within this context, the challenge is to provide a model- and tool-independent description of systems and associated test cases, which provides a common

basis for different simulation tools and methods, even when implementing complementary modelling paradigms.

- *Methodology development*: Urban energy systems are not only complex due to their size. The integration of multiple energy carriers also requires taking into account a diverse range of stakeholders (energy providers, network operators, prosumers, etc.) that have different and sometimes competing interests. Therefore, urban energy systems require holistic assessment approaches that enable the evaluation of both short-term (operational) and long-term (strategic) aspects. However, the challenge is that there is no generally agreed-upon methodology for how to carry out such holistic assessments based on the technical and economic models available.

The recent developments in data harmonization, model harmonization and methodology development shown in this paper are (preliminary) results from three independent research projects. Figure 1 shows how the presented research results and the addressed research trends overlap. Please note that the presented results have to be understood as selected examples of current research trends and are not representative for the entire topic.

DATA HARMONIZATION

The *IntegrCiTy project*[1] focuses on the development and implementation of an integrated decision support environment for city planners and energy providers to improve efficiency and resilience of urban energy supply infrastructures. An important part of this decision support environment is the adoption of an international standard for the data model (and its implementation as database for data storage and management), which is used to represent the city and its infrastructure. This database serves as information hub providing integrated and harmonised data for simulation-based assessments and the visualization of the simulation results, see Figure 2 for an overview. In the following, the aspects of the IntegrCiTy approach regarding data harmonization are presented.

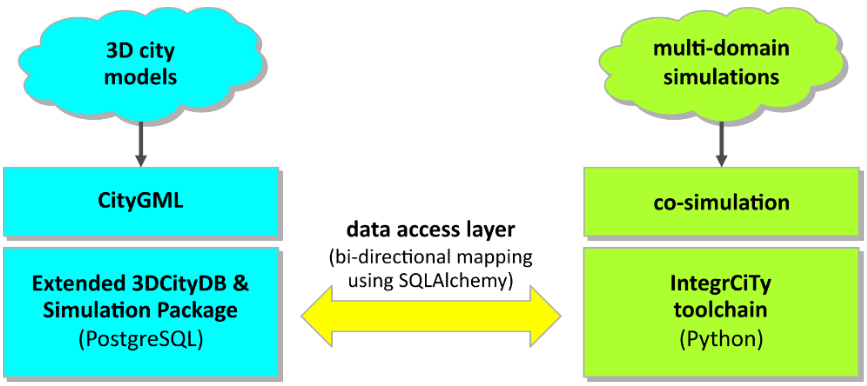

Figure 2: Project IntegrCiTy aims to use a semantic database as information hub for all simulations in the decision support environment. Taken from (Widl, Agugiaro, & Puerto, 2018).

Semantic 3D city models

Semantic 3D city models provide a representation of urban space, comprising a description of all its relevant entities (buildings, infrastructure, water bodies, etc.). They describe spatial and non-spatial properties and include information about topology, hierarchy and appearance. The big advantages of semantic 3D city models are the clear data structures, ontologies and semantics they provide, which help facilitate data provision and exchange between different domains and applications. The probably most advanced data model in this context is the Open Geospatial Consortium's *CityGML data model* (Gröger & Plümer, 2012), an international open standard based on the *Geography Markup Language*[2] (GML).

[1] See: http://iese.heig-vd.ch/projets/integrcity
[2] See: http://www.opengeospatial.org/standards/gml

