Applied Energy 222 (2018) 67–78

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A survey and statistical analysis of smart grid co-simulations

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HIGHLIGHTS

- Definition of state-of-the-art co-simulation and provision of recent trends.
- Review of 26 different Smart Grid simulation frameworks and their applications.
- Analysis of several parameters: research topic, computational effort & problem size.
- Correlation of different application, showing trends in simulation tools.

ABSTRACT

Smart Grids consist of multiple actors and physical phenomena, which are often difficult to capture in one single simulation framework. Therefore, researchers increasingly couple distinct simulators to form novel “co-simulations”. In this paper we present a literature survey of 26 smart grid co-simulation frameworks. First of all, we present our understanding of a co-simulation. We then classify the 26 frameworks on multiple characteristics, such as simulation tools, synchronization methods and research topics. Finally, we present correlations between different key characteristics, analyze possible research gaps and discuss possible trends and future development areas in the field of smart grid co-simulations.

1. Introduction

Electric power grids are complex dynamic systems, which are continuously perturbed by multiple actors: grid operators measure and control distinct areas of the power system, energy traders plan and dispatch generators, and substations are increasingly equipped with smart controllers responding to changes in power flow or voltage. The integration of renewable energies adds a further degree of complexity; such power sources are less predictable than conventional power plants and may be installed at many decentralized locations in the grid [1]. To measure and coordinate the renewable in-feed, grid operators may implement more information and communications technology (ICT) solutions and create a “Smart Grid”. The electric power system may interact with gas and heat networks as well, e.g. when excess renewable feed-in is converted into other forms than electric energy (for example [2] or [3]). However, the term “Smart Grid” also dictates an increased communication need amongst the actors of the power system. For example, the “2017–2026 research and innovation roadmap” by ENTSOE [4] focuses on network constrained market simulation tools, interactions between various regulatory frameworks and joint Transmission System Operator (TSO) and Distribution System Operator (DSO) activities, to name a few.

In research, a common practice to test smart grid concepts is by means of simulations. However, due to the above described complexity, modelling a smart grid is far from simple. Simulators often do not capture both the physical power grid, the ICT components, the decisions from multiple grid operators and market actors, as well as heat, power and gas networks. Instead of tackling all these factors by one simulation, researchers develop so called “co-simulations”, which consist of multiple simulators, coupled together by a software interface. Each simulator may cover a different aspect of the smart grid. Together, the simulators allow researchers to analyze complex interactions and dynamics in more detail.

Rehtanz and Guillaid [5] describe a co-simulation as “hybrid simulation models and different representations which are executed in individual runtime environments”, with a particular challenge to synchronize this complex setup. The focus of their work is real-time simulation for hardware in the loop (HIL) and electromagnetic transient (EMT) simulations.

The work by Mets et al. [6] surveys power grid and communication

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https://doi.org/10.1016/j.apenergy.2018.03.123
Received 20 September 2017; Received in revised form 23 February 2018; Accepted 27 March 2018

network co-simulations. Their approach to co-simulation is motivated by the fact that creating a new simulation environment, which simulates power and ICT network, is "potentially time-consuming and expensive". Hence the survey provides an in-depth look at existing simulations and presents a classification of different co-simulation environments. In the author's opinion, the main challenge is, "to connect, handle and synchronize data and interactions between both simulators using their respective simulator interfaces".

A recent survey by Cintuglu et al. [7] provides a systematic study for smart grid cyber-physical testbeds, being testing environments for novel smart grid concepts. Amongst the four testbed categories are simulations, HIL environments, real-time simulators and hardware-based platforms. Co-simulations are addressed as part of the first category, though they are not the primary focus of the survey. A broad view on co-simulation in power systems is outlined by Schloegl et al. [8]. In this work the authors presents a morphological box with eight different categories of simulators. However, this box is subsequently applied to only one particular co-simulation.

Building on these recent works, our goal is to provide a more general survey of 26 smart grid co-simulations, focusing on features such as involved simulators, research topics, open source availability as well as the mechanism for synchronizing different simulators.

The structure of our paper is as follows: Section 2 gives a common understanding about the term "co-simulation" and its implications. Section 3 explains the methods of our survey, e.g. the search and classification procedure. Section 4 contains the results of the survey and Section 5 provides an in-depth discussion and analysis of the results.

2. A common understanding of co-simulation

In this work, simulations are addressed which are applied to smart grid relevant topics; examples can be found in Refs. [9,10] or [11] and an introduction to smart grids can be obtained from Refs. [12] or [13]. In this section, our understanding of a co-simulation in the context of smart grids and its required components is presented.

2.1. Definition of co-simulation

A co-simulation is a special kind of simulation in which multiple simulations are coupled together. We first investigate the essential parts of a co-simulation:

- Simulation models (B)
- Simulation solvers (C)
- Runtime infrastructure (D)
- Simulation synchronization (E)
- Different types of simulations (F)

2.2. Simulation models

Simulation models are mathematical models describing a real world phenomenon through mathematical rules and language. There exist many categories of mathematical models: for instance, one can categorize models according to temporal (static versus dynamic) and spatial properties (e.g. ordinary versus partial differential equations). Electric power systems for example are commonly simulated with models such as *algebraic, statistical* and *(partial, delay) differential equations* [14–16]. Communication networks, on the other hand, are commonly simulated as *discrete event systems* [17]: this is a model where state changes (events) occur at discrete instances in time and an event takes zero time to happen. Lastly, some models are described via parameters or measured curves.

2.3. Simulation solvers

We refer to "solvers" as the mathematical/computational solution method that is applied to either exactly solve a model or approximate its solution with sufficient numerical accuracy. Power system models, for example, are commonly solved by numerical methods, e.g. [18,19]. Communication network models, on the other hand, are solved by computational loops, which process upcoming events (e.g. the sending of a data package) in a causally correct fashion. The loops are stopped when all scheduled events are processed or a certain computation time limit is reached [17].

Solvers are not necessarily limited to solving only one model, they can solve different models or they can be able to solve many instances of the same model with different parameters.

2.4. Runtime infrastructure

"Runtime infrastructure" refers to the underlying architecture which orchestrates, coordinates and exchanges information in the simulation (often called "communication infrastructure"). Such infrastructures may not be needed for every simulation setup, but are important in co-simulations. They rely on a central coordinator (e.g. INSPIRE and VPNET), whereas others, such as HLA, Mosaik or OpSim rely on a more complex system (see Table 2). In his book [20], Fujimoto classifies computers in two groups, which define the communication infrastructure:

(1) Parallel Computers, e.g. symmetric multiprocessor, are tightly coupled systems which often share the same memory and are able to do inter process communication. Their communication latency is typically less than 100 µs.
(2) Distributed Computers are often composed of several computers from different manufacturers. Normal network technology is often used to interconnect these machines, creating a typical latency of around 10 ms (for LAN Networks) up to seconds for radiofrequency or satellite based communications.

