*Review*

# Survey of Simulation Tools to Assess Techno-Economic Benefits of Smart Grid Technology in Integrated T&D Systems

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**Abstract:** In order to succeed in the energy transition, the power system must become more flexible in order to enable the economical hosting of more intermittent distributed energy resources (DER) and smart grid technologies. New technical solutions, generally based on the connection of various components coupled to the power system via smart power electronic converters or through ICT, can help to take up these challenges. Such innovations (e.g., decarbonization technologies and smart grids) may reduce the costs of future power systems and the environmental footprint. In this regard, the techno-economic assessment of smart grid technologies is a matter of interest, especially in the urge to develop more credible options for deep decarbonization pathways over the long term. This work presents a literature survey of existing simulation tools to assess the techno-economic benefits of smart grid technologies in integrated T&D systems. We include the state-of-the-art tools and categorize them in their multiple aspects, cover smart grid technology, approach methods, and research topics, and include (or complete) the analysis with other dimensions (smart-grid related) of key interest for future power systems analysis such as environmental considerations, techno-economic aspects (social welfare), spatial scope, time resolution (granularity), and temporal scope, among others. We surveyed more than 40 publications, and 36 approaches were identified for the analysis of integrated T&D systems. As a relatively new research area, there are various promising candidates to properly simulate integrated T&D systems. Nevertheless, there is not yet a consensus on a specific framework that should be adopted by researchers in academia and industry. Moreover, as the power system is evolving rapidly towards a smart grid system, novel technologies and flexibility solutions are still under study to be integrated on a large scale. This review aims to offer new criteria for researchers in terms of smart-grid related dimensions and the state-of-the-art trending of simulation tools that holistically evaluate techno-economic aspects of the future power systems in an integrated T&D systems environment. As an imperative research matter for future energy systems, this article seeks to contribute to the discussion of which pathway the scientific community should focus on for a successful shift towards decarbonized energy systems.

**Keywords:** power system simulation; integrated T&D systems; simulation tools; techno-economic simulation; future power systems; smart grid technology; energy system planning; DERs; decarbonization; flexibility; survey

## 1. Introduction

The socio-economic assessment of smart grids is a matter of interest for public authorities and utilities [1–4]. However, conventional transmission planning and generation expansion tools are not well suited to the new environment with more uncertainties in the forecast, and more flexibility constraints (including decentralized end-use flexibility assets) should be considered when planning for a future grid in a decarbonized economy.

Previous studies have mainly adopted energy system planning and simulation models, e.g., OSeMOSYS [5], MESSAGE [6], IAM [7], LEAP [8], etc., to design optimal portfolios

of generation technologies throughout the long-term planning horizon, including the type, construction time and scale of power plants required to meet the power demand [9]. However, these energy-model-based approaches that ignore electric grid equations and other limitations do not apply to emerging power systems with a rising influx of renewable energy and end-use smart grid flexibilities. The new characteristics of power systems with high VRE penetration levels consisting of all variations covering the electricity demand, supply, and smart grid flexibilities, should be considered in long-term system planning and cost-benefit assessments studies while moving forward.

As illustrated in Figure 1, the paradigm shift to planning models with increasing VRE seeks to go from a traditional planning model (left column) to an integrated planning model (right column). We need new tools to assess the value of flexible solutions such as energy storage and P2P electricity trading for all the possible services with which the power system can be provided (including needs for the distribution networks reinforcements), factoring in the conflicts of potential usage and accessing the various sources of flexibility (e.g., exchange of energy and reserve capacity services [10]). In order to achieve such a goal, new planning tools should work on planning and operation horizons altogether to identify the economically efficient levels of deployment for the various flexibility solutions, factoring in sources of potential, their costs and effects of scaling them up, and the effects of competition in accessing sources of value (congestion management, meeting capacity requirements for the security of supply, short-term flexibility requirements, etc.).
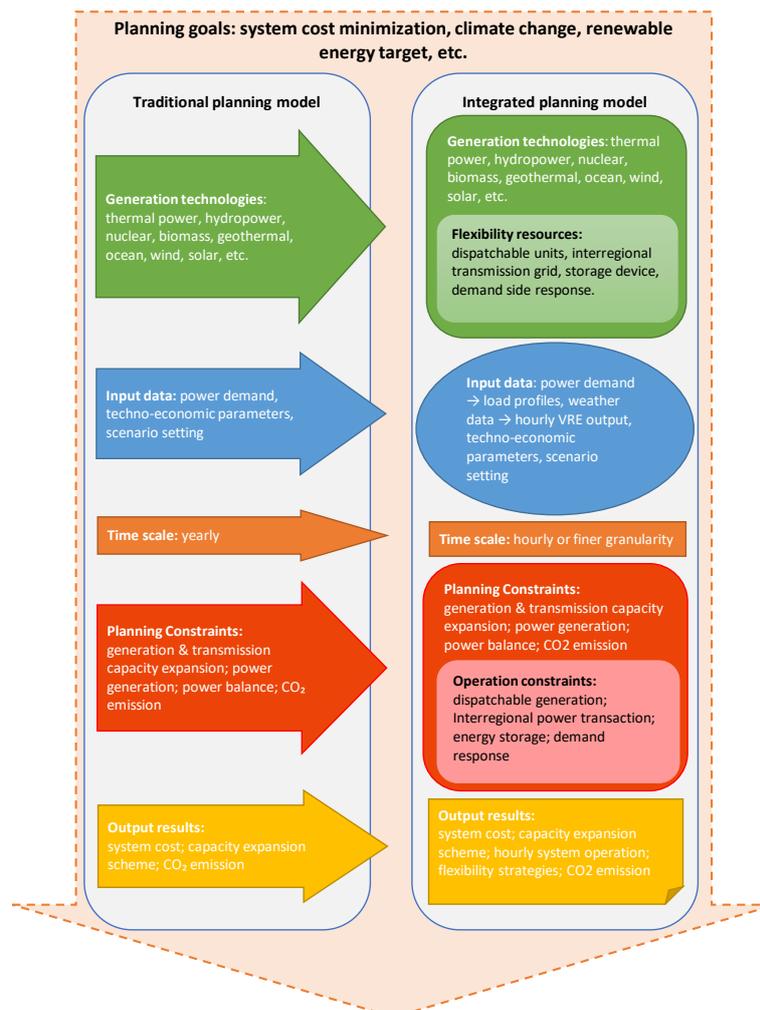


**Figure 1.** The paradigm shift to planning models with increasing VRE [9].

A new tool for economic assessment of technology impacts and unlocking of decentralized flexibility should provide several benefits compared with pre-existing studies [11–14].

## 2. Smart Grid Technology and Future Power Systems

### 2.1. Anticipated Changes in Future Power Systems

While the primary objective of a power system is to provide energy services with affordable costs to society within certain conditions and quality requirements, many countries have included an additional condition to the energy service; this is to supply the energy demand with sustainable resources for achieving low or zero-carbon energy systems in future. This transformation is being met mainly by the penetration of renewable energy resources, market [15], policy adoption, and flexibility options. In turn, this means a lot has to be studied to obtain the power systems ready for the transition as such changes can compromise the main objective of the energy service. For instance, as more inverters are introduced into the system, some services, such as inertia response or high-fault current, can be compromised and may affect the stability of the system [3,16]. Furthermore, the variability of renewable energy resources or the behaviour of smart consumers drastically changes the traditional planning and operational paradigms. For instance, the increased usage of renewable energy resources during the lockdown restrictions of the COVID-19 pandemic brought new challenges to the system operation, as discussed in [17].

In [4], the authors allege that anticipated changes in future power systems include at least:

- Generation shifts from central dispatching units to intermittent renewables.
- Generation shifts from a central connected transmission system to a decentralized connected distribution system generation.
- Generation shifts from a few large-centralized units to several small-distributed units.
- Electricity consumption will increase significantly.
- Electrical storage will be a cost-effective solution for system services.
- Measuring units will hugely increase the power system observability.
- Large amounts of fast-acting distributed resources would offer reserve capacity.
- ICT developments will support a more decentralized managed power system.

In turn, the authors in [14] claim that the conventional electricity network will evolve into the so-called smart grid, which comprehends:

(i) Increasingly low-carbon and distributed generation (even at the point of power consumption);

(ii) A transition of distribution networks from passive networks (planning worst-case peak demand scenarios) to active systems, where ICT and controllable distributed resources can provide real-time services while interacting with the transmission operator [18];

(iii) A more active transmission system by the introduction of flexible and controllable technologies FACTS and HVDC systems for controlling power flows, system integrity protection schemes (SIPS) which will enhance the power management after a network outage [19,20], and wide-area monitoring and control devices which with the support of ICT system improve the monitoring and control of the network in real-time and throughout wider areas [21];

(iv) The demand becomes controllable, and consumers become active participants in network and market operations. This opens a full portfolio of new opportunities for coordinating and aggregating consumers and network needs and increasing the flexibility through smart appliances [22]. Moreover, other energy demands can be served by electricity (e.g., heating, cooling, transport) which in turn will increase the flexibility of the system [23].

In the context of the smart grid, an increase or decrease in the system frequency can be compensated by the coordination of various actions from fast generation units and flexible loads (e.g., non-critical loads, battery systems such as electric vehicles, back-up distributed generation). On the other hand, network congestions can be handled by

changing system topology or impedances (control of FACTS or HVDC systems) instead of running a costly generation supply. This new operational flexibility can be utilized to deal with both real-time operation and time-ahead scheduling (where decisions are made regarding the uncertainty of variable generation). Such management of multiple operational flexibilities would increase network utilization and reduce levels of costly generation reserves [14,20,24].

### 2.2. Planning the Smart Grid, Challenges

In planning the smart grid, despite the increasing presence of ICT systems, fast-control devices, storage, and active demand, it is not definitive that investment in heavy assets would be needed. These operational flexibilities can rapidly deal with or even eliminate network congestions [25,26]. Moreover, the role of redundant transmission and generation assets can be shifted by the implementation of more operational flexibilities, strongly linked to the planning and operation stages which should be meticulously studied for system expansion [27]. Additionally, environment-friendly solutions and meeting energy policies must be taken into account when planning the network rather than just the traditional economic and reliable drivers. In the smart grid paradigm, energy system planners should proactively design network expansion (considering the increasing demand for renewables resources and their very short construction times) instead of just reacting to new generation proposals and be supportive of network operations through the promotion of flexible smart grid technologies to become resilient to the unknow future scenarios [14].

The improvement of control and operational flexibilities in the power system is imperative to deal with the variability of renewable energies and to defer investment in conventional infrastructure. If no proper upgrades in smart grids are implemented in the network, the system would not be able to take the increasing renewables energy penetration in a cost-efficient manner, or it would be even infeasible [25]. However, this also means that system operators will need to control a much wider set of points to guarantee a reliable and economic operation of the system. Along with these wider setpoints and optimization variables, the operators will be handling much more information from smart technologies (e.g., smart meters, PMUs) at all levels, but allowing them to have a wider view of the system and, in turn, improve the state estimation of the system [28].