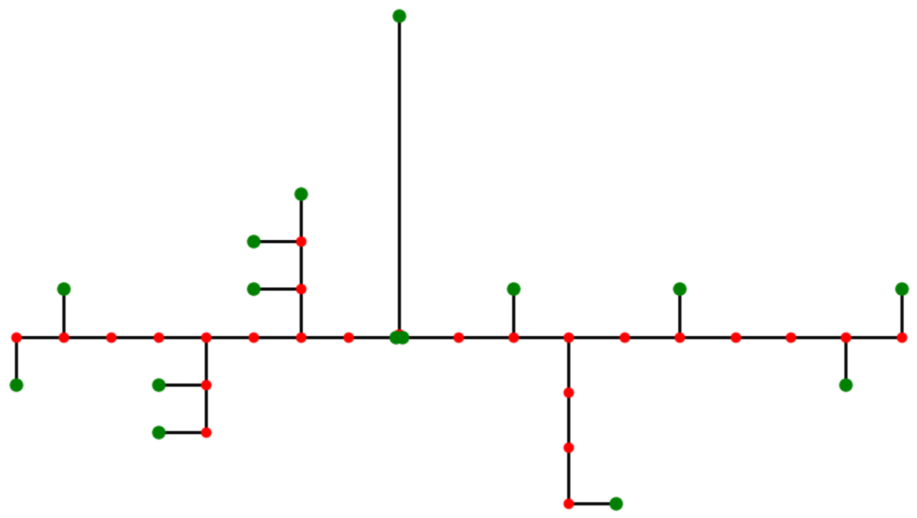

Figure 3: Visualization of a topographical network representation.

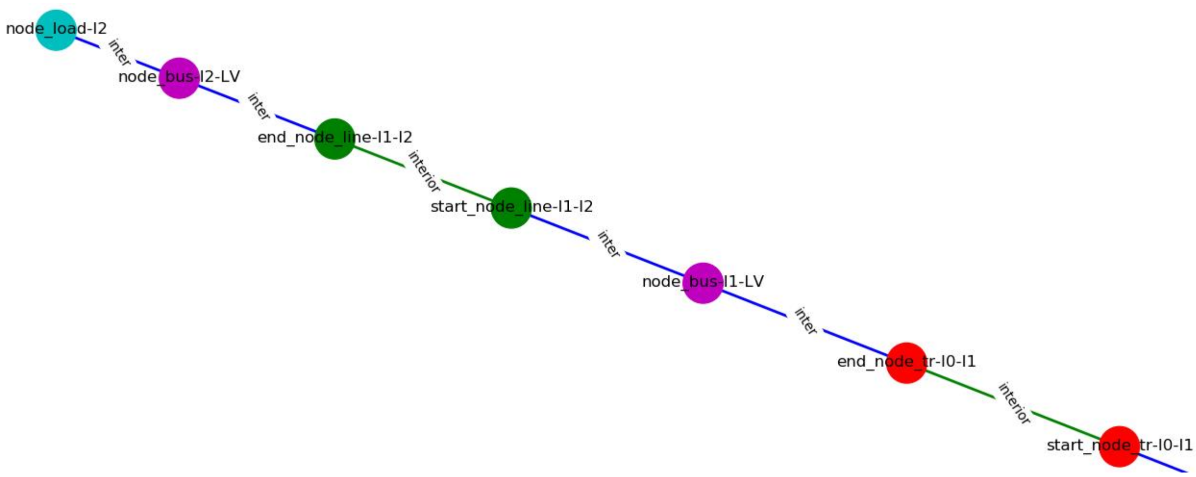

Figure 4: Visualization of a topological network representation.

A reference implementation called the *3D City Database* (Yao, et al., 2018) – also referred to as *3DCityDB* – provides a database schema of the CityGML data model and comes with several open-source tools for importing/exporting data to/from the database. In the context of energy-related simulations, the 3DCityDB support for extensions (Yao & Kolbe, 2017) via so-called *Application Domain Extensions* (ADE) is of special interest. For instance, the *Energy ADE* (Agugiaro, Benner, Cipriano, & Nouvel, 2018) extends the CityGML standard with features and properties necessary to perform energy simulations and to store the corresponding results. Furthermore, the *Utility Network ADE* (Kutzner & Kolbe, 2016) defines a topological and topographical model for utility networks and supplying infrastructures. Included are, amongst others, network hierarchies of arbitrary depth, nesting of network components, and modelling of multi-domain networks.

An example of how valuable data for energy-related simulations can be stored to and retrieved from an extended 3DCityDB is shown in Figure 3 and Figure 4. For this example, the features of an electrical network have been translated into the data model provided by the Utility Network ADE, stored in the 3DCityDB and then visualized from the available data in the database.[3] The figures show the topographical and (a part of) the topological representation of the CIGRE low voltage distribution network (CIGRE Task Force C6.04.02, 2014), respectively:

[3] See: https://github.com/IntegrCiTy/dblayer/tree/master/examples

- Figure 3 shows some of the details of the network, depicting cables as solid black lines, busbars, plates and poles as green dots and connected loads as green dots. Each of these elements is stored in the database as individual item, including their semantic attributes and geographical features.
- Figure 4 shows that the Utility Network ADE provides on top of the topographical data also extensive topological information. More specifically, it visualizes the topological representation of a transformer (red dots), two busbars (magenta dots), a cable (green dots) and a load (cyan dot). The two busbars and the load are represented by single nodes, whereas the transformer and the cable are each represented by two nodes connected through a so-called "interior link" (green lines). For the cable the two nodes represent the two ends, for the transformer they represent the high and low voltage side. The interior links are used to indicate that the nodes are part of the same network feature. All of these network features are connected to each other through so-called "inter-feature links" (blue lines), providing an unambiguous network topology.