These two groups require different programming strategies and therefore present their own challenges to the runtime infrastructure.

2.5. Simulation synchronization

Simulation synchronization describes the way in which time stamped data is exchanged between simulation solvers. The topic of time and data synchronization is often solved by the runtime infrastructure (see [21,20,22] or [23]). In Ref. [20] p. 51 it is cited that "*Errors resulting from out-of-order event processing are referred to as causality errors, and the general problem of ensuring that events are processed in a time stamp order is referred to as the synchronization problem.*" It implies that very tight limits for the simulation infrastructure are required. Parallel computers might handle this, but distributed computers present a major challenge requiring special attention, due to their latencies discussed in the previous subsection.

The first major class of algorithms for solving this problem is called "*conservative synchronization*", where each simulator strictly processes events in a time stamp order. For example, a dynamically defined barrier for all simulators, which only allows a next simulation iteration after all simulators have finished. It is referred to as "*barrier synchronization*".

The next class is called "*optimistic synchronization*", wherein errors are detected during the simulation and different mechanisms are used to revert them. For example, a pre-defined number of events are stored and in case of an out-of-order event, the simulation is reversed to a time before this event and executed again with this event in order; hence it is called "Time Warp". The name "*optimistic*" comes from "optimistically", assuming that there are no causality errors.

The third class is *"web-based"* and uses web-services such as REST or SOAP. It focuses on model reuse and providing a better interoperation between different simulators. In addition, cloud computing has emerged as an attractive alternative with virtualization playing a key role. The integration of specialized hardware, such as GPUs, serves as a coprocessor and features a substantial amount of parallel threads.

The three classes of algorithms are not mutually exclusive; there exist variations and hybrid algorithms, combinations and derivations of the aforementioned, with their benefits and drawbacks. The emphasis of all is on as-fast-as-possible execution. In summary, a synchronization method is vital to ensuring causally correct simulation results. Therefore, our survey will take into account the synchronization method as a key characteristic of co-simulations.

2.6. *Different types of simulations*

There exists a wide variety of co-simulations and their categorization into different types was performed in previous publications. For example, in Ref. [5] Rehtanz et al. present four different categories. The focus is on real-time simulations and the authors define simulations either as "real-time" or "with real-time constraints". Therefore, this reference addresses co-simulation timing complexity, though model sizes and solver complexity are not considered. There may also be the need to simulate faster than real-time, but this is not regarded.

Another definition, based on model complexity, was established by Schloegl et al. [8]. The authors also define four different types of simulations. However, this definition does not incorporate the difference between strongly (parallel) and loosely (distributed) coupled simulations.

In Fig. 1 we propose an alternative scheme with two additional categories. We associate solvers to CPUs used for solving equations - this is a simplification, as modern CPUs tend to be able to run several programs nearly in parallel by e.g. Hyper-Threading. The horizontal axis shows three different simulation architectures: (1) Single simulation architectures only use one solver and solver communication is not an issue. (2) Parallel simulation architectures (e.g. tightly coupled systems) need an inter solver communication, which can be achieved easily as modern computers and operating systems incorporate many different technologies (shared memory, loopback …) for a fast interprocess communication. (3) Distributed simulation architectures are more complex, due to the need of an interconnection technology between solvers (TCP/IP, InfiniBand …) and a runtime infrastructure, to solve the challenge of synchronization. Following the approach in Ref. [8], the vertical axis contains two categories which represent whether the simulation contains one or more models.

Incorporating real-time constraints into Fig. 1 could be done via a line. Below the line, the simulation is slower than real-time, exactly on the line, the simulation runs at real-time and above the line the simulation executes faster than real-time. A generalization of this line cannot be given here, as it depends on several factors, which are not generally definable (e.g. model size, time complexity, number of CPUs, solver speed …).

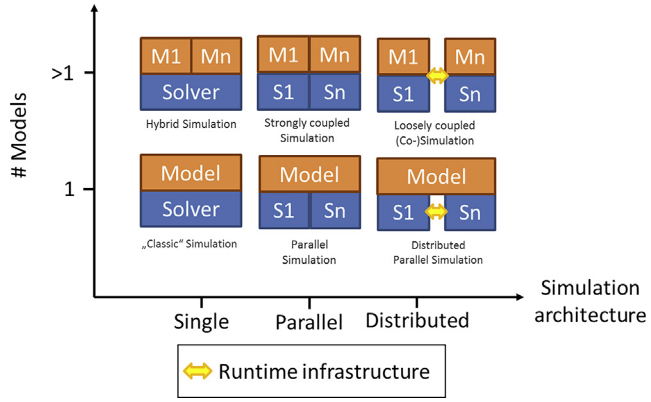

Fig. 1. Six different types of simulations. They are separated by their "degree" of complexity defined by the number of models and used architecture.

Because time and model size are key factors for co-simulations, we will consider them in our survey. However, the model size cannot easily be deduced from publications, therefore a slightly easier obtainable measure is used: the number of buses in the grid simulation.

3. Performing the survey

We surveyed over 50 publications on 26 smart grid co-simulations. Our requirement on such a simulation is that when it runs multiple times with the same initial conditions, it must produce the same results. Therefore, we decided against the inclusion of frameworks without time (and data) synchronization, as random effects from network latencies can influence the results. Many agent-based simulations (ABSs) are supposed to work independently, hence, time synchronization is not part of Multi-Agent Systems (MASs) and their interactions are purely event based [24,25].

We started our search by considering referenced works (for example [5,6,8]). From this, we built up a list and expanded it until we arrived at 26 different co-simulation environments. Based on the surveyed publications, we deduced several key characteristics which are summarized in Tables 2 and 3 below.

Comparing different co-simulations is challenging; not all of them are accessible and their focus may vary strongly. Instead of comparing the frameworks directly, we established correlations and histograms of their key characteristics. In this section, we describe the characteristics of our survey.

3.1. *Framework name, open availability and power system simulators*

Not all co-simulations were named, hence they are numbered for convenience. Furthermore, we listed if the framework is available as open source. The characteristic "power system simulator" contains which simulator was used for the electric grid. For example, pandapower is capable of simulating static load-flows [26]. For a detailed description, interested readers are referred to [6].

3.2. *Real-time and HIL capabilities, additional systems and synchronization*

Further key characteristics are the real-time and hardware-in-the-loop (HIL) capabilities of a co-simulation framework. We also list additional simulators to the aforementioned "power system simulator". Most additional simulators, such as NS2, NS3 or OMNeT++, emulate communication networks [6].