There is also urgent to evaluate the dynamics and stability of the system, which occur in scales of seconds or less than a second in both planning and operational stages due to the increasing penetrations of such ICT systems in the power system [29,30]. It is expected that redundancy security will be displaced by the increasing levels of automation, control, communications, and monitoring [29,31,32]. However, the in-deep analysis should be carried out to balance redundancy levels and advanced control actions allowed by smart grid technologies and new operational flexibilities [32,33].

In the same context, planning at all stages should necessarily consider an adequate analysis of uncertainty due to the presence of variable energy resources and active demand to minimize the risks that such technologies could introduce to the system rather than ignoring the multiple scenarios that the network could face or the implementation of inefficient solutions. Alongside this, network congestion should be correctly managed in real-time operation and most when large forecast errors are faced. Under this problem, investment in flexible solutions should be fostered instead of traditional solutions that cannot uptake an uncertain future [34–36]. For instance, the impacts on the power system during the COVID-19 pandemic are studied in [17]. The reduction of power demand for different sectors such as transportation or industry was analyzed, alongside the changes in the daily profile of residential consumers. The authors also analyze the impacts of the pandemic on the ongoing investment projects in the energy sector and the energy efficiency and climate impacts due to the change in the energy demand during the pandemic.

Existing models for power system planning considering uncertainty remains within one of the four categories of problems resulting from the combination of [14]: (i) the *temporal framework* considering the uncertainty of future evolution decisions called *dynamic* or *multi-*

*stage planning*, in which each period decisions cons the uncertainty of successive ones (in contrast to *static* or *single-stage planning*) [37]; and (ii) the *stochastic programming* which models the *uncertainty characterization* (use of probabilistic models to represent uncertainty), in contrast to *robust optimization*, in which probability distribution is a hard problem, and so users propose probability scenarios [38,39].

### 2.3. Critical Aspects Understudying for Future Power Systems

Following, we briefly discuss three main critical aspects of understudying for a transition to future power systems. (i) The deployment of active network elements has been turning the system to be more controllable. (ii) It is essential to identify all available flexibility options and classify them to capture an accurate representation in simulation tools. (iii) The challenges of modelling and simulation of future smart power systems, including the role of distributed energy resources, active or flexible loads, energy storage systems, and active network elements.

### 2.3.1. Active Network Elements

The presence of distributed energy resources, flexible loads, ICT systems, or storage in distribution systems is turning the system to be more controllable. The power flow through distribution networks is becoming highly dynamic (presence of inverse or bidirectional power flows). It is paramount for researchers to study how these active elements are to be considered in the network operation (real-time and time-ahead scheduling operation). Here, we discuss some main aspects of active elements which are still being studied in the context of future power systems, as summarized in Figure 2.
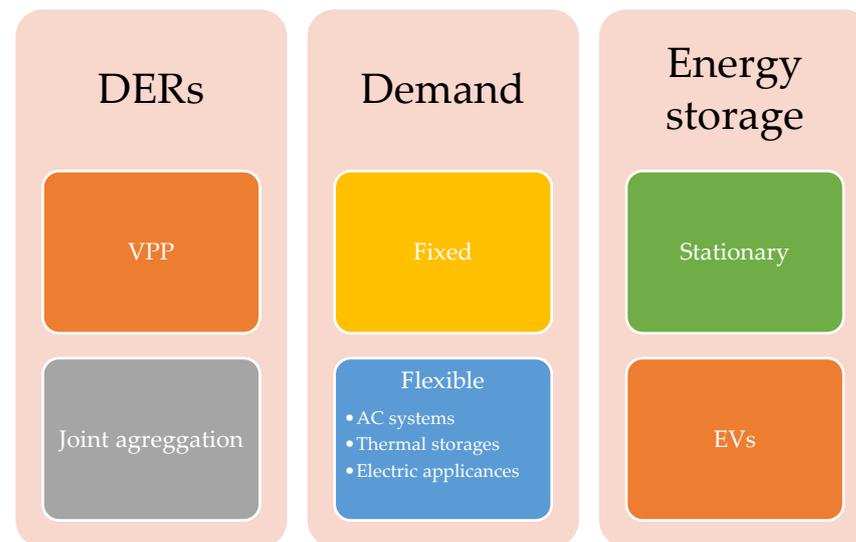


**Figure 2.** Active network elements understudying for future power systems.

➢　Distributed energy resources

Distributed energy resources (DERs) are one of the most important (if not the most) characteristics o modern power systems. The variability and uncertainty of such technologies bring the system (both transmission and distribution networks) reliability and stability challenges [26,40]. In this context, new tools and advanced control concepts for appropriate load balancing and also ancillary services should be considered at the distribution operation level [41]. One approach to reaching more flexible generation systems is the aggregation of DERs, which claim to improve the performance and stability of the system. Some concepts include:

A.　Virtual power plants (VPP) tend to become the immediate future of a distributed generation. It can be defined by the smart aggregation of multiple DERs. They open the possibility for smart energy consumption in a decentralized environment through

the optimal balancing of generation and demand. They can better manage possible deviations and forecasts of production and demand. In addition, VPP would pose better positioning in energy markets, provide frequency and voltage support and so reduce network losses [41–43].

B. Joint aggregation conceptualizes the aggregation of various renewable power producers to obtain major profits and reduce uncertainty in the forecasting and then compromise more reliable power in the energy markets. Of course, this would signify changes in the current energy market schemes [44,45].

➢ Demand

For modern power systems, loads can be considered to be controllable (or flexible, smart) and uncontrollable (or fixed, traditional) loads. Some users can provide flexibility to the system by adjusting their load to balance the power supply at some point in time. This is controlled by the distribution system operator, given the monetary compensation for the user to participate [46,47].

One important feature of flexible loads is the capacity to store energy in different forms for later use. This is also important as they can shift their consumption from one period of time to another without necessarily changing their overall consumption or reducing their quality of life. In fact, flexible loads may tend to increase energy consumption because of storage losses or more use of certain devices due to cheaper energy prices [41].

Therefore, any user able to store energy can, in principle, provides flexibility. Most attention has been focused on (i) air-conditioning systems, (ii) heat pump and thermal storage systems, (iii) electric vehicles, and (iv) some electric household appliances. Some services that flexible load can provide to the network include peak load reduction, optimal load scheduling, and provision of ancillary services.

➢ Energy storage

Energy storage (also identified as DER in [48]) is flexible enough to act as both a load and a generator in the power system. Some traditional energy storage is located at the transmission level as pumped hydro plants. In modern power systems, with the increasing penetration of DERs, small batteries are being integrated into the distribution network as support for a small-scale variable distributed generation [49,50]. Moreover, the growing presence of electric vehicles is a key solution for cost-effective energy storage systems as a secondary use [51].

### 2.3.2. Smart Grid Flexibility

Flexibility is defined as the ability of the power system to adjust its operation to both expected and unexpected variations in the system behaviour or performance, e.g., changes in generation, network configuration, or demand, in response to weather conditions, consumer needs, or network outages [52]. In a power system with high shares of variable renewable energy (VRE), it is mandatory to integrate different sources of flexibility for a stable operation. In [53], Lund et al. review the many sources of flexibility to enable high levels of variable renewable generation. In this context, it is essential to identify all available flexibility options and classify them to capture an accurate representation in simulation tools.

The authors in [52] performed an updated literature review of flexibility options and classification schemes. They found that flexibility is defined from different sources within the network, as summarized in Figure 3.
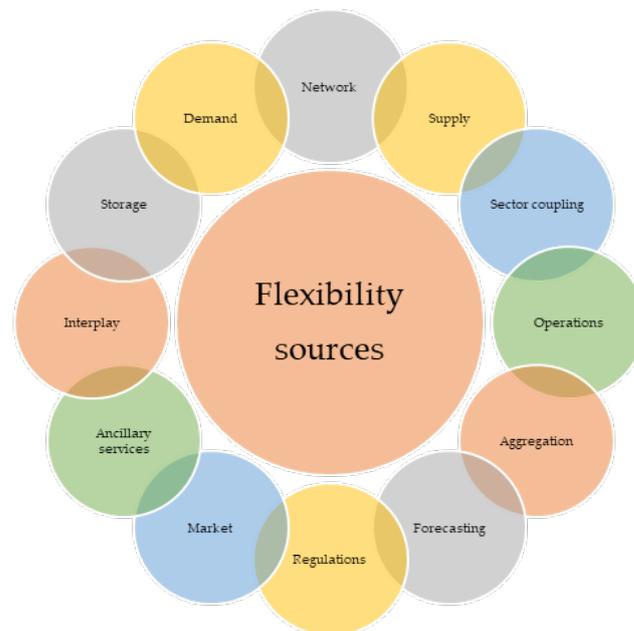
**Figure 3.** Classification of flexibility by its source.

Despite the detailed description of different technical flexibility options in the literature, in [54], the authors defined a hierarchical order and relation between different options. A more exhaustive analysis, including all options, is then presented in [52]. The authors include other two dimensions: temporal and geographic, and related all these technical flexibility options and their operation with social and economic drivers. Temporal flexibility is defined as the ability to change the input and output power in time (decreasing or increasing generation or demand), and geographical flexibility is the ability to balance demand and generation from different locations. The new scheme is summarized in Figure 4.
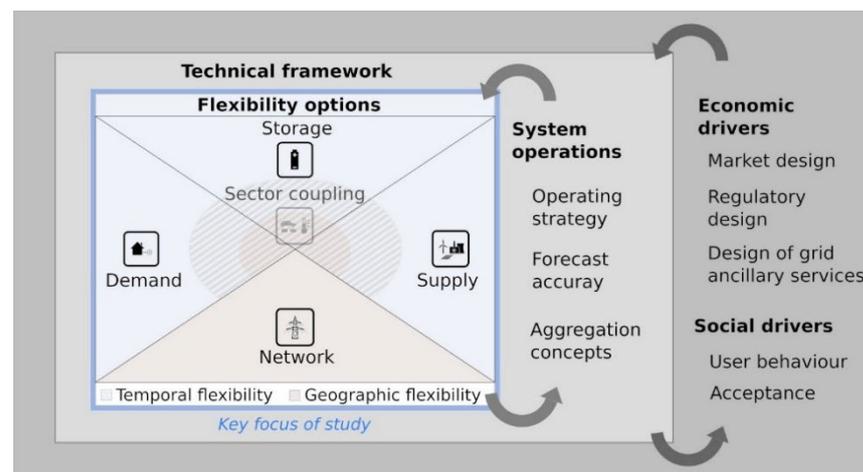


**Figure 4.** Flexibility classification in energy systems [52].

*2.4. Modelling of Future Power Systems*

This section seeks to highlight the challenges of modelling and simulation of future smart power systems, including the role of distributed energy resources, active or flexible loads, energy storage systems, and active network elements. Moving towards decentralized power systems and distributed controls requires several other system elements to be considered in the equation, such as ICT infrastructure, innovative market models [15], a more detailed distribution system, operational flexibilities, and home energy modelling. As

a suitable solution, there has been an increasing interest in researchers combining different existing (or in design) simulation tools to integrate all these new and innovative system characteristics (the so-called co-simulation technique).