In the context of data harmonization for the IntegrCiTy project, the representation of a network with the help of CityGML is interesting for several reasons:

- *Stakeholder interoperability*: The data model is open-source and freely available, independent of any specific simulation model or tool. Such a universal data format enables different stakeholders to work together, for instance city planners, network operators and researchers.
- *Tool interoperability*: The data model provides a complete view of the network, with sufficient semantic, topographical and topological information to generate simulation models for any simulation tool. At the same time, is can be used to store simulation results in the 3DCityDB, associate these results with individual elements (e.g., maximum voltage levels at individual busbars) and visualize them.
- *Urban data context*: Embedding the data model of a network within a 3D city model allows to put it into the greater context of the actual urban energy system, enabling the linking with information from other city objects, such as buildings or other city objects like streetlamps, etc. (Den Duijn, Agugiaro, & Zlatanova, 2018; Boates, Agugiaro, & Nichersu, 2018).

Analogous examples and arguments can be made for other relevant domains, especially for the assessment of district heating networks and buildings. As such, semantic 3D city models offer a promising approach to provide data for different types of simulations in the context of integrated urban energy systems in a consistent and harmonized way.

Simulation Package

An important asset in IntegrCiTy's decision support environment is a co-simulation toolchain that enables detailed technical assessments of proposed changes and extensions to urban energy systems. As mentioned above, an essential prerequisite for creating meaningful simulation models is the availability of high-quality data, for which the 3DCityDB is utilized in the IntegrCiTy toolchain. However, on top of the domain-specific data provided through the CityGML data model and its extensions, additional meta-information is required to execute a simulation. This is especially true for co-simulation approaches, which require configurations for each individual tool (e.g., integrator steps sizes or initial conditions) as well as specific information regarding the coupling and orchestration of the tools.

Consequently, the logical next step is a persistency schema for this type of information that integrates with the CityGML data model. To this end, the Simulation Package data model has been developed (Widl, Agugiaro, & Puerto, 2018), in order to link CityGML-based semantic 3D city models and urban energy system simulations. Figure 5 shows the UML class diagram of the Simulation Package, which defines the following classes:

- *Class Simulation*: Instances of this class are the top-level objects describing a co-simulation setup, linking all entities required to define the composition of the coupled tools. Instances can optionally reference class *Scenario* from the CityGML *Scenario ADE* (Schüller, Agugiaro, Cajot, & Marechal, 2018), which allows a systematic representation of different scenarios within a city.

- *Class Node*: Instances of this class represent the basic simulation units of a co-simulation setup and are basically an abstraction of simulation models and tools. Instances can be linked with CityGML objects, which allows to link them to domain-specific semantic data of a city model (useful, for instance, for automated model creation or validation).
- *Class AbstractPort*: This is an abstract class that is further specialised into class *InputPort* and class *OutputPort*, which represent the input and output variables of a simulation node. Ports are intended to represent only a single scalar variable and must correspond to a variable in the associated simulation model. Instances can be linked with CityGML objects, which allows to link them to domain-specific semantic data of a city model (useful, for instance, for automated model creation or validation).
- *Class PortConnection*: This class can be used to link ports of different nodes, which corresponds to the exchange of one scalar value between these two nodes.
- *Class SimulationTool*: Instances of this class contain information specific to the simulation tool associated to a node.