The synchronization method is also considered to be an important characteristic. If a concrete synchronization method is presented, it will be listed and classified, based on its description in the literature. Nine different methods were found in the survey (including several sub methods), which were classified into three categories:

I. **Discrete event synchronization:** simulations are based on events, which can occur at any time. A "data packet" in this context is considered to be an event. This allows the co-simulation to react to events, but the simulation time is progressed discontinuously and continuous-time processes (e.g. differential equations) must be considered with some caution. Most often, this class is used when communication simulators are part of the co-simulation, or when distributed computers with LAN communication are applied to solve the models (as LAN uses data packets).

"**Global event driven**": a global event scheduler is used as the global time reference and coordinator and time stepped processes are treated as special events [27]. A global schedule is created by this coordinator and only one process is allowed to run at a time. Based on this schedule, the control is handed over to the according simulator.

"Discrete EVentS" (DEVS) is a timed event system. Its modular and hierarchical formalism is used for modelling and analyzing general systems [28]. Synchronization is achieved by using a special coupling algorithm. There exist several different algorithms, but basically the simulation is triggered by events, which in turn invoke outputs and external transitions. It also schedules new internal transitions to a future time step given by the component.

"Conservative": a simulator is blocked until it can make sure that all following events are after the last received one and it is safe to process. (see [23]). Every calculation can be split into two phases. The first phase is executed when all simulators finished processing and the next time step is calculated, events are now exchanged. The second phase is the start of the simulators processing the next time step.

"HLA" uses different algorithms for synchronization [29]. It consists of three components: Framework and Rules, Federate Interface and Object Model Template Specification. It is carried out using discrete events and differentiates between "super real-time" and "less real-time" simulations. Conservative-, optimistic-, barrier-, time-stepped synchronization algorithms are all available for HLA.

"Discrete Event" (mosaik) is similar to the global event driven category [30]. Each simulator must provide a self-description. Based on this description, mosaik creates a schedule with predefined synchronization points and sends step commands to every simulator. A directed acyclic schedule graph is used to determine the order of these step commands.

"Models of Computation" (Ptolemy) are nine different modes which are interchangeable and are able to work together [21]. The models are distinguished by their timed nature: untimed (reactive) and timed (superdense packed time). Every model uses a "director" which is responsible for the execution of its "actors".

II. **Time stepped synchronization** contrasts with discrete event synchronization: based on a scheduled regular time interval, the simulation time is progressed continuously (though with "small gaps" i.e. the resolution). This class is often used when a system of differential equations is solved and sampled in regular intervals. Reacting to "events" is only possible during those steps, which introduces additional, possibly harmful, time delays into the simulation.

"**Time Stepped**": several synchronization points are predefined. Simulators run independently until they reach such a point, at which they suspend themselves and exchange information. The downside is that, if an interaction is required in between the synchronization points, the simulators have to wait until the next point, resulting in unwanted delays.

"**EPOCHS**" utilizes a runtime infrastructure which is responsible for simulation synchronization and communication between simulators [31]. In a time-stepped fashion, each simulator is executed until a preset simulation time is reached. When this point is reached by all, their interaction is allowed and the infrastructure chooses the next synchronization point. Time steps are user-selectable and scale the granularity of a co-simulation.

"Round robin" slices time into equal portions and a server assigns these portions to each simulator. In a circular order the simulators are allowed to perform their calculation. It can be used preemptive, i.e. when the server forces a stop condition when the time quota expires.

III. **Barrier synchronization:** a barrier is introduced into the simulation. Every simulator is executed up to this barrier and will stop and wait for a signal to resume its calculation. Most of the time this is done via a central controller or monitor, awaiting input from all slave controllers. Most programming languages support this type of synchronization through their threading APIs on parallel computers.

"Client – Server model": a central controller is responsible for the co-simulation [32]. The controller runs the simulation programs based on its configuration file and collects their output. These runs can be parallelized on modern hardware, but a barrier is used to synchronize the simulators, due to the central controller deciding which one is next.

Table 1
Smart grid research areas.

Integrated Systems (IS)
- **IS01** Interactions and responsibilities between distribution grid operators and other stakeholders
- **IS02** Compatibility issues between Pan-European and national markets and stakeholders
- **IS03** Ancillary system services, sustainable system operations and low level system user dispatching
- **IS04** Advanced forecasting techniques for sustainable operations and power supply
- **IS05** Grid State monitoring
- **IS06** Architectures and tools for operations under abnormal conditions, restorations and defense Plans
- **IS07** Storage in all energy carrier forms
- **IS08** Information and communication needs for Smart Grids
- **IS09** Training tools
- **IS10** Pre-Standardization models and functions
- **IS11** Materials

Retail and Consumers (RC)
- **RC01** Consumer Driven local services, markets considering distribution grid constraints
- **RC02** ICT for Smart Consumers
- **RC03** Electric Vehicles (EV) for Smart Consumers

Distribution Systems (D)
- **D01** Smart, flexible distributed demand and generation response for Secure Distribution System Control
- **D02** Extended Distribution System Protection across the value chain
- **D03** Integrated Distributed Energy Storage infrastructure planning in distribution systems
- **D04** Electric Vehicle (EV) integration into Distribution systems
- **D05** Risk Based DSO Operation: Real time calculations to identify additive margins offered by line monitoring, could help to solve critical situations
- **D06** ICT System security for Distribution Operation
- **D07** Power Electronics Technology for Smart Distribution
- **D08** DC: an option for the LV grid in the future

Transmission Systems (T)
- **T01** Transmission Grid Infrastructures
- **T02** HVDC Grid based system
- **T03** Bulk Energy Storage infrastructure, planning, integration, operation
- **T04** Long distance electricity wheeling
- **T05** Energy carrier technologies for the energy service consumer
- **T06** Incentives, monitoring and controls for large scale consumers

Transmission and Distribution Systems (TD)
- **TD01** Grid Asset System Planning (life cycle)

Socio-Economics (SE)

Our survey considers both the three main synchronization methods and their sub-categories, in the columns "Synch. class" and "Synch. method" of Table 2 respectively.

3.3. Research area classification

The survey also addresses research areas to which a co-simulation framework has at least been applied, based on the publications. For example, some frameworks may be applied to investigate wide area monitoring issues, whereas others may emulate electric vehicles. A detailed description of a "research area" lies beyond the scope of this survey; instead, we employ 30 research areas from the European Technology Platform Smart Grids [9,10], listed in Table 1. This section describes the six main categories, which subdivide the research areas.