2.4.1. Simulation Approaches

Simulation of power systems can be arranged into four groups: static and quasi-static, transient, and dynamic simulation. In static and quasi-static simulations, the network is assumed to be in a steady state. Usually, voltages and currents are simulation variables at system nodes. Quasi-static simulation allows more flexibility to study the system behaviour over longer periods. In contrast, transient and dynamic simulations consider a system to be in non-equilibrium. This demands a more meticulous design and modelling, which in turn is more computationally intensive, restricting the analysis to short period spans or reduced system models. In this regard, accurate and suitable network models should be developed to combine and understand the effects of new technologies in the system (at all stages) and foresee the challenges and opportunities in the system operation. In [41], the authors propose some of the simulation requirements for future power systems, as shown in Figure 5.
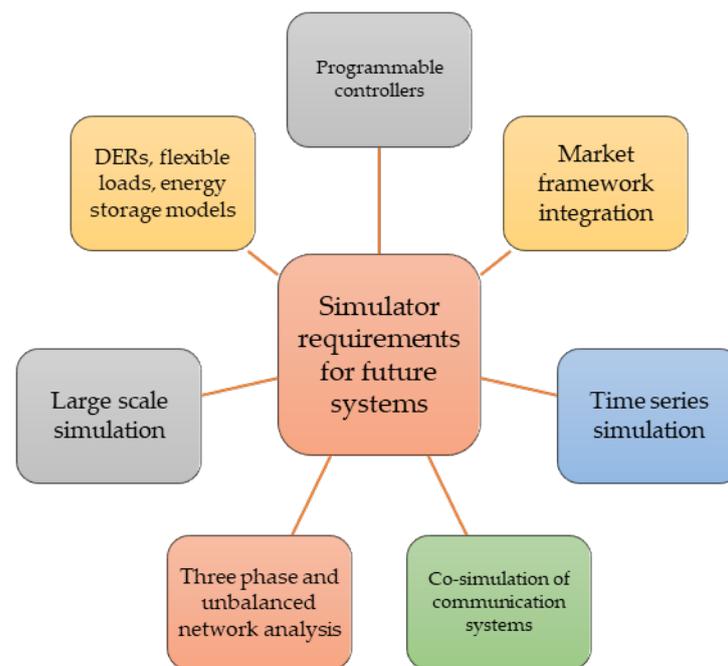


**Figure 5.** Simulator requirements for future power systems.

In general, simulation of future power systems may also include the development of highly detailed operational power systems, scenario analysis, long-term planning simulation, and inclusion of uncertainties.

In this regard, there are several different models available, but it is still difficult to define a middle point between the highly-detailed operational power systems and good enough granular long-term planning models [55]. These different models can be classified into six groups [56]:

1. Generation expansion planning.
2. Production cost optimization.
3. Hydro-thermal coordination.
4. Maintenance optimization.
5. Unit commitment.
6. Economic dispatch.

All of these models are based on the same principles (physical, economic, and technical), but depending on the size and complexity of each model, their formulation is developed [57]. For instance, generation expansion planning can be formulated as a mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP), or a linear programming (LP) problem; production cost optimization as a MILP or LP problem; hydro-thermal coordination as an MINLP; unit-commitment as a binary problem; or economic dispatch as an LP problem [56].

The generation expansion planning models focus on the economic optimization of the investments by maintaining the security and quality of the system and meeting environmental concerns and other modern concerns such as flexibility or renewable generation goals. This may be very computational demanding as many constraints are to be considered over long-time periods, and therefore, this is simplified by introducing linearization and relaxation techniques in the power system model [58,59]. For this reason, solving time and space dimensions can be considered the key challenge for solving optimization models for modern energy systems [60]. Currently, most generation expansion planning models neglect the need for operational flexibility by focusing only on long-term planning horizons [61].

On the other hand, for short-term periods in the range of days, weeks, seasons or up to years, the production cost optimization is preferred for modelling the system along with mid-term considerations of maintenance optimization, hydro-thermal coordination models and in synchronization with shorter time ranges for unit-commitment and economic dispatch models [56,62]. For these models, the optimization is usually focused on the economic operation of the power system over a long period. Existing publications, such as the ones presented by Palmintier et al. [63] and Pavičević et al. [56], claim that the state-of-the-art modelling framework which can accurately model real-world systems is the binary formulation. Nevertheless, there is still a need to study energy systems more comprehensively and exhaustively where higher renewable energy sources and DERs shares are present and consider different time and spatial resolutions.

### 2.4.2. Simulation Tools and Flexibility Options

Regarding the modelling tools, one way to better understand the design of future power systems and study flexibility options is to play with energy system modelling tools. As a key topic for researchers, there exists a vast range of modelling tools (several open access); however, there is no standard, and it is not clear how the different flexibilities are represented in those tools. The very recent analysis presented in [52] tries to fill this gap by contrasting different open tools (for modelling modern energy systems). The authors surveyed the developers of these tools and compared them with the newly introduced "Open ESM Flexibility Evaluation Tool". The main remarks are that there is an increasing interest of developers in including sector coupling in the analysis, yet network flexibility, storage system, or system operations are still underrepresented. There is no single tool that covers all flexibility options to a proper degree; however, a combination of some could result in a basis for holistic modelling. The holistic representation assessment of all flexibility categories (presented in Figure 4) from [52] is summarized in Figure 6.

Most of the tools cover all flexibility aspects, especially on the supply side. The tool TransiENT [64] seems to be the most potent model in this assessment, having a remarkable representation of supply and storage but regarding demand representation, BALMOREL [65] and EMMA [66] perform much better. In the context of network representation, models such as eGo [67], PANDAPOWER [68], and GRIDCAL [69] outstand. Concerning sector coupling, several models consider a high degree of integration (DispaSET [70] on the top), while some others only focus on the electricity sector and barely include elements from the transport or heating sectors.
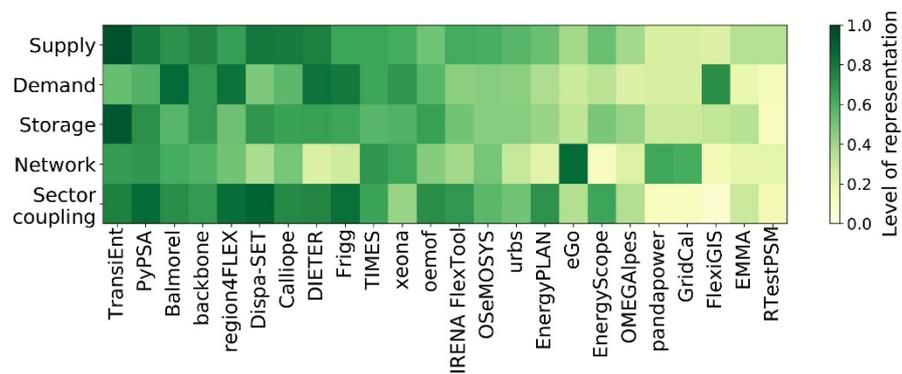
**Figure 6.** Holistic representation of flexibility options in open modelling tools [52].

2.4.3. Spatial and Temporal Scopes

Regarding the covering of the spatial and temporal scopes and time resolution (Figure 7), the results showed that only 80% of the models had a national scope. In all models, the simulation can be performed for periods from days to years, and just a few models allow simulation for shorter periods of less than a few days, and for time resolution, the most used granularity is hourly (80% of the models), and 30% of the models allow other resolutions larger or smaller than an hour.
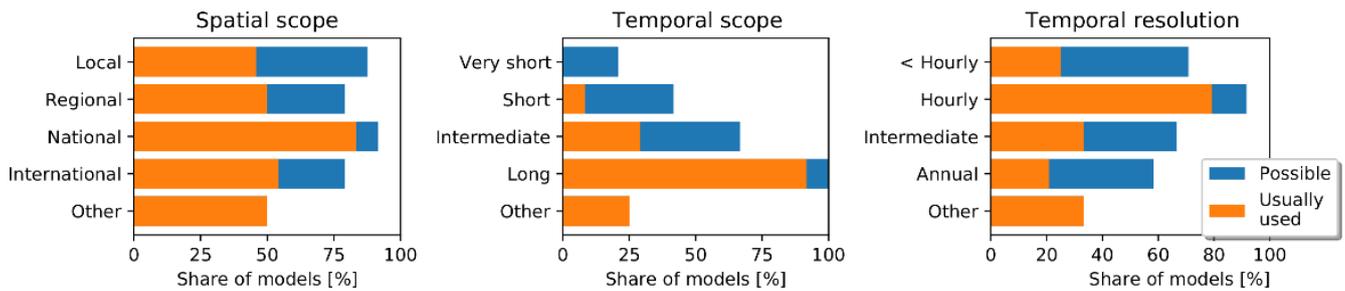


**Figure 7.** Representation of spatial scope, temporal scope, and temporal resolution in open modelling tools [52].

In general, technical parameters of flexibility are better represented than those addressing system operation. Perfect foresight is used for investments and dispatch decisions for most of the models, and uncertainty and behavioural characteristics are not included. This last is important to enabling operational flexibility for dealing with unforeseen changes in the energy systems [52].

## 3. Integrated Transmission and Distribution Systems
### 3.1. Modelling Approaches

Traditionally, transmission and distribution systems (T&D systems) have been analyzed independently, with different frameworks, characteristics, requirements, paradigms, and tools/software. In this context, the distribution side has been represented as a constant load when transmission system analysis, and in turn, transmission systems have been modelled as voltage sources when distribution system simulation. With the increasing penetration of DERs and smart grid technologies, the distribution system is becoming more and more active, which signifies both challenges and opportunities for power system analysis. In this regard, it becomes imperative to study both transmission and distribution systems adequately and especially when analyzing phenomena that have an impact on both systems [71].

Despite integrated transmission and distribution systems have not yet been found as a commercial solution for modelling modern power systems, its potential for shifting from traditional power systems analysis approaches has taken the interest of researchers

in recent years who have been trying to develop frameworks and software for steady-state and dynamic simulation of integrated power systems and on the top, validate the advantages of such modelling approach in the analysis of power systems [72]. Moreover, a common way to study the impact of smart grid technologies is through simulation, but this task is far from simple due to the complexity of representing and modelling the different characteristics and effects of such solutions in the power system.