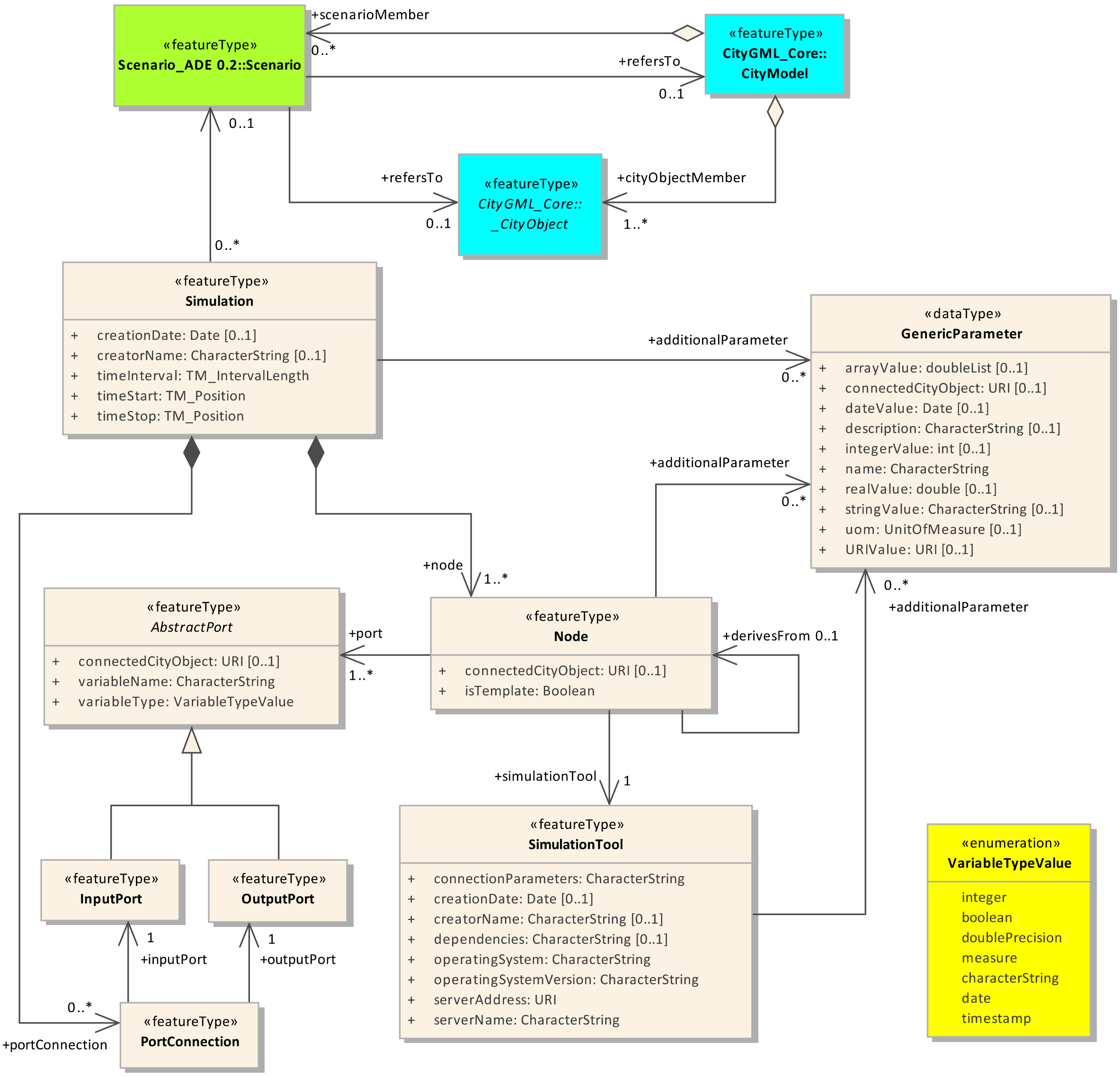

Figure 5: UML class diagram of the Simulation Package data model. Taken from (Widl, Agugiaro, & Puerto, 2018).

The Simulation Package is a first step towards linking the semantic 3D city models from CityGML and urban energy system simulations. As such, the design aims to be as generic as possible, in order to enable its application to a large variety of (co-)simulation tools.

MODEL HARMONIZATION

The *SmILES project*[4] aims at improving the knowledge on the integration of electrical and thermal storages in local multi-energy systems. Within this context, a primary goal is to provide best practice examples for the simulation-based assessment of multi-carrier energy systems, which includes the sharing of simulation methods and systems among partners.