"Integrated Systems" (IS) covers research areas in which a distinct separation between stakeholders is not possible, or topics which apply to more than one stakeholder. Examples are ancillary services, forecasting architectures, grid monitoring (e.g. WAMS), grid restoration and defense plans. It also includes storage technologies, standardization, training tools and smart materials.

Table 2
List of different co-simulation environments (ND = No data).

Case	Appl. Refs.	Name of co-simulation	Open Source	Power system simulators	Additional simulators	Synch. method	Synch. class	Real-time	HIL
1	[33,34,27]	GECO	No	PSLF	NS2	Global event driven	Discrete event	No	No
2	[35,36,37]	ADEVS	Yes	MATLAB, adevs	OMNeT + +, NS2	“Discrete EVentS” (DEVS)	Discrete event	No	No
3	[38]	BoFit	No	Modelica, Neplan, PowerFactory, Integral	OMNet + +, HECTOR, R, GNS3, Netsim	ND	ND	No	No
4	[39,40]	DACCOSIM	Yes	*None*	Modelica	Time stepped (HLA, Optimistic & Prudent Mode)	Time stepped	No	No
5	[31,41,42]	EPOCHS	No	PSCAD/EMTDC, PSLF, OpenDSS	NS2, AgentHQ, OMNet + +	EPOCHS, Time stepped	Time stepped	No	No
6	[43,23]	FNCS	Yes	GridLAB-D, PowerFlow	NS3	Conservative	Discrete Event	No	No
7	[44]	*ND*	ND	PowerFactory	OMNet + +, JADE	ND	Discrete Event	Yes	No
8	[45]	GridIQ	Yes	PSAT	JADE	Time stepped	Time stepped	No	No
9	[46,47,48]	*ND*	No	GridLAB-D	MATLAB	Time stepped	Time stepped	No	No
10	[49]	GridSpice	Yes	GridLAB-D, MATPOWER	GridLAB-D	Discrete Event (HLA like)	Discrete Event	No	No
11	[50,51,52]	INSPIRE	No	PowerFactory	OPNET	HLA-Based	Discrete Event	Yes	Yes
12	[53,54,55]	MACSimJX	Yes	MATLAB	JADE	Global event driven	Discrete Event	No	No
13	[56]	MECSYCO	Yes	Modelica, EMTP-RV	NS3, OMNet + +, OPNeT	DEVS	Discrete Event	No	No
14	[57,30,58,59,60,61]	mosaik	Yes	PYPOWER, IPSYS, Opal-RT, PowerFactory, Pylon	MasSim, JADE, Modelica, MATLAB	“Discrete Event” (mosaik)	Discrete Event	Yes	Yes
15	[62,63,64,65,66]	OpSim	No	pandapower, Opal-RT, Jpower, PYPower	MATLAB, Openfire	Conservative	Discrete Event	Yes	No
16	[67]	PowerNet	No	Modelica	NS2	Time stepped	Time stepped	Yes	No
17	[68,69,21]	Ptolemy	Yes	*None*	MeDICi	“Models of Computation”	Discrete Event	Yes	Yes
18	[70,71]	VirGil	Yes	PowerFactory	OMNET + +, Ptolemy II, Modelica	Discrete Event	Discrete Event	Yes	Yes
19	[72,73]	VPNET	No	VTB	OPNET	Time stepped	Time stepped	No	No
20	[74,75,76]	SMB	No	PowerFactory	EVSim, OCPP-Simulator, OMNeT + +	Discrete Event	Discrete event	Yes	Yes
21	[77,78]	*ND*	No	PowerFactory	EVSim, MATSim, MATLAB	Round robin, Time stepped [79]	Time stepped	ND	ND
22	[80,81]	*ND*	No	RSCAD	Matlab	Time stepped	Time stepped	Yes	Yes
23	[82]	*ND*	ND	OpenDSS	NS2	Discrete Event	Discrete Event	No	No
24	[32]	*ND*	ND	GridLAB-D	AMES	Client – server model	Barrier	Yes	ND
25	[42,83]	*ND*	Yes	OpenDSS	OMNeT + +	EPOCHS Time stepped	Time stepped	No	No
26	[84,85,86]	OrPHEuS	No	PowerFactory	Modelica (Dymola), STANET[a]	Ptolemy	Discrete Event	ND	ND

[a] Was not actually part of the simulation (see [84]).

Table 3
List of simulated applications (ND = No data).