Having stated the necessity of capturing transmission and distribution systems interactions, smart grid technologies impacts, ICT systems and other flexible solutions in energy systems, lately, many efforts have been put in place to propose frameworks and simulation tools capable of capturing these interactions and impacts. In general, these approaches can be classified as standalone integrated T&D tools and T&D co-simulation tools [73].

### 3.2. Standalone T&D Frameworks

Standalone T&D frameworks model both transmission and distribution systems in one single platform. These approaches can lead to an accurate representation of T&D systems; however, the computational burden is the main barrier for large-scale systems. In fact, there are two main problems associated with the development of standalone T&D models [73]. (i) The simulation cost can be significant as real-world distribution systems comprehend thousands of buses, and in turn, transmission systems can be connected to thousands of such distribution systems. Then, the scalability problem does not allow that there exist many commercial tools to be available at present. (ii) Moreover, T&D models do not take advantage of the several legacy tools available which simulate transmission and distribution systems independently. Problems in the convergence for large T&D systems may also appear because of the very particular topologies of distribution systems and their different techniques to solve power flows compared to transmission systems.

Co-simulation is a technique used to couple different subsystems to be modelled and simulated in a distributed manner. Each subsystem is modelled without having the entire system in mind. Meanwhile, the coupled simulation is performed by blindly executing the subsystems. During the coupled simulation, the subsystems will exchange data. In this context, co-simulation can be considered as the combined simulation of the already well-established tools and semantics when they are analyzed with their appropriate solvers [31,74]. Co-simulation has demonstrated its benefits in the evaluation of multi-domain and cyber-physical systems by offering flexible solutions considering multi-domains over different time steps at the same time [75]. Co-simulation also enables the possibility of assessing large-scale systems as the calculation burden is shared among different solvers.

### 3.3. T&D Co-Simulation

Co-simulation is a technique used to couple different subsystems to be modelled and simulated in a distributed manner. Each subsystem is modelled without having the entire system in mind. Meanwhile, the coupled simulation is performed by blindly executing the subsystems. During the coupled simulation, the subsystems will exchange data. In this context, co-simulation can be considered as the combined simulation of the already well-established tools and semantics when they are analyzed with their appropriate solvers [74]. Co-simulation has demonstrated its benefits in the evaluation of multi-domain and cyber-physical systems by offering flexible solutions considering multi-domains over different time steps at the same time [75]. Co-simulation also enables the possibility of assessing large-scale systems as the calculation burden is shared among different solvers.

With the increasing trend of emerging new technologies on the distribution side (e.g., PV panels, wind turbines, small-scale energy storage, electric vehicles, distributed generation, etc.) and the introduction of novel energy trading markets on the customer side, the distribution network is taking a more active role in the power system which in turn, is demanding more analysis in the area of transmission and distribution co-simulation.

Traditionally, the transmission system is simulated using a balanced single-phase AC power flow analysis. However, in an integrated T&D context (necessary to assess the impact of DERs and other smart grid technologies) with a higher unbalance and the PCC, a single-phase simulation is no longer adequate [76]. A detailed three-phase AC power flow analysis should be implemented for the analysis of the transmission system in order to consider the effects of phase unbalances.

In turn, the distribution system needs to be studied with a full three-phase representation to assess the impact of load unbalances. Several legacy software (e.g., OpenDSS) solve the distribution system using different mathematical approaches and allowing multiple penetration levels of smart grid technologies and novel flexibilities.

The available literature for co-simulation in power systems is very extensive, and some works have reviewed the many techniques developed over the years (e.g., [41,77–80]).

Regarding the transmission and distribution coupling in the co-simulation model, the approaches can be twofold: loosely coupled and tightly coupled T&D systems.

In a loosely coupled co-simulation approach, the system changes are assumed to be rather slow, and then the variables of interest are exchanged in a subsequent time step until the system converges after multiple iterations. On the other hand, a tightly coupled co-simulation framework is desired when studying faster system dynamics in T&D control coordination. In this scheme, the system's variables are exchanged at each time step, and the simulation does not advance until the boundary variables do converge. This concept can be referred to as co-iteration at each time step [72].

## 4. Survey of Techno-Economic Tools for Integrated T&D Systems

Several approaches have been proposed for the co-simulation of transmission and distribution systems over the last few years. Some of these tools do focus on the steady-state analysis of the transmission and distribution systems, others on the dynamic aspects of the co-simulation, and some other few consider both steady-state and dynamic aspects. Since there are various proposed frameworks and co-simulation tools available so far, some efforts have been put in place for contrasting and surveying these many techniques developed over the years [72,73,77,78,81] and remarking their advantages and limitations by considering some dimensions of interest such as used software, grid considerations, interface, steady-state or dynamic aspects, among others.

In [72], the authors presented a review of integrated T&D modelling research methods for steady-state and dynamic modelling of power systems. The approaches are classified by their proposed structure to couple the transmission and distribution systems both for steady-state and dynamic analysis. The work in [73] aimed to assess and compare the different system coupling protocols: decoupled, loosely coupled, and tightly coupled, for queasy-static T&D co-simulation analysis. The survey presented by Mohseni-Bonab et al. [77] and Vogt et al. [78] categorized the multiple T&D co-simulation frameworks on their used simulation tools, synchronization methods, and research topics. In addition, in [78], the authors contrasted different key characteristics of such frameworks to identify the gaps, whereas in [81], the work presented a comparative study of different interface techniques that are employed for T&D co-simulation.

In this review, we include the state-of-the-art of co-simulation tools for integrated transmission and distribution systems and include (or complete) the analysis with some other dimensions (smart-grid related) which are of key interest for future power systems such as environmental considerations, techno-economic aspects (social welfare), spatial scope, time resolution (granularity), or temporal scope. We surveyed more than 40 publications and identified 36 approaches for the analysis of integrated T&D systems.

In Table 1, we first present all surveyed bibliographies. To facilitate recognition, they are numbered as review "Case". The title and authors are also shown. Moreover, they are presented in chronological order regarding publication date.

**Table 1.** List of surveyed bibliography by review case, year of publication, authors, title, and references.

| Case | Year | Authors | Title | References |
|------|------|---------|-------|------------|
| 1 | 2011 | Hua Lin, et al. | Power System and Communication Network Co-Simulation for Smart Grid Applications | [82] |
| 2 | 2012 | Zechun Hu, Furong Li | Cost-Benefit Analyses of Active Distribution Network Management. Part I: Annual Benefit Analysis | [83] |
| 3 | 2012 | Zechun Hu, Furong Li | Cost-Benefit Analyses of Active Distribution Network Management. Part II: Investment Reduction Analysis | [84] |
| 4 | 2014 | IEA | The Power of Transformation, Wind, Sun and the Economics of Flexible Power Systems (IMRES) | [85] |
| 5 | 2014 | IEA, Simon Müller | The Power of Transformation, Wind, Sun and the Economics of Flexible Power Systems (BID3) | [85] |
| 6 | 2014 | T. Stetz, et al. | Techno-Economic Assessment of Voltage Control Strategies in Low Voltage Grids | [13] |
| 7 | 2015 | Strbac, G., et al. | Value of Flexibility in a Decarbonised Grid and System Externalities of Low-Carbon Generation Technologies | [2] |
| 8 | 2015 | Anne Sjoerd Brouwer, et al. | Least-cost options for integrating intermittent renewables in low-carbon power systems | [86] |
| 9 | 2016 | Bryan Palmintier, et al. | Experiences integrating transmission and distribution simulations for DERs with the Integrated Grid Modeling System (IGMS) | [87,88] |
| 10 | 2016 | Sergi Rotger-Griful, et al. | Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response | [89] |
| 11 | 2016 | Zhengshuo Li, et al. | Coordinated Transmission and Distribution AC Optimal Power Flow | [90] |
| 12 | 2016 | Qiuhua Huang and Vijay Vittal | Integrated Transmission and Distribution System Power Flow and Dynamic Simulation Using Mixed Three-Sequence/Three-Phase Modeling | [91] |
| 13 | 2017 | Arjan S. Sidhua, Michael G. Pollittb, Karim L. Anayab | A social cost-benefit analysis of grid-scale electrical energy storage projects: A case study | [92] |
| 14 | 2017 | Rodrigo Moreno, et al. | Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. | [14] |
| 15 | 2017 | Renke Huang, et al. | An open-source framework for power system transmission and distribution dynamics co-simulation | [93,94] |
| 16 | 2018 | A. Battegay | Economic assessment of smart grids flexibilities | [11,95] |
| 17 | 2018 | P.M. De Oliveira-De Jesus, C. Henggeler Antunes | Economic valuation of smart grid investments on electricity markets | [1] |
| 18 | 2018 | Gayathri Krishnamoorthy, Anamika Dubey, et al. | A Framework to Analyze Interactions between Transmission and Distribution Systems | [96–98] |
| 19 | 2018 | Ramakrishnan Venkatraman, et al. | Dynamic Co-Simulation Methods for Combined Transmission-Distribution System with Integration Time Step Impact on Convergence | [99] |
| 20 | 2019 | Gianluigi Migliavacca, et al. | TSO-DSO Coordination for Acquiring Ancillary Services from Distribution Grids the Smartnet Project Final Results | [80,100,101] |
| 21 | 2019 | B.P. Hayes, S. Thakurb, J.G. Breslinb | Co-simulation of electricity distribution networks and peer to peer energy trading platforms | [102] |
| 22 | 2019 | Seyed Masoud Mohseni-Bonab, et al. | IC-GAMA: A Novel Framework for Integrated T&D Co-Simulation | [103] |