A lot of work has gone into the development of new models and tools for assessing multi-carrier energy systems in recent years. As a matter of fact, these models and tools cover a large spectrum of applications, ranging from system design and planning to operational aspects such as closed-loop control and forecasting. Unfortunately, the methods and tools used for these different kinds of applications often require intrinsically different types of models. For instance, depending on the type of application an electrical network can be modelled using differential equations (transient or electro-mechanic phenomena), algebraic equations (quasi-static power flow) or simple energy balances (the so-called copper plate).

A challenge arises when one tries to compare or combine these applications, as is the case within the SmILES project. Simulations models themselves are not a good basis to share information about the considered system configurations and test cases, because in terms of complexity and spatial/temporal resolution they provide only a model-specific representation, which is in general very hard to re-interpret within the context of another type of model.

Therefore, the SmILES project aims at providing the means to specify use cases, test cases and complete energy systems in a way that is independent of specific models, tools or methods. This is done with the help of templates that – when filled adequately – contain all the information required about a system for implementing different types of models, see Table 1 for an overview.

Table 1: Documentation requirements according to the SmILES project. Adapted from (Gehrke & Jensen, 2018).

Documentation of …	**Type of information**	**Examples**
use case	desired dynamic behaviour of the entire system	peak shaving, consumption reduction, optimal storage operation
test case	specific implementation of a use-case for an assessment according to a test objective	evaluate performance of peak shaving using a PV surplus and batteries on a sunny day
system configuration	static system data	line impedances, network topology, nameplate data
control function	extrinsic dynamic behaviour of individual system parts	solar MPP tracker, constant flow pump, energy market
input data	exogenous influence on the system and its components	weather data, EV driving patterns, energy prices

Within this context, SmILES builds upon a clear distinction between the static components of a system – referred to as the *system configuration* (SC) – and the dynamic behaviour of certain components and their functional role in the system. A part of this dynamic behaviour is described through *control functions* (CF), i.e., the mechanisms governing the extrinsic behaviour of a specific element. These are not in the scope of the SC description and are documented separately. In the following, an overview of the SC description and the CF description is given.

System Configuration description

While some aspects of a SC description (Nguyen, et al., 2018) can be easily formalized (this applies in particular to quantifiable information and object relations), others are contextual and defy a rigid format. Therefore, a description format must be able to include free-text descriptions as well as coded

[4] See: https://www.ecria-smiles.eu

information. A mixture of textual paragraphs, tables and figures was considered most appropriate to provide enough flexibility and freedom for authors of the SC description.

The development of the SC description was guided by multiple requirements. The key design criteria were defined based on preliminary work within the SmILES project and previous experience from the project partners:

- *Model-independent description*: The system configuration is a detailed, technical description of an energy system (a list of energy domains, system components and their interrelations such as connectivity and hierarchy) and the inherent properties of the components (component attributes and constraints). The SC description collects these parameters, but they are to be documented independently from any choice of modelling. For example, a hot water tank can be characterized by the maximum temperature at the top and minimum temperature at the bottom, which can be documented in the SC description. There are however several ways to model such a tank, for instance using stratified thermal layers or a capacity model. This choice should however not be included in the SC description.
- *System Breakdown*: The SC description needs to be adaptable to different levels of detail. Furthermore, relations and interfaces between components must be documented. To this end, the concept of the *System Breakdown* (SBD) has been introduced, which provides an organized overview of all components that constitute the SC. All elements are conceptualized as classes and organized on different branches of a tree to reflect different domains and levels of detail. The “vertical” relations between the classes (sub-classing and containment) are depicted analogous to UML notation. See Figure 6 for a simple example.
- *Element connections*: The “horizontal” relations between instances of classes (e.g., a specific e-boiler provides domestic hot water in a specific building) were chosen not to be depicted in the SBD (for easy readability). They are defined and listed in a separate section of the SC description.
- *Element instance specification*: The instances of the different classes can be listed and characterized in a separate section, but they are not shown in the SBD (for easy readability).
- *Energy and information flows*: Global exchange flows can be depicted using graphical representations of the SC. By relying on representations typical for each particular domain (single-line diagrams, energy flows charts, etc.) it is easy to grasp the relations and connections between the elements of the SC.