Case	Appl. Refs.	Name of co-Simulation	Application grid size (bus)	Application timespan (s)	Research area in application	Application - short description
1	[33,34,27]	GECO	39; 39; 127	**0.1; 0.6; 0.6**	IS05, IS06	Agent-based remote backup relay protection scheme.
2	[35,36,37]	ADEVS	12; 17	**20; 2**	IS05, IS06, D06	Offshore DC Micro grid cold start scenarios; wide-area cooperative automatic load-control.
3	[87]	BoFit	*ND*	***ND***	TD01	Co-Simulation of market, grid and communication network.
4	[39,40]	DACCOSIM	No grid	**58,000**	SE	Heat transfer between buildings.
5	[31,41,42]	EPOCHS	5; 145; 4	**0.8; 10; ND**	IS05, IS06,	Agent-based power system protection scheme; Protection scheme for transient power system stability; Wide-area monitoring.
6	[43,23]	FNCS	18; ND	**ND; 21,600**	IS01, D01, D06, RC01, RC02	Demand response/real-time pricing for a residential energy management system. Possibilities to support the transmission grid.
7	[44]	*ND*	13	**150**	D01, D06	Agent-based monitoring and voltage control in the distribution grid.
8	[45]	GridIQ	6	**ND**	IS05, IS06	Agent-based balancing of power generation and demand.
9	[46,47,48]	*ND*	13	**84,000**	RC01, D01	Volt-var control, mitigating wind power fluctuations by controlling multiple heat pumps.
10	[49]	GridSpice	> 2935 (plus distr. grid buses)	**86,400**	IS01, IS03, D04,	Optimal placement of solar panels in distribution networks, considering transmission network effects.
11	[50,51,52]	INSPIRE	39; 39	**150; 29**	IS05, IS06, T02	Evaluation of the real-time performance of wide-area monitoring, protection and control; impact of communication delays on grid monitoring.
12	[53,54,55]	MACSimJX	7; 14; ~11;ND	**86400; 86400; 0.25; 32,400**	IS05, IS06, IS07, D01	Generation and demand scheduling in a micro grid-market scenario; multi-agent controller to maintain system continuity during fault; modelling a solar microgrid controller.
13	[56]	MECSYCO	~12	**0.0015**	D01, D02, D06	Agent-based MV grid fault detection and load shedding.
14	[57,30,58,59,60,61]	mosaik	~52; 3; 38; ND; ~130	**86400; 5000; 86400; 86400; ND**	IS01, IS03, D01, D04	Coupling Opal-RT and PYPOWER; agent-based control of island grid; FMU tests; Voltage stability of grid simulation with a real PV-converter hardware; evaluation of electric vehicle charging strategies
15	[62,63,64,65,66]	OpSim	635; ND; 1210; 117,000	**120; ND; 28800; 31,536,000**	IS01, IS03, D01, D06	Reactive power provision from DSO to TSO; real-time voltage controller-the-loop testing; annual simulation of multi-voltage grid model.
16	[67]	PowerNet	2	**6**	D06	Influence of communication delays wind turbine voltage controller.
17	[68,69,21]	Ptolemy	No grid	**6000**	IS05, IS06	Modelling middleware architecture for PMUs, taking into account uncertainties such as sensor failure and environmental conditions.
18	[70,71]	VirGil	7; 10	**86400; 3600**	D01, SE	Demand response to reduce cable loading, load following, ancillary service provision by flexible load
19	[72,73]	VPNET	5; ND	**0.1; 0.03**	D02, D06	Agent-based fault protection scheme for a ship DC power system; DC-DC boost converter in which the power switch duty cycle is computed remotely
20	[74,75,76]	SMB	14; ND; ~7	**86400; 28800; 86,400**	IS03, D01, D04	Comparison of different EV charging strategies; voltage controller testing; modelling cyber-security attacks to develop secure smart grid control applications.
21	[77,78]	*ND*	105; 52	**86400; 86,400**	D01, D04	Evaluate impact of EV charging on electric network; investigating the PV-battery systems on distribution grid voltage imbalance
22	[80,81]	*ND*	33	**86,400**	IS03, IS05, IS06	Verification of the performance of a volt-VAR control algorithm for reconfiguration of a distribution network.
23	[82]	*ND*	ND	**20**	D01, D06	Study the impact of combined PV-storage control systems on the grid voltage, for different controller transmission power levels.
24	[32]	*ND*	6	**86400, 864000, 2,592,000**	IS02	Analyzing the influence of load changes on nodal prices, in a real-time market-grid coupling scenario.
25	[42,83]	*ND*	14; 30; 13	**86400; 864000; 300**	IS05	Evaluation of a state estimation algorithm, voltage monitoring and voltage control in the distribution grid.
26	[84,85,86]	OrPHEuS	> 137 (137 house connections on feeder)	**31,536,000**	D03, T05	Combined power, heat and gas simulations, to investigate potential benefits of sector-coupling for lowering distribution grid expansion costs.

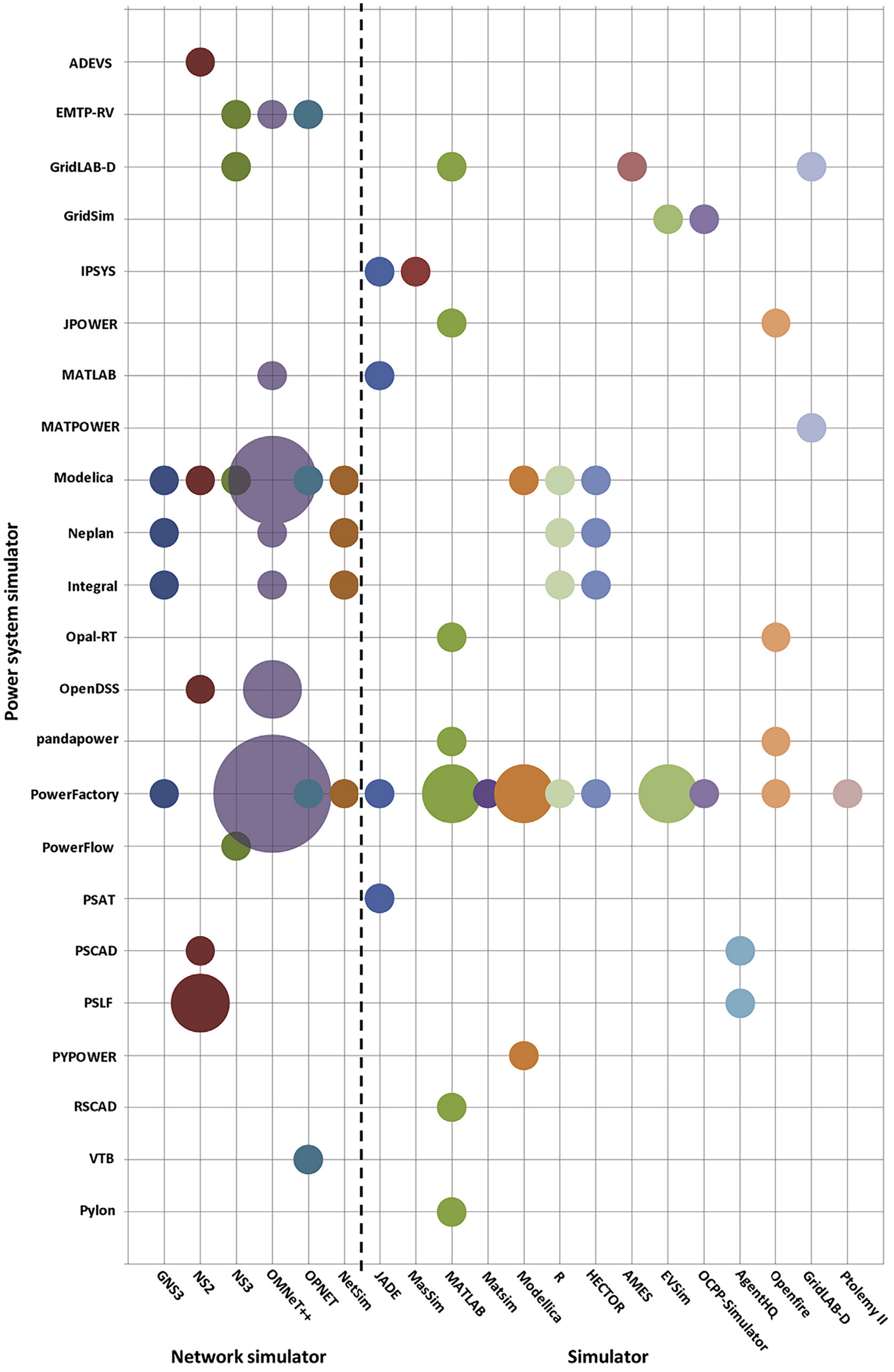

Fig. 2. Correlation between power system simulator and other simulation tools.