**Table 1.** *Cont.*

| Case | Year | Authors | Title | References |
|------|------|---------|-------|------------|
| 23 | 2019 | Bryan Palmintier, et al. | Design of the HELICS High-Performance Transmission-Distribution-Communication-Market Co-Simulation Framework | [104] |
| 24 | 2019 | Yaswanth Nag Velaga, et al. | Advancements in co-simulation techniques in combined transmission and distribution systems analysis | [97] |
| 25 | 2019 | Gayathri Krishnamoorthy and Anamika Dubey | Transmission–Distribution Cosimulation: Analytical Methods for Iterative Coupling | [98] |
| 26 | 2019 | Hieu Trung Nguyena, et al. | An integrated transmission and distribution test system for evaluation of transactive energy designs | [105] |
| 27 | 2020 | Ali Hajebrahimi, et al. | A Corrective Integrated T&D Co-Simulation for Scenario Analysis of Different Technology Penetration | [106] |
| 28 | 2020 | Seyed Masoud Mohseni-Bonab, et al. | Transmission and distribution co-simulation: a review and propositions | [77,107] |
| 29 | 2020 | Guna R. Bharati, et al. | An Integrated Transmission-Distribution Modeling for Phasor-Domain Dynamic Analysis in Real-time | [108] |
| 30 | 2021 | Sushrut Thakar, et al. | An Integrated Transmission-Distribution Co-Simulation for a Distribution System with High Renewable Penetration | [71] |
| 31 | 2021 | Alok Kumar Bharati and Venkataramana Ajjarapu | A Scalable Multi-Timescale T&D Co-Simulation Framework using HELICS | [109] |
| 32 | 2021 | Nadia Panossian, et al. | Synthetic, Realistic Transmission and Distribution Co-Simulation for Voltage Control Benchmarking | [110] |
| 33 | 2021 | Wenbo Wang, et al. | Transmission-and-Distribution Frequency Dynamic Co-Simulation Framework for Distributed Energy Resources' Frequency Response | [111] |
| 34 | 2021 | Alexander Hermann, et al. | A Complementarity Model for Electric Power Transmission-Distribution Coordination Under Uncertainty | [112] |
| 35 | 2021 | Xin Fang, Mengmeng Cai, and Anthony Florita | Cyber-Physical Events Emulation Based Transmission and Distribution Co-Simulation for Situation Awareness and Grid Anomaly (SAGA) Detection | [113] |
| 36 | 2021 | Gregorio Muñoz-Delgado, et al. | Integrated Transmission and Distribution System Expansion Planning under Uncertainty | [114] |

To this point, and according to our criteria, we summarize and analyze some of the most important dimensions and characteristics of these surveyed frameworks to assess the techno-economic benefits of smart grid technology in integrated T&D systems. As there is not a standard path to develop and design integrated T&D systems tools, the analysis of existing gaps is not yet generalized or well-established (approaches are still heterogeneous from every researcher's view), and several framework features are presented in different manners from every publication. Consequently, we try to normalize the information to our best criteria. In addition, we do not intend to replicate the information presented in other related studies (such as in [72,73,77,78,81]); however, some information will be displayed in order to have a better understanding of the general problem.

*4.1. Power System Approach: General and Specific Objectives*

In terms of general purpose, we identified simulation frameworks for integrated T&D systems analysis whose main objective goes from market modelling, specific system analysis (e.g., transient stability), system operation, and short-term planning to long-term planning. Some approaches claim to cover more than one general objective and can simulate the power system at different temporal time scopes and time frames.

Regarding specific targets, the surveyed approaches include VRE integration, dynamic T&D co-simulation, large-scale T&D co-simulation, or investment aspects. General-purpose and specific targets of all cases are presented in Table 2.

**Table 2.** Power system analysis: general purpose and specific target.

| General-Purpose | Specific Target | Case |
|---|---|---|
| Long-term planning | VRE integration | 4 |
| Long-term planning and Economic dispatch | VRE integration | 5 |
| Long-term planning and Market modelling | Quantifying system integration costs of low-carbon generation technologies | 7 |
| Long-term planning and System operation | Low-carbon electricity, smart grid context | 14 |
| | VRE integration | 8 |
| Long-term planning, System operation and Market modelling | The economic value of smart grids | 16 |
| | Large-scale T&D, communications, market co-simulation | 23 |
| | TSO-DSO coordination | 20 |
| Short-term planning and Market modelling | The economic value of smart grids | 17 |
| Short-term planning and System operation | Hosting capacity | 6 |
| | Integrated T&D under uncertainty | 36 |
| | Investment deferral | 2 |
| | Investment reduction and VRE curtailment | 3 |
| System operation | The Cost-benefit of energy storage | 13 |
| | Dynamic T&D co-simulation | 12 |
| | | 15 |
| | | 19 |
| | | 29 |
| | | 30 |
| | | 33 |
| | HIL coupling | 10 |
| | Large-scale T&D co-simulation | 31 |
| | Power system and communication integration | 1 |
| | T&D AC OPF | 11 |
| | T&D co-simulation | 22 |
| | | 24 |
| | | 27 |
| | | 28 |
| | T&D co-simulation | 32 |
| | | 35 |
| | T&D coupling | 18 |
| | | 25 |
| System operation and Market modelling | Integrated T&D for transactive energy | 26 |
| | Interactions between T&D systems | 9 |
| | P2P trading | 21 |
| | T&D co-simulation | 34 |

### 4.1.1. Long-Term Planning

On the side of long-term planning, we identified eight proposed frameworks that are mainly focused on technology integration (e.g., VRE integration, low carbon electricity, the value of smart grids, etc.). These approaches are mainly characterized by their temporal scope, which goes to more than a decade. Moreover, they are focused on the long-term planning of specific cases (for one or various countries in particular), meaning closed approaches and specific methods, and therefore, they can be difficult to replicate.

For instance, in Cases 4, 5, 8, and 16, the focus is on VRE integration and the economics of smart grid solutions and flexibilities [11,85,86]. In Case 7, the authors aim to quantify the impact of system flexibility on the cost of decarbonizing the UK electricity system by 2030 by calculating the approximate level of system integration costs of generation technologies (defined as system externalities) that should be attached to individual low-carbon technologies in different scenarios [2]. In Case 14, the specific target is to explain the level of complexity associated with the low-carbon, smart grid context and highlight how this affects infrastructure planning concepts and practices [14].

### 4.1.2. Market Modelling

Regarding market modelling, we identify nine cases that include market analysis at different levels. In Case 26, the presented platform models a centrally managed wholesale power market operating over a high-voltage transmission grid linked to one or more distribution systems. A primary envisioned use of this platform is the study of Transactive Energy System (TES) designs [105]. On the other hand, Case 21 evaluates the potential impacts of peer-to-peer energy trading and other local electricity trading mechanisms on the control, operation and planning of the electricity distribution networks.

### 4.1.3. System Operation

In the general view, system operation is the most studied field, with 33 of our reviewed approaches including some aspects of this topic. These include the analysis of dynamics of T&D integration, hardware-in-the-loop (HIL) coupling, the role of communications, or some specific flexibilities impacts such as energy storage or P2P trading.

### 4.1.4. Integral Approach

Despite this, we identified three frameworks presenting a more integral approach for integrated T&D system analysis. In Case 16, the authors present the FlexiS model. This model optimizes the deployment of smart grid solutions together with the investment in generating units and in the transmission network [11]. In turn, Case 23 introduces the Hierarchical Engine for Large-scale Infrastructure Co-simulation (HELICS), a layered high-performance co-simulation framework that builds on the collective experience of multiple national laboratories to offer increased scalability and advanced features for modelling highly integrated cyber-physical-energy systems [104]. Finally, in Case 20, the SmartNet project developed a challenging simulation platform, modelling in detail T&D networks and ancillary services markets and implementing a very detailed dataset of generators and loads [13].

In Case 28, the authors propose a very promising framework for not only integration of transmission (and generation) and distribution systems but also including customer system, the IGTDCSs platform. The proposed framework also comprises several technological dimensions such as stochastic optimization, high-performance computing, and high-level design software architecture for planning integrated and flexible power networks and optimizing their technological trajectories and operational functioning considering uncertainties [77]. The projected road map expects to combine static, quasi-static and dynamic models of the electrical network, loads, buildings, transactional energy markets, and ICT in a multi-tool distributed agent capable of simulating the behaviour of the intelligent network over a horizon that may range from less than a second to several years [77].

*4.2. Methodology and Implemented/Developed Tool*

Depending on how frameworks approach the coupling problem between transmission and distribution systems, which can be (i) considering system dynamics to be rather slow, so the exchanged variables do not happen at the same iteration every time; or (ii) considering faster dynamics, where appointed variables between systems are exchanged at each iteration every time step. Therefore, the integration of T&D systems is twofold: tight and loose couplings. In a loosely coupled co-simulation, the system changes are assumed to be slow, and variables are exchanged in a subsequent time step until the system converges. Conversely, a tightly coupled co-simulation is preferred for faster system dynamics in T&D control coordination. Here, the exchanged variables occur at each time step, and the simulation does not advance until the boundary variables do converge [72].

In Figure 8, we identify frameworks with loosely and tightly T&D couplings. When there is no T&D coupling, it refers to frameworks with no transmission and distribution network integration (electrical integration); however, other types of couplings can be identified. For instance, Case 1 performs a tight coupling between distribution and communication systems for smart grid applications [82]. In Case 10, the authors present a coupling co-simulation environment with a HIL infrastructure for demand response assessment [89].
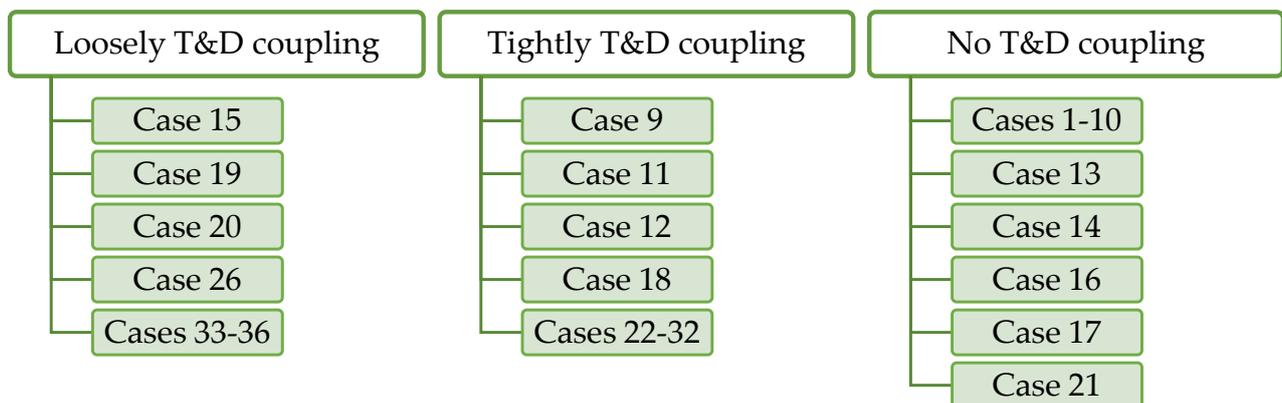
| Loosely T&D coupling | Tightly T&D coupling | No T&D coupling |
|---|---|---|
| Case 15 | Case 9 | Cases 1-10 |
| Case 19 | Case 11 | Case 13 |
| Case 20 | Case 12 | Case 14 |
| Case 26 | Case 18 | Case 16 |
| Cases 33-36 | Cases 22-32 | Case 17 |
| | | Case 21 |

**Figure 8.** Classification of T&D integration by coupling approach.

The methodologies adopted to address the power flow problem, optimization, stochastic simulation, integration of communications (when corresponding), market modelling, and some other technology integration are also highlighted in this section. Finally, when available, we identified the integrated T&D simulation tool, software used to model transmission and distribution networks, and language used to interface among different systems. All this information is summarized in Table 3.