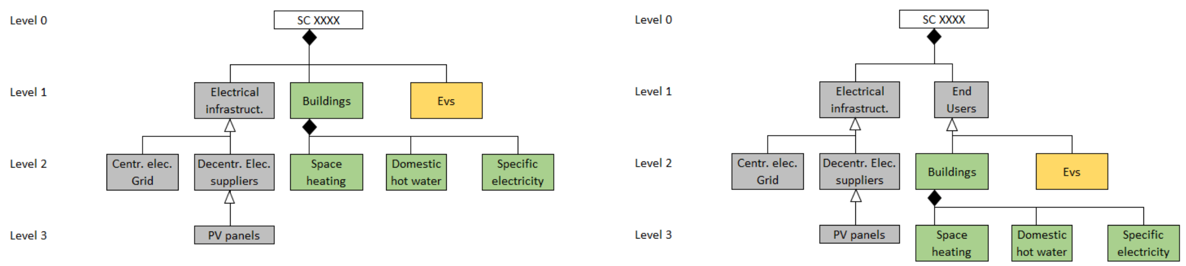

Figure 6: Two possibilities of a system breakdown for the same system, but focusing on different modelling aspects. Taken from (Nguyen, et al., 2018).

Control Function description

For the CF description (Gehrke & Jensen, 2018), an adaptation of the *Scientific Algorithm Documentation Standard* (SADS) (National Oceanic and Atmospheric Administration, 2018) has been deemed most appropriate. The SADS defines a set of guidelines for the scientific documentation of algorithms, developed by the *US National Oceanic and Atmospheric Administration* (NOAA). Its underlying purpose is to describe a standard method for articulating scientific algorithms in such a way as to be understood by other interested parties.

Adapting the original SADS to the SmILES project required a number of changes in order to reflect the narrower purpose and different application case, the need for support for additional types of functions and adaptations of the intended workflow. Last but not least, in order to reduce the expected workload associated with documenting potentially dozens of control functions, an effort was made to reduce the number of required categories as well as to shrink the document length. The following main adaptations were performed:

- *Reflection of narrower purpose*: CF descriptions are not intended to be standalone descriptions and are de facto useless without being embedded into the context of a use case, system configuration and possibly test description. Due to this narrower focus on the description of control functions (rather than generic algorithms), the interaction with a control function can simply be described in terms of inputs and outputs.
- *Focus on current implementation*: CF descriptions are not intended to serve as a reference for the future development of control functions. They are merely meant to provide a snapshot of a current implementation. Therefore, the development lifecycle of CFs does not need to be considered, unlike the lifecycle of algorithms in the original SADS.
- *Additional function types*: Algorithmic functions, the domain of the original SADS, are only a subset of what may constitute a control function. To reflect the broader use, algorithmic descriptions became only one of several optional descriptions, including new description sections for deterministic and stochastic functions. Additionally, an option was added to describe embedded control functions which are implicitly contained or embedded in simulation models, solvers, optimization algorithms etc.

Within the SmILES project, the SC and CF description together provide the basis for model harmonization, i.e., they enable the project partners to implement consistent models of the same overall system using different types of models. These descriptions further form the basis for linking models, enabling on- or offline coupling by a common definition of boundary variables. At the time of writing, the description definitions are considered to be work in progress and are to be updated by the end of the project.

METHODOLOGY DEVELOPMENT

When looking at individual components, the technology required for implementing multi-carrier energy systems is already mature and available. However, this does not apply at the system level, where the interaction of networks and components and the resulting implications are not yet completely understood. Furthermore, the implementation of such systems in the context of integrated urban energy systems raises new questions regarding economic and regulatory feasibility, which are beyond today’s best practices for the individual domains. The challenge is to provide a holistic approach for designing and assessing such systems, addressing the full range of related questions.

This issue has been addressed by the OrPHEuS project5, which has proposed and implemented a new holistic approach for studying the potential of multi-carrier energy networks. One of the main challenges in devising such an approach is the fact that complementing aspects with different spatial and temporal resolution have to be considered jointly. More specifically, both technical assessments and economic assessments are needed, in order to be able to provide meaningful recommendations regarding operational and strategic aspects, see Figure 7. To this end, a dedicated methodology for holistic assessments has been developed (Widl, et al., 2018), which relies on a co-simulation approach for the technical assessment and dedicated optimization models for the economic assessment. Figure 8 shows the conceptual workflow of this proposed approach in the following.