In contrast, "Retail and Consumers" (RC) specifically focuses on consumers of energy products and services. It covers demand response and demand side management, new energy and ancillary service markets, ICT for smart consumers and electric vehicle integration. "Distribution Systems" (D) and "Transmission Systems" (T) are dealing with distribution and transmission grids respectively. "Transmission and Distribution Systems" (TD) covers issues common to both "D" and "T", such as asset planning.

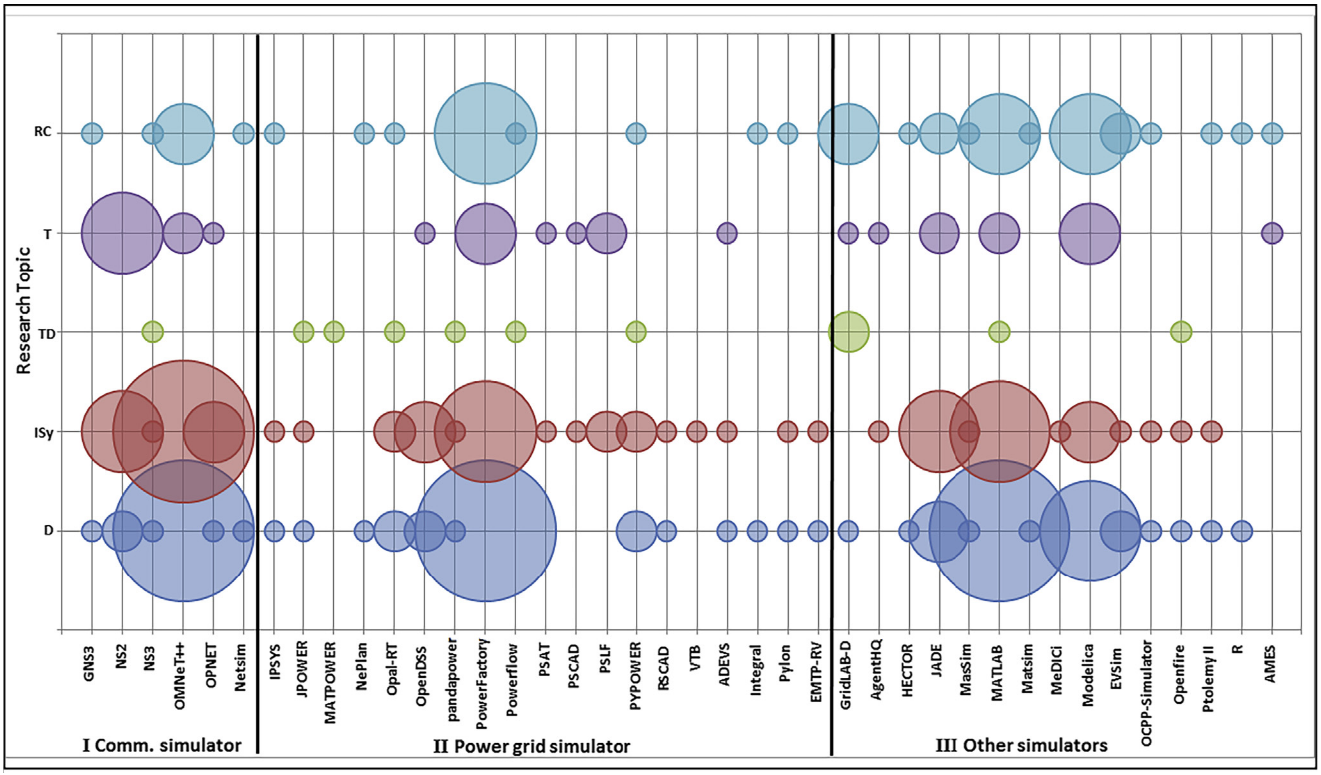

Fig. 3. Correlation between research topics and different simulators. Abbreviations: **D**: Distribution Systems, **ISy**: Integrated Systems, **TD**: Transmission and Distribution Systems, **T**: Transmission Systems, **RC**: Retail and Consumers.

Lastly, the category "Socio-Economics" (SE) deals with topics related to sociological questions of consumer demand response, as well as grid-building interactions. Few surveyed co-simulations covered the SE category; hence, it was decided to consider only its underlying grid-building topic into one "SE" research area.

4. Discussion of results

In this section, we analyze different aspects of the surveyed co-simulations in Tables 2 and 3. First, we correlate power grid simulation tools with "other" simulation tools (see Fig. 2). This reveals if there exist "popular" combinations of simulation tools, or if their composition is mostly random. Second, we correlate research topics and simulation tools (see Fig. 3). This illustrates which simulation tools are often or seldom used in a co-simulation of specific research topics. Third, we compute histograms of research topics, power grid size and simulation time (see Fig. 4, Fig. 5, Fig. 6). This provides some deeper insight into

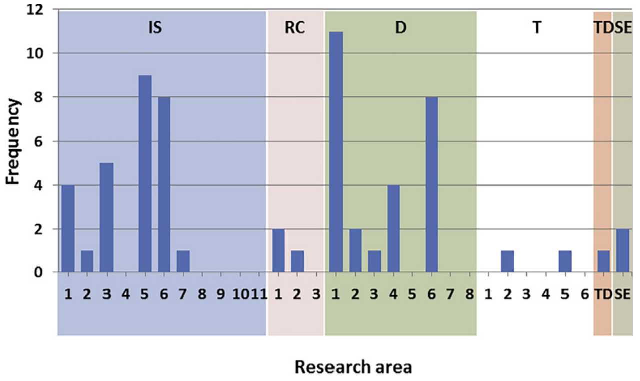

Fig. 4. histogram of research areas in which the surveyed co-simulations are applied.

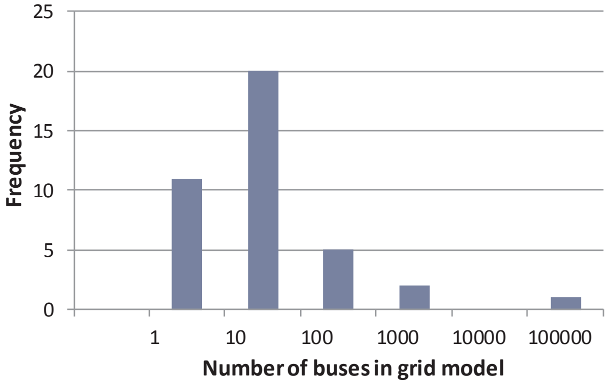

Fig. 5. histogram of the number of buses in the grid model of surveyed co-simulation applications.