When there is no T&D coupling, the analysis, in general, focuses on transmission and distribution planning with no or poor consideration of network constraints. These cases are more related to market analysis or economic dispatches studied. The presence of more tightly coupled analysis may be assumed to be an increasing interest in studying the faster dynamic interactions between transmission and distribution systems due to the growing penetration of smart grid technologies and several other flexibility solutions which have been recently proposed.

**Table 3.** Methodology and implemented/developed tools.

| Case | Method/Approach | Designed/Used Tool |
|---|---|---|
| 1 | A global scheduler for co-simulation and two simulators share the same timeline instead of running independently. The repeating rounds in power system dynamic simulation are broken into individuals and expanded over the timeline as discrete events for the global scheduler. | Co-simulation framework integrates: Positive Sequence Load Flow (PSLF) software for power system dynamic simulation and Network Simulator 2 (NS2) for communication network simulation. Interface in Java and C++. |
| 2 | An autonomous regional active network management system (AuRA-NMS) offers active and flexible control in maintaining voltage, constraint management, and supply restoration to distribution levels that are traditional passive with very little visibility and controllability. The system allows the online state of the whole network to be obtained and enables a more efficient and timely control and management to realize the notion of an active distribution network. | AuRA-NMS |
| 3 | Two operational conditions with different REG outputs and security constraints under $N-1$ contingencies are considered in the proposed formulation. This is solved iteratively by the Benders' decomposition method. The REG output is optimally curtailed when any security constraint is violated, and loss of curtailment is calculated approximately based on the output duration curve (ODC) of REG.<br>For costs: annual loss because of REG output curtailment, the investment cost of each circuit is converted to the equivalent annual cost. | AuRA-NMS |
| 4 | Levelized cost of flexibility (LCOF). Cost-benefit analysis obtained by power system modelling (the Investment Model for Renewable Energy Systems (IMRES). The cost-benefit of a flexibility option was calculated as net system cost savings divided by the cost of the flexibility option itself. | IMRES |
| 5 | Levelized cost of flexibility (LCOF). Cost-benefit analysis obtained by power system modelling (the BID3 model). The cost-benefit of a flexibility option was calculated as net system cost savings divided by the cost of the flexibility option itself. | BID3 |
| 6 | The cost-benefit analysis is conducted: (i) a PV expansion scenario is defined for the investigated LV grid, covering a time frame of 10 years. (ii) The extent of necessary grid reinforcements is defined for each year, considering the leveraging effect of each of the VCS. (iii) One-year RMS simulations are performed to assess the operational costs for each year and each VCS. | Matlab and MATPOWER. |
| 7 | Depending on how the system is allowed to adapt to the addition of low-carbon generation, three different methods to quantify the relative integration cost are distinguished: Predefined replacement, Optimised replacement, and Difference in marginal system benefits. The whole-system cost WSC is the sum of the LCOE of the technology under consideration and the corresponding System Integration Cost (SIC). | Whole-electricity System Investment Model (WeSIM) |
| 8 | The method consists of four main steps: (i) define plausible non-fossil generation scenarios, (ii) define the capacities of complementary options. (iii) optimize fossil generation capacity with PLEXOS, and (iv) run hourly simulations with PLEXOS. | PLEXOS |

**Table 3.** *Cont.*

| Case | Method/Approach | Designed/Used Tool |
|---|---|---|
| 9 | Integrated Grid Modeling System (IGMS) is an Independent System Operator (ISO)-to-appliance scale electric power system modelling platform that combines off-the-shelf tools to simultaneously model 100 s to 1000 s of distribution systems in co-simulation with detailed ISO markets, transmission power flows, and AGC-level reserve deployment. | IGMS. Transmission is represented with the FESTIV model. IGMS couples it with MATPOWER. The distribution system is represented through many instances of GridLAB-D. |
| 10 | VirGIL uses PowerFactory as a power system simulator, OMNeT++ for the communications network simulator, and Modelica for the building model and control. To enable HiL simulation, a Ptolemy II environment is used. The communication between the different components is performed using the standard Functional Mockup Interface (FMI). | VirGIL Power Factory, OMNeT++, Modelica |
| 11 | A new decomposition algorithm, called heterogeneous decomposition (HGD), is proposed to overcome the difficulty of solving the non-convex constrained optimization TDOPF. "Heterogeneous" means that the TDOPF is decomposed into a series of decoupled subproblems with different characteristics. | All programs are coded and tested in MATLAB. IPOPT is used as the solver. |
| 12 | The proposed integrated T&D power flow (TDPF) is solved by iteratively solving a three-sequence power flow for the transmission system and a three-phase power flow for each distribution system. In the proposed T&D dynamic simulation (TDDS) algorithm, the multi-area Thévenin equivalent (MATE) approach is employed in the network solution step to address the challenge related to different network representations in the transmission and distribution systems. | T&D power flow (TDPF) T&D dynamic simulation (TDDS) Used software not identified. |
| 13 | The uncertain benefit and cost streams are evaluated through a Monte Carlo simulation and then arranged through a discounted cash flow to provide a net present social value of the investment. | Not identified |
| 14 | The proposed framework considers decision variables in two different time scales (investment and operation), and the presence of long-term uncertainty to reflect the changing landscape faced by system planners, especially in terms of available technologies, costs and market conditions, energy policy and incentives. | FICO® Xpress |
| 15 | Co-simulation in FNCS is achieved by extending the participating simulators through simple interfaces. The simulator interfaces provide functions needed for messaging and time synchronization. A centralized control process, the FNCS broker, facilitates all communication between the simulators. | FNCS GridPACK™ and GridLAB-D™ Communication using the ZeroMQ library. |
| 16 | Stochastic modelling: (i) a pure and perfect competition between stakeholders and (ii) the economic rationality of the decisions of the power system's stakeholders. It identifies the economically efficient levels of deployment for the various flexibility solutions, factoring in sources of potential, their costs and the effects of scaling them up and the effects of competition in accessing sources of value (congestion management, generating capacity requirements, short-term flexibility requirements, etc.). | FlexiS |

**Table 3.** *Cont.*

| Case | Method/Approach | Designed/Used Tool |
|------|-----------------|--------------------|
| 17 | It is assumed that under a competitive electricity market (where agents are free to sell or buy electricity) an equilibrium is reached when the power system is running at maximum social welfare conditions. The multilevel nature of smart grid investments. | Python |
| 18 | The transmission system model in MATLAB includes a detailed three-sequence network model with a 5 min ahead economic dispatch formulation solved using AC optimal power flow (ACOPF) model. Economic dispatch is implemented to achieve power balancing. OpenDSS is used to simulate and solve the three-phase unbalanced distribution system models. | The transmission system and coupling interface are simulated using MATLAB while OpenDSS is used to model the distribution system. |
| 19 | The T&D subsystems are coupled using series computation and parallel computation. In both methods, the key idea is to solve the subsystems independently and at every integration time step, the input to each of the subsystems is updated from the corresponding output of the other subsystem. | CoTDS co-simulation Dynamic event using PSAT. Distribution systems using available MATLAB tools. |
| 20 | TSO-DSO coordination schemes are compared using a cost-benefit analysis with the following indicators: cost of mFRR (manual Frequency Restoration Reserve); cost of aFRR (automatic Frequency Restoration Reserve), forecasting errors, network losses; unwanted measures. This creates a further imbalance which is solved by aFRR. | SmartNet simulation platform. |
| 21 | This paper develops a co-simulation framework designed to investigate the potential network impacts from various alternative trading mechanisms, including blockchain-based P2P energy trading platforms. | OpenDSS, Matlab interface, and Python energy trading simulator. |
| 22 | The proposed IC-GAMA uses MATLAB to model transmission networks and distribution network power flow is programmed using GAMS. The interface coupling of the T&D models is implemented in MATLAB. Bus voltages and angles obtained from transmission network load flow and active and reactive power flow (P, Q) obtained from distribution network flow are interchanged at the PCC. | IC-GAMA: Integrated transmission and distribution (T&D) co-simulation (GAMS and MATLAB tools). |
| 23 | To optimize performance, speed development, and enable clean, modular maintainability, HELICS utilizes a layered architecture. Clear Application Programming Interfaces (APIs) between each layer, enable the development of the individual layers to occur in parallel, with each layer free to make internal changes and optimize performance without impacting the other layers. | HELICS |
| 24 | The proposed framework couples the analysis of the two systems by iteratively exchanging the power flow variables at the PCC. | Transmission system and interface in Python. Distribution in OpenDSS. |
| 25 | Mathematical Representation of T&D Cosimulation Interface. First-Order and Second-Order Updates Using Fixed-Point Iteration and Newton's Method. Accurate Simulation During System Unbalance and Demand Variability. | Transmission system and interface using MATLAB while distribution system in OpenDSS. |

**Table 3.** *Cont.*

| Case | Method/Approach | Designed/Used Tool |
|---|---|---|
| 26 | The Integrated Transmission and Distribution Transactive Energy System (ITD TES) Platform is an agent-based platform that permits the modelling of transmission and distribution systems linked by market processes, two-way data and signal flow, and two-way power flows. | ITD TES Platform: A transmission system by the AMES Wholesale and distribution levels uses Power Market Test Bed. GridLAB-D. Data exchange using FNCS. A DSO agent implemented in Python. TCP/IP middleware to handle communication among C1–C3. |
| 27 | The model follows: (i) Scenario generation. (ii) Scenario reduction tool. (iii) In the first iteration of T&D, a security constraint AC optimal power flow is executed by MATPOWER. (iv) Check voltages violations, if any, the algorithm creates a corrective signal for transmission optimal power flow. Otherwise, check the T&D convergence. (v) After convergence, the algorithm performs the simulation for all-day hourly, all scenarios and strategies. | MATPOWER for transmission level. OpenDSS for distribution load flow. These two models are connected through a Python-based interface. |
| 28 | T&D systems are solved independently, and the interactions are captured by interchanging the solutions obtained from the two simulators. Here the distribution side is the primary point for starting T&D full power flow. An iterative framework is proposed by exchanging the solutions. The integrated model is solved when the solutions from the decoupled models converge. | Matlab for the transmission system. OpenDSS. Python for the interface. |
| 29 | The distribution network is treated as a lumped dynamic load for the transmission analysis, whereas the transmission network is seen as a dynamic voltage source for the distribution analysis. Dynamic Thevenin equivalent of the transmission network is used in the distribution network model to replace the substation voltage source. | ePHASORsim from OPAL-RT. Imports a PSS/e transmission model and a CYME distribution model. |
| 30 | During the power flow, the distribution system is represented as a constant power load in the positive sequence and as constant current injections in zero and negative sequences. During the dynamic simulations, all sequence components are represented by current injections. In the distribution system model, during both power flow and dynamic simulation, the transmission system is represented by an unbalanced three-phase voltage source. | OpenDSS and InterPSS. Data exchange using HELICS. |
| 31 | The developed T&D co-simulation framework uses the HELICS interface. The power system dynamics are modelled as a set of differential-algebraic equations (DAEs): one for the transmission system and the other for the distribution system. The implementation of the DAE solution is performed in the commercial solvers. | PSS/E and GridLAB-D. Co-simulation uses HELICS and is driven using Python to enable multi-timescale T&D co-simulation. |
| 32 | The distribution model is split up into 120 different instances of OpenDSS that are spread across computational cores. The transmission model is simple enough to be contained on a single Windows workstation. HELICS enables us to use tight coupling of the transmission and distribution systems through co-iteration. | OpenDSS and PowerWorld. HELICS co-simulation platform. |