Definition Stage

In the definition stage the investigation starts with the development of a basic concept for the multi-carrier energy system. In this phase the direct involvement of all relevant stakeholders is crucial, as it defines the actual object of investigation.

The first step is the definition of goals that should be achieved. These goals are defined by the stakeholders, reflecting their interests and needs. For instance, the goal of an energy provider could be to reduce or eliminate the dependence on fossil fuels. Based on the specific goals, a set of strategies

[5] See: http://www.orpheus-project.eu

for the operation of the hybrid network needs to be developed. These strategies have to define which potential synergies in generation, storage and consumption between the available energy carriers should be targeted.

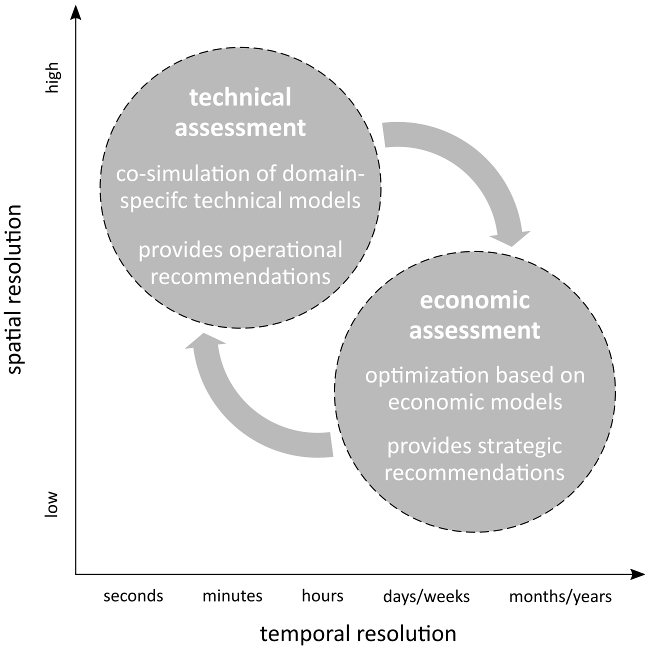

Figure 7: A holistic assessments aims at addressing complementing aspects (using different simulation approaches). Taken from (Widl, et al., 2018).

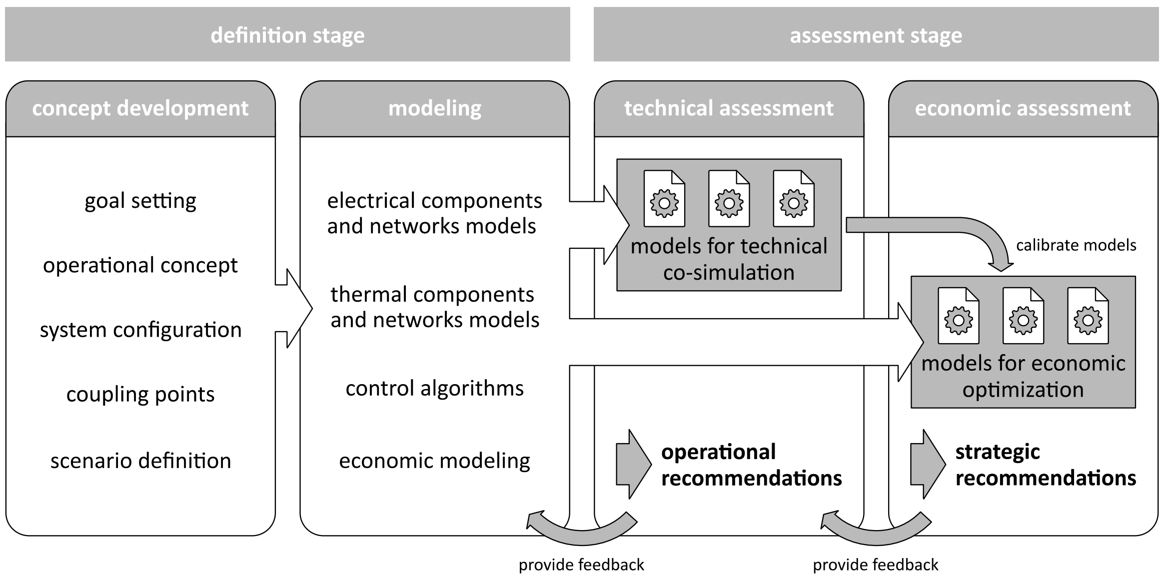

Figure 8: Methodology proposed in the OrPHEuS project for hybrid network assessments. Taken from (Widl, et al., 2018).