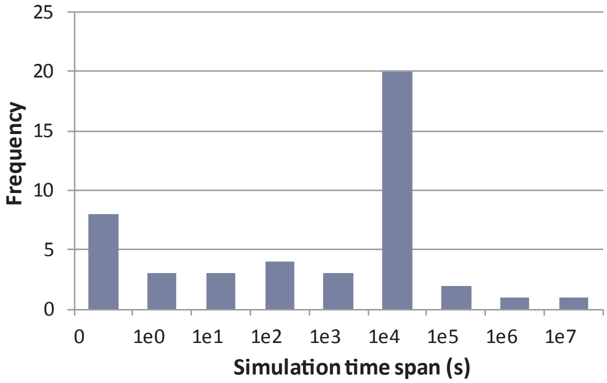

Fig. 6. histogram of the simulation time span of surveyed co-simulation applications.

the type of problems that are commonly solved with a co-simulation. We conclude our discussion with some additional properties of the simulation tools.

4.1. Correlation between different simulation tools

First, we analyze if there exist trends for combining particular simulation tools in a co-simulation. For this purpose, a correlation was created in Fig. 2, based on the results in Table 2. A circle represents the combined use of two tools. If one simulator was coupled with two or more simulators, these will be individual points. The size of a circle directly correlates to the number of different applications. Here we will only discuss some prominent features of the correlation, due to its scattered nature.

The correlation elucidates that PowerFactory is combined with most other simulators, with some preference for OMNeT + + and EVSim. This is probably due to its easy extensibility and wide distribution. On the other hand, Modelica is often coupled to communication simulators, especially OMNeT + +.

OMNeT + + is quite often used in conjunction with different power grid simulators. Also, NS2 was often coupled with PSLF and used more often than NS3. This is interesting, considering the fact that active development of NS2 stopped in 2010. Jade is also used quite often with different power simulators due to its agent based abilities.

On a closer look, GridLAB-D is present on both axes because some authors use it as a power system simulator [e.g. case 6, 10 and 24 in Table 1] while other authors use it to model another aspect. It is interesting to note that, while GridLAB-D is often mentioned in publications, only a few of the 26 surveyed co-simulations apply this tool.

4.2. Correlation between research topic and simulation tools

In Fig. 3 we have correlated research topics with simulation tools. For clarity, we grouped the simulators into three categories: communication network simulators (I), power grid simulators (II) and “other” simulators (III). The last category includes all tools which are not used to emulate a power grid or communication network in the surveyed co-simulation literature.

It can be seen that the research topics “Distribution Systems” (D) and “Integrated Systems” (IS) contain nearly all simulation tools. Co-simulations which address research topic D seem to have some preference towards Omnet + +, PowerFactory, Matlab and Modelica. Co-Simulations which address research topic IS seem to employ NS2, Omnet + +, PowerFactory, Matlab and Modelica more frequently than other simulators. On the other hand, the research topic “Transmission Systems” (T) is only addressed with a subset of the simulation tools, of which the communication simulator NS2 seems to be used frequently.

4.3. Distribution of research areas

A frequency distribution of research areas from Table 1, which are applied in the surveyed co-simulations, was derived (see Fig. 4). Many co-simulations are applied to more than one area; with a total histogram frequency of 62, roughly 2.4 research areas are on average considered per co-simulation. We observe that the areas “Integrated Systems” (IS) and “Distribution Systems” (D) are the most prominent ones, whereas “Transmission Systems” (T), “Retail & Consumers” (RC), “Transmission & Distribution Systems” (TD) and Socio-Economical (SE) have a low frequency. The high counts in “Integrated Systems” occur because many co-simulations emulate transmission grid state monitoring and restoration after grid faults (area IS05 and IS06). Likewise, the high counts in “Distribution Systems” are due to various co-simulations dealing with control methods for distribution grids or combined grid & ICT simulations (areas D01 and D06 respectively).

4.4. Distribution of number of buses in grid model

A second histogram in Fig. 5 illustrates how many buses the power grids in each co-simulation application contain. It must be clarified a priori that this number is *not* a mathematical problem size, since an EMT simulation of only a few buses can contain a substantial amount of equations. Rather, we think of “number of buses” as how much topological detail a co-simulation captures. Also, we must point out that the histogram in Fig. 5 focuses on each *application* of a co-simulation: e.g. if a co-simulation is applied to study two power grids, one with 39 and one with 1000 buses, the histogram contains 2 entries at 39 and 1000 buses.

The majority of surveyed co-simulation applications are applied to grids with 100 buses or less. For example, 3 of the surveyed co-simulation applications on protection schemes utilize the New England 39 bus model.

4.5. Distribution of simulation time spans

A final histogram was derived for the simulation time span: the period of simulated time over which the co-simulation is performed. Similar to the last section, it must be clarified that the histogram focuses on each *application* of a co-simulation: e.g. if a co-simulation is applied to study two problems, one with a simulation time span of 10 s and one with 3600 s, the histogram contains two entries at 10 and 3600 respectively. In contrast to the histogram of bus numbers, the simulation time span covers a wide range of different values with a peak between 10^4 and 105 s (see Fig. 6). The histogram peak is caused by the fact that 20 co-simulation applications have simulation time spans of about 1 day. For example, frameworks such as VirGil are applied to study demand-response effects over this time period. Frameworks such as GECO on the other hand, dealing with fault protection schemes, may focus on transient phenomena in the sub-second range.

4.6. Synchronization, open source, real time and HIL

From the 26 investigated cases, 11 were available as open source while performing the survey. This is in particular interesting for understanding the fundamentals and principles of a co-simulation; also a deep evaluation of the used code would be possible. Another interesting part was the synchronization mechanism, which was explained in Section 3.2:

(1) Discrete event (15 cases), based around “events” happening.
(2) Time stepped (9 cases), with equidistant time steps.
(3) Barrier synchronized (1 case), using a central controller approach.

One case did not present any details about their synchronization method. Finally, regarding the real-time capabilities, 10 out of 26 cases contained a real-time simulator: the whole co-simulation environment was able to perform calculations (and all communications) at least in real time. This is especially important if the simulation is combined in a HIL environment (at least 6 out of 26 cases), as external hardware components cannot be included in data and time synchronization.

4.7. Power-to-Gas and Power-to-Heat are sayings or self concepts (idioms)

Power-to-Gas (PtG) and Power-to-Heat (PtH) describe sector-coupling processes in which energy is transferred between the electric power grid and gas or heating networks. During the conduction of this survey, a number of publications on simulations of PtG and PtH were found. Their applications ranged from studying how disruptions in the electric power system affect the gas network [88] to investigating how sector-coupling could be used to lower the cost of grid expansion [84,85,86]. At least two types of simulation are used for emulating PtG and PtH:

- Coupling different simulators to form a co-simulation, such as the OrPHEuS environment in "Case 26" of Tables 2 and 3. Or "Case 15" OpSim, which was recently expanded, but the results are not yet published.
- Solving combined multi-physics equations of heat, gas and electricity networks in one single time frame with one simulation tool, e.g. Matlab [89] or SAInt [88]. Such simulations were not included in Tables 2 or 3, because they were performed with only one simulation tool and no synchronization or software-coupling was needed.