**Table 3.** *Cont*.

| Case | Method/Approach | Designed/Used Tool |
|---|---|---|
| 33 | The transmission system simulator performs the time-domain simulation, whereas the distribution system simulator performs the QSTS simulation. The detailed information exchanged through each simulator includes physical power system values and communications signals. The DER static power flow models are also considered in the distribution simulators. | HELICS, ANDES, and OpenDSS. |
| 34 | The proposed coordination approach is to optimize prices and capacity limits at the physical interface of TSO and DSO. For given values of these variables, the DSO pre-qualifies the participation of DSO-level resources in the day-ahead market by capping their quantity bids. Decompose the model using a multi-cut Benders' decomposition approach. | Matlab |
| 35 | The proposed Situational Awareness of Grid Anomalies (SAGA) includes four major components: an external forecasting model for renewable power and other supporting information forecasting, a T&D co-simulation core for T&D optimization, a cyber system modelling for the DERs and appliance communications, and the data visualization and analytics. | SAGA ANDES and OpenDSS. Cyber-physical events emulation, DER generation profiles, and generation scheduling optimization developed in Python. |
| 36 | For the long-term uncertainty: demand growth forecasts. For the short-term uncertainty, historical data. The co-optimized expansion planning model under uncertainty is formulated as an instance of stochastic programming. Network effects for the transmission network by dc load flow and the distribution level by linearized ac load flow. | Simulation in GAMS. Mixed-integer linear programming in CPLEX. The alternative instances of second-order cone programming in Gurobi. |

We identify HELICS, first developed in Case 23, as the most popular adopted co-simulation tool for some other approaches. HELICS stands for the Hierarchical Engine for Large-scale Infrastructure Co-simulation, a layered, high-performance co-simulation framework that allows a collective experience of multiple laboratories. It offers increased scalability and advanced features for modelling highly integrated cyber-physical-energy systems [104]. In Case 30, the authors use HELICS to integrate a transmission system, and a high renewable penetrated distribution system. The focus is on analyzing the transient stability after tripping several PV units. OpenDSS and InterPSS are used for network representation. The authors aimed to study a specific problem rather than develop a new co-simulation framework. This is also true for Cases 31, 32, and 33. The authors adopt HELICS as a co-simulation platform for exchanging data among different federates.

In Case 15, the FNCS (framework for network co-simulation) is introduced. It is a middleware interface and framework that manages the interaction and synchronization of the transmission and distribution simulators. It connects different transmission and distribution simulators in a single environment through an application program interface (API) [93]. The FNCS platform is adopted in Case 26 for developing the Integrated Transmission and Distribution Transactive Energy System (ITD TES) Platform. It is an agent-based platform that allows the modelling of T&D systems, including market processes, two-way data and signal flow, and two-way power flows [105].

### 4.3. Steady-State Analysis

The steady-state analysis of power systems aims to assess the system in equilibrium or a given operating point. It is handled by mainly solving algebraic power flow equations, which are iterated to reach a suitable solution. In an integrated T&D system, this also comprehends an iterative exchanging of appointed variables (voltages and currents) at the point of common coupling (PCC) between transmission and distribution systems software. The developed algorithms for steady-state analysis can be used for analyzing several operating conditions and for system planning studies which include certain network changes such as VRE introductions.

Two surveyed studies do not include steady-state analysis; rather, the focus is on valuing flexibility options, integration costs and market-related aspects. In Case 7, the authors identify and quantify the system integration costs of low-carbon generation technologies in the context of the future, largely decarbonized UK electricity system [2]. They analyze the network capacity only in terms of nominal interconnection capacity. On the other hand, Case 8 evaluates the efficacy of five complementary options to integrate intermittent-RES at the lowest cost using the PLEXOS tool for Western Europe in the year 2050 [86]. Large-scale electricity storage and expansion of interconnection capacity are considered to balance supply and demand temporally and spatially.

### 4.4. Dynamic Analysis

When it turns to the dynamic of power systems, the analysis gets more complicated. With faster period simulations, the exchange of appointed variables at the PCC between transmission and distribution systems requires more detailed coding. In addition, the computational burden is still a barrier when larger time scopes are required. A key aspect is time coordination. Therefore, the method for dynamic integrated T&D systems should appoint time control and variable exchange between systems at very short timescales.

We identified 16 cases addressing dynamics in an integrated T&D context. In Case 30, the TDDS tool is used to simulate a single line-to-ground fault on the distribution system. During the dynamic simulation, all sequence components are represented by current injections. In the distribution system model, during both power flow and dynamic simulation, the transmission system is represented by an unbalanced three-phase voltage source. Once solved the co-simulation power flow, the dynamic models in both the T&D systems are initialized. For each time step, the sub-transmission system is integrated, and the boundary voltages are sent to the distribution system, which are then integrated, and the updated boundary currents are sent back to the sub-transmission system [71]. The co-simulation is performed using a time step of 20 μs.

In Cases 1, 12, 15, 19, 29, 31 and 33, the approaches use time steps from milliseconds. In Case 29, the distribution network is handled as a lumped dynamic load for the transmission analysis and the transmission network is treated as a dynamic voltage source for the distribution analysis. The series impedance and voltage of the Thevenin equivalent are updated every time step. In turn, for the transmission model, the distribution network is represented as a variable impedance load whose value is adjusted at every time step based on the power consumption at the distribution substation [108].

In Case 19, two methods for dynamic co-simulation of Combined Transmission and Distribution Systems (CoTDS) are proposed using parallel and series computations of the T&D systems. Both approaches are solved by presenting a detailed mathematical formulation for solving the dynamics with differential-algebraic equations (DAEs). The authors handle the distribution system dynamics by node-level dynamic component modelling in conjunction with a three-phase distribution system power-flow solver [99].

### 4.5. Spatial Scope

Spatial scope differs for every surveyed framework. Although the final objective is to be able to simulate an integrated T&D system in large-scale and real-world conditions, the modelling complexity and computational burden are still a big barrier. Co-simulation has facilitated this task to some point as it allows parallel simulation.

The survey identified spatial scopes going from modelling a building, benchmark systems (most common-used as study cases), real-world distribution networks, city and regional scopes, national scope, and covering of various countries. In general, the spatial scope is inversely proportional to time scope and resolution.

### 4.6. Temporal Scope and Time Resolution

As discussed in Section 3.1., a more integral approach for integrated T&D system analysis is desired. A holistic approach may include several stages in the analysis, including system operation (steady-state and dynamic analysis) and short-term and long-term planning. This implies that integrated T&D tools may work at different timeframes, going from less than a second to several years.

Integrated T&D tools, which include dynamic analysis, are designed to evaluate the system for a few seconds or dozens of hours. Although HELICS allows analysis for several years and considers dynamic analysis, it is not clear the simulation feasibility when large-scale systems are considered with different dynamic behaviours at different timeframes.

In Case 9, the IGMS tool claim to extend previous co-simulation work by increasing the spatial and temporal resolution by (i) Including multi-period market dynamics, from day-ahead security-constrained unit commitment down to 2–6 s AGC at the bulk power level. (ii) Simulating large-scale power systems with hundreds of transmission nodes, thousands of full-scale distribution feeders, and millions of end-use customers; (iii) Providing a rich set of automated tools for data management, scenario creation, run coordination, and output processing [87].

### 4.7. Optimization and Uncertainty Considerations

Our survey also identifies frameworks that include optimization and stochasticity to some degree. Different optimization approaches have been identified so far. In Case 4, the BID3 tool optimizes the hourly generation of all power stations on the system, taking into account fuel prices and operational constraints. In Case 8, the PLEXOS tool optimizes power system operations from a system perspective across timescales. The work in Case 14 presents an optimization framework for planning networks that deal with uncertain scenarios and represents increased operational details [14]. The model presented in Case 16 optimizes the smart grid deployment solutions along with the investment generation and transmission network and includes a stochastic representation of uncertainties [11]. In Case 28, the proposed framework comprehends stochastic optimization, high-performance computing, and high-level design software architecture for planning integrated and flexible power networks and optimizing their technological trajectories and operational functioning considering uncertainties [77].

### 4.8. VRE and DERs

The review highlighted which frameworks consider the impacts of variable renewables energy (VRE) and distributed energy systems (DERs) in the analysis. However, the interest in studying integrated T&D systems is rather "recent", the introduction of future power system technologies such as VER, DERs, and other flexibilities in the analysis is becoming more boarded every time. These smart grid technologies insert a massive additional degree of complexity in the analysis. Several sources of flexibility at the distribution level are still being studied so far (e.g., P2P, V2N, virtual power plants, etc.). In a later stage, these models may be included in the integrated T&D systems analysis.

### 4.9. Economic Aspects

In terms of economical evaluation, 16 surveyed frameworks include economic aspects in their analysis. One interesting approach to evaluate the economics in integrated T&D systems considering the multilevel structure of the smart grid is the social welfare concept. It is defined as a microeconomic concept representing the sum of all producers' and consumers' surpluses. Under a competitive energy market (where market participants are free to sell or buy energy), an equilibrium can be achieved when the energy system is functioning at maximum social welfare conditions [1,115].

In Cases 4 and 5, for instance, the IMRES and BID3 frameworks are utilized to evaluate the economics of flexible power systems. They use the Levelized cost of flexibility (LCOF) and cost-benefit analysis obtained by power system modelling. The cost-benefit of a flexibility solution is calculated as net system cost savings divided by the cost of the flexibility option itself [85].

In Case 17, the authors evaluate the economics of smart grid investments in electricity markets. The social welfare concept is adopted to this end [1]. Some other cases using social welfare as an economic concept for evaluation include Case 13, Case 16, and Case 34. In Case 36, the proposed stochastic program is driven by the minimization of the expected total cost, which comprises the costs related to investment decisions and system operation [114].