Once the overall concept is laid out, a detailed description of the system configuration is required, i.e., a description of the existing and planned infrastructure including generators, storages, network layouts, demand structure, and system constraints. Based on this system configuration and the operational strategy, a preliminary list of potential coupling points and operational scenarios can be compiled.

The second part of the definition stage covers the implementation of the previously defined concept in the form of models and algorithms. This includes the implementation of components and network models, control algorithms and economic models.

Assessment Stage

In the assessment stage the technical and economic feasibility of the proposed scenario is evaluated. The results of this stage are operational and strategic recommendations for the stakeholders. A model-based approach has been chosen that consists of two complementary steps that use different simulation approaches (see Figure 8).

The assessment stage begins with the technical assessment to check the technical feasibility of the system setup regarding operational conditions and technical performance indicators. For the OrPHEuS project, a co-simulation approach was adopted for the technical simulations, as it was deemed particularly useful. Especially the possibility for experts of all involved engineering domains to use their domain-specific modelling and simulation tools was considered a great advantage.

The raw results of the technical simulations can be further processed and translated into technical key performance indicators, which can then be used to compare different operational strategies and/or system configurations. This enables investigators to draw concrete conclusions, selecting the operational strategy and/or system configuration that performs best in view of the operational goals defined during the definition stage.

Since the technical assessment alone cannot answer all important questions, the second and final step of the assessment stage addresses the economic side. Long-term effects and indicators like the internal rate-of-return of investments need to be evaluated by an additional economic model. The economic investigation comprises an analysis of currently existing structural barriers and potentially the design of novel business models that enable a distribution of benefits, where all stakeholders can profit.

The results from the technical assessment can then be used to calibrate and fine-tune the economic model, which is subsequently executed to evaluate the long-term aspects of the scenario. Due to the longer time scale of the economic calculations and the need to determine optimal investment choices, usage of the co-simulation environment developed for the technical simulations would be prohibitively expensive. Thus, the approach chosen for the economic studies is to use simplified linear models of the system components, so that the model calculations can be done with the help of state-of-the-art integer program solvers.

This workflow enables an efficient and precise evaluation of both short-term (operational) and long-term (strategic) aspects. As such it provides the possibility to cover the assessment of system configurations, control strategies, business models and regulatory conditions in one coherent approach.

CONCLUSION

In this work, three very different efforts from three independent research projects have been presented:

1. *Data harmonization*: One of the goals of the IntegrCiTy project is to demonstrate the usefulness of a coherent, standardized data model (and its implementation as database) for semantic 3D city models for urban energy system simulations and linked applications. The idea is to ease the process of data provisioning, model generation and results visualization through the utilization of a standardized and consistent data model.
2. *Model harmonization*: A main goal of the SmILES project is the definition of a model-independent system specification, covering both static and dynamic aspects. The intention behind this is to provide a common basis for different – sometimes even complementary – modelling approaches, with the goal to make them comparable and linkable.
3. *Methodology development*: One of the main achievements of the OrPHEuS project was the definition of a holistic methodology for assessing multi-carrier energy networks. By following this methodology, it can be guaranteed that the technical and economic assessments are consistent and that the interests of all involved stakeholders are addressed.

Even though these three efforts may seem unconnected at first, they share indeed a lot of common ground. First of all, they acknowledge simulation-based assessments as the most cost- and time-effective way of evaluating various aspects of integrated urban energy systems. However, they also recognize that for a successful simulation-based assessment not only models and tools are required and therefore aim to provide supporting methods and concepts accordingly. Furthermore, the results of these three (and similar) projects aim to be the basis for improved simulation workflows in the future and in fact complement each other. The usage of harmonized data models would ease the efforts associated with model harmonization (and automated model generation). And harmonized models that produce consistent results are a pre-requisite for implementing holistic assessment methodologies, especially when the models implement complementary types of modelling paradigms.

In conclusion, the three projects presented in this work give direction for future research, in order to enable simulation-based assessments of complex systems. Luckily, promising approaches already exist in the context of urban energy systems simulations, and with time and effort they may become best-practice approaches in the future.

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