Given the complexity of multi-physics (co)-simulations, the electric grid models used in the surveyed studies usually have a fairly small number of buses, e.g. about 30 buses in [88,89], as well as 137 buses in [84]. Moreover, these PtG and PtH simulations are usually carried out over fairly long time spans (days or years) with simulation step sizes around 15 min. As a consequence, short-term dynamic effects in the electric power grid are neglected.

5. Conclusion

In this work, 26 Smart Grid co-simulations were surveyed on key characteristics such as the applied simulation tools, synchronization mechanisms, research topics and problem complexity. From this survey, as well as the author's domain knowledge, a number of conclusions can be drawn.

5.1. Conclusions from survey results

The most used simulation tools were Powerfactory and OMNet + +. Considering problem complexity, grid models with 100 or less buses seemed to be in favor. Simulation time spans were widespread; however, we observed two peaks at sub second and at 10^4–105 s. The first peak was caused by various co-simulations dealing with grid faults and the second peak existed because various examples considered one day in their application. As these time spans seem to be well covered, longer time spans, in the order of months, could provide interesting insight into seasonal effects (e.g. weather or market models).

Eleven co-simulations were based on Open Source software. We cannot distinguish if this is a trend or a continuous development, but Open Source software benefits from being easily available and being evaluable through other institutes and companies. On the downside, many projects were released "as-is" and were not properly maintained. As a side note, naming is rather important to make a simulation framework known in the community. Without a name, it is hard to find relevant information about a framework aside from the first publication.

Regarding the synchronization methods used, there was a clear trend towards discrete event synchronization. In the authors opinion this is understandable. Barrier synchronization is most often chosen for parallel computers based on the relative simple implementation on these architectures, but on distributed systems this method loses its advantages: An increasing amount of data needs to be transported (start and stop signals) and all simulators must wait for the slowest one, wasting computational potential.

Time stepped methods offer more flexibility and the advantage of not having to wait for other simulators, but their downside is that communication can only happen at certain points in time. Thus real-time applications need either to halt / wait or the time steps need to be chosen very small. For the authors, this method seems to be a possibility to enhance barrier synchronized simulators, such that they can be integrated into larger simulations. For example when a commercial product is used, which can only be controlled to a certain degree, time stepping the whole simulation can provide faster calculation times without the need to wait for the slowest participant.

The most flexible and by far most used concept is based around discrete events. It allows reacting to new events, and integrates well with modern distributed computer architecture. Also it is well suited for parallel systems through the support of loopback interfaces. One disadvantage is the modelling of time-continuous processes, because they need to be approached via slicing methods.

We regard this method to be the most promising for upcoming new technologies, based on cloud computing. As mentioned in Section 2.5, "*web-based*" or cloud based systems are under discussion [90] and new concepts such as simulation-as-a-service may be of interest. Also, concepts like virtualization will provide interesting opportunities because they allow for more portability and easier configuration of runtime infrastructures and a simplified process of setting up required software for a particular simulator.

Lastly, we categorized the research topics of the surveyed co-simulations on the basis of 30 EU smart grid research areas. Most co-simulations were applied to research areas from the category "Integrated Systems" or "Distribution Systems". Other research areas, such as "Compatibility issues between Pan-European and national markets and stakeholders", "Training tools" and "Integrated Distributed Energy Storage infrastructure planning in distribution systems" scarcely used. This may suggest some potential future applications for co-simulations.

5.2. Potential future co-simulation research areas from an ENTSO-E roadmap

The European Network of Transmission System Operators for Electricity (ENTSO-E) published a "research, development and innovation roadmap 2017–2026" [4]. Some applications for simulations in this roadmap are:

(1) **Network-constrained market simulation tools** that provide recommendations about specific network management and market designs. In particular, market processes were scarcely covered by the 26 surveyed co-simulations.
(2) Simulation options that account for **interactions between various regulatory frameworks**. These were not considered by the 26 surveyed co-simulations.
(3) Planning tools, methodologies and simulation software to assess the options for a pan-European power system, in particular for the transmission system infrastructure.
(4) To account **for coupling with other energy networks** (especially gas but also heat and cold) in the planning studies (simulations), e.g., dynamic coupling between gas and electricity networks.
(5) Improved defense and restoration plan for the pan-European grid and development of new tools to help TSOs to increase their reliability. Account for **failure modes of ICT (including sensors) in the different simulation tools**.
(6) **Joint TSO/DSO activities** - few co-simulations in our survey have addressed this; those which combined distribution and transmission grid models, did often not explicitly account for interactions between grid operators.

The common denominator of these applications is that they focus on more than one actor or physical aspect from the smart grid domain. Hence, some could potentially be tackled by using co-simulations.

5.3. Potential future co-simulation research areas based on the author's domain knowledge

A major challenge for Smart Grids is buffering the stochastic feed-in of renewable energies by some means of "flexibility". This is of key importance, as electric loads and (renewable) generation must be balanced at all times to avoid congestions or frequency deviations in the power grid. "Flexibility" can be obtained from electric storages (e.g. electric vehicles), but can also be achieved by feeding excess renewable generation into gas networks or by giving incentives to flexible consumers to shift their consumption patterns. From the author's point of view, at least three important future research directions for co-simulations arise from these challenges:

- **Investigating flexibility markets**, in which grid operators forecast grid congestions and buy flexibility from specific providers (e.g. virtual power plants). Co-simulations may be used to investigate how profitable such markets are under different congestion cases.
- **Simulating interactions between grid operators**. For example, if congestions arise in the transmission grid and flexibility options in the distribution grid are contracted to remedy the congestion, an information exchange between TSO and DSO is necessary.
- **PtH and PtG to reduce grid expansion costs**. Increasingly, grid operators focus on optimizing the electric, gas and heating networks as a whole. Co-simulation frameworks such as OrPHEuS can be used to estimate possible cost-reductions in power grid expansion, when adopting this holistic viewpoint.

In summary, there exists a wide variety of relevant Smart Grid research topics, which could be tackled in future works through co-simulations. Our survey results could be used to aid researchers in setting up new simulations, choosing adequate compositions of simulators or expand existing co-simulation platforms.

Acknowledgment

This work presents selected results from the project, “OpSimEval”, performed by Fraunhofer IEE and University of Kassel, funded by the Federal Ministry for Economic Affairs and Energy under grant no. 0325782A,B, based on a decision of the Parliament of the Federal Republic of Germany. The authors take full responsibility for the content of this paper.

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