### 4.10. Environmental Impact

Undoubtedly, one key aspect of future power systems is the environmental impact evaluation of any proposed solution. We identified a few papers (5 cases) coping with this aspect. In Case 7, the flexibility is evaluated to meet carbon targets (emission target 50 or 100 g/kWh) in the UK through 2050 [2]. Case 8 computes the $CO_2$ emitted, $CO_2$ stored, and specific CO2 emissions per scenario in Western Europe in 2050 using PLEXOS [86]. In Case 13, the social cost of carbon is defined as the shadow price for the value of each tonne of carbon dioxide that is abated by the SmarNet project [92]. In Case 16, the authors consider a lifecycle assessment methodology (LCA). It accounts for (i) the CO2 emissions due to the deployment of smart grid equipment and (ii) their consequences on the power generation mix and the expansion of the network [11]. Finally, in Case 20, the total amount of $CO_2$ emissions is a monitored factor [80].

### 4.11. Interoperability

We define interoperability as the ability of an integrated T&D simulation tool to support a variety of platforms (distribution, transmission, communications, or market solvers) in the integration analysis, data exchange, and time coordination. In this context, an interoperable simulation tool can interface different solvers or languages for the same purpose, integrated T&D analysis.

We identified two frameworks that are capable of interoperating different system solvers. These are HELICS presented in Case 23 and FNCS in Case 15. Rather than T&D co-simulation tools per se, they are designed to support different solvers for the T&D co-simulation analysis and allow the exchange of information and timely coordination between different software.

The interoperability of FNCS is performed in Case 26, like the interoperability of HELICS is tested in Cases 30, 31, 32, and 33.

Finally, we summarize all surveyed dimensions and integrate them in Table 4.

**Table 4.** Survey overview of techno-economic tools for integrated T&D systems: reviewed dimensions.

| Case | Steady-State | Dynamics | Modelled System * | Spatial Scope ** | Temporal Scope *** | Temporal Resolution *** | Optim. | Uncert. | DERs | VRE | Econ. | Power Flow | Envi. Impacts | IOP **** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Yes | Yes | T | BC | Seconds | milliseconds | | | | | | Positive Sequence Load Flow | | |
| 2 | Yes | | D | RDN | 1 year | 30 min | | | | Yes | Yes | Optimal power flow | | |
| 3 | Yes | | D | RDN | 1 year | 30 min | | | | Yes | Yes | Optimal power flow | | |
| 4 | Yes | | T | N | >10 years | hourly | Yes | | Yes | Yes | Yes | Not specified | | |
| 5 | Yes | | T | VC | >10 years | hourly | Yes | | Yes | Yes | Yes | Not specified | | |
| 6 | Yes | Yes | D | R | 1 year | 1 min | | | | Yes | Yes | DIgSILENT | | |
| 7 | | | G | N | >10 years | hourly | Yes | Yes | | Yes | Yes | No power flow | Yes | |
| 8 | | | G | VC | >10 years | hourly | Yes | | | Yes | Yes | No power flow | Yes | |
| 9 | Yes | Yes | T, D | BC | 1 year | seconds | Yes | Yes | | Yes | | DC power flow model and GridLAB-D. | | |
| 10 | Yes | Yes | C | B | 24 h | 10 s | | | Yes | | | Power Factory | Yes | |
| 11 | Yes | | T, D | BC | GOP | GOP | Yes | | | | | Semi-definite-positive (SDP)-relaxation | | |
| 12 | Yes | Yes | T, D | BC | Seconds | milliseconds | | | | | | 3-sequence and 3-phase power flows | | |
| 13 | Yes | | D | C | Years | peak demand | | | | | Yes | Not specified | Yes | |
| 14 | Yes | | T | BC | >10 years | hourly | Yes | Yes | | Yes | Yes | Linearized power flow model. | | |
| 15 | Yes | Yes | T, D, Co | BC | Seconds | milliseconds | | | | Yes | | GridPACK and GridLAB | | Yes |
| 16 | Yes | | T | N | >10 years | Real-time | Yes | Yes | Yes | Yes | Yes | Not specified | Yes | |
| 17 | Yes | | D | C | 1 year | 2 seasons per year | Yes | | Yes | Yes | Yes | Traditional power flow | | |
| 18 | Yes | Yes | T, D | BC | 24 h | 1 min | Yes | | | | | 3 sequence power flow and OpenDSS | | |
| 19 | Yes | Yes | T, D | BC | Seconds | milliseconds | | | | | | PSAT, 3 phase power flow | | |
| 20 | Yes | | T, D | N | >10 years | 15 min | Yes | Yes | Yes | Yes | Yes | DC power flow model and linearized model | Yes | |
| 21 | Yes | Yes | D | R | 24 h | 5 min | | | | Yes | Yes | 3 phase modelling | | |

**Table 4.** *Cont.*

| Case | Steady-State | Dynamics | Modelled System * | Spatial Scope ** | Temporal Scope *** | Temporal Resolution *** | Optim. | Uncert. | DERs | VRE | Econ. | Power Flow | Envi. Impacts | IOP **** |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 22 | Yes | | T, D | BC | GOP | GOP | | | | | | MATPOWER and NLP | | |
| 23 | Yes | Yes | T, D, Co | R | Years | minutes | Yes | Yes | Yes | Yes | Yes | Supports a variety of platforms | | |
| 24 | Yes | | T, D | BC | 24 h | 1 min | | | Yes | | | 3-sequence and 3-phase power flows | | |
| 25 | Yes | | T, D | RDN | 1 h | 1 min | | | Yes | | | 3-sequence model and OpenDSS | | |
| 26 | Yes | Yes | T, D, Co | BC | 2 days | 1 min | Yes | | Yes | | Yes | AMES, GridLAB-D | | Yes |
| 27 | Yes | | T, D | BC | 24 h | hourly | | | Yes | Yes | | MATPOWER and OpenDSS | | |
| 28 | Yes | | T, D, C | BC | 24 h | hourly | Yes | Yes | | Yes | | MATPOWER and OpenDSS | | |
| 29 | Yes | Yes | T, D | C | Seconds | milliseconds | Yes | | Yes | | | PSS/end a CYME | | |
| 30 | Yes | Yes | T, D | RDN | Seconds | microseconds | | | | Yes | | InterPSS and OpenDSS | | Yes |
| 31 | Yes | Yes | T, D | BC | Seconds | milliseconds | Yes | | Yes | Yes | | PSS/E and GridLAB | | Yes |
| 32 | Yes | | T, D | C | 24 h | 15 min | | | | | | Power World, OpenDSS | | Yes |
| 33 | Yes | Yes | T, D, Co | BC | Seconds | milliseconds | | | | Yes | | ANDES, OpenDSS | | Yes |
| 34 | Yes | | T, D | BC | GOP | GOP | Yes | Yes | | Yes | Yes | Linear lossless power flow and AC power flow | | |
| 35 | Yes | Yes | T, D | C | 24 h | 5 min | Yes | | Yes | | | ANDES, OpenDSS | | |
| 36 | Yes | | T, D | BC | 1 year | 4 seasons per year | Yes | Yes | Yes | Yes | Yes | DC load flow and linearized AC load flow | | |

* G: generation, T: transmission, D: distribution, C: consumer, Co: communication; ** BS: benchmark system, B: building, RDN: real distribution network, C: city, R: regional, N: national, VC: various countries; *** GOP: given operation point; **** Interoperability.

## 5. Remarks and Discussion

Integrated T&D simulation of power systems is a relatively new area of research. Despite this, as reviewed in this study, this area has produced a large amount of work and literature. Several different frameworks were reviewed in this study which may be claimed as a definitive solution. As a relatively new research area, there are various promising candidates to simulate integrated T&D systems. Nevertheless, there is not yet a consensus on a specific framework that should be adopted by researchers in academia and industry. Moreover, as the power system is evolving rapidly towards a smart grid system, many novel technology and flexibility solutions (e.g., P2P, networked microgrids, V2G, etc.) are still under study to be integrated on a large scale. In a later stage, these smart grid solutions should be implemented in the integrated T&D analysis.

Furthermore, several future directions are proposed in the surveyed literature. For instance, in Case 36, the authors plan to devote their work to implementing alternative coordination schemes and considering strategic planners, which may require the use of game theory while accounting for information confidentiality. The adoption of a multi-stage or dynamic framework is also envisioned. Another avenue of research is the extension of the approach to consider some other practical aspects such as more accurate power flow models, discrete nature of generation investments, new generation technologies, and storage devices [114].

In Case 32, the results showed the relevance of using realistic, tightly coupled transmission and distribution co-simulation when assessing DERs. The fact that the datasets are also geographically matched opens future research opportunities to consider geospatially accurate transportation patterns, building codes, renewable resources, and other location-specific studies [110].

The work in Case 28 shows a promising pathway for a holistic, integrated T&D approach. By developing a prototype informed by software engineering and complex system design approaches, the authors aim to demonstrate the relevance of a unified vision of IGTDCS simulation on a minute-by-minute horizon and, in a later stage, benefit electromagnetic transient simulation or stability co-simulation tools. The proposed road map aims to combine static, quasi-static, and dynamic models of the electrical network and its equipment, loads, buildings, transactional energy markets, and telecommunications in a multi-tool distributed agent capable of simulating the behaviour of the intelligent network over a horizon that may range from less than a second to several years. They also state the necessity of considering optimization tools for power system analysis according to the nonlinear behaviour of technology penetration [77].

The HELICS tool proposed in Case 23 prioritizes for future study the documentation, integrating advanced features, evaluating the scalability of the tool, developing interfaces for additional simulators, and establishing an active community of contributors [104].

The FNCS tool developed in Case 15 establishes future directions by (i) developing more transient dynamic models in GridLAB-D, such as induction motor, wind turbine, and more electronic interfaced converter and inverter models; (ii) implementing co-simulation with distribution systems integrated with the models developed in (i) to investigate more dynamic interactions between distribution and transmission systems, such as the low-voltage ride-through problems; and (iii) implementing co-simulation for large-scale systems to test this approach's scalability [93].

Case 12 states a pathway to modelling the dynamic analysis of DERs and enhancement of the distribution system simulation algorithm to deal with meshed networks. Furthermore, the application of the developed simulation capabilities to comprehensively investigate the impacts of DERs on the T&D systems [91].

In Case 11, the future focus is on solving the T&D optimal power flow (OPF), defined as a non-convex problem, in order to guarantee a globally optimal solution. A mixed-integer T&D OPF will include a combination of the adopted heterogeneous decomposition (HGD) and other discrete variable methods. In addition, uncertainty and "N$-$1" operational constraints are expected [90].

In Case 9, the IGMS tool expects to explore price interactions between transmission markets and price-responsive distribution loads and expand the co-simulation by including

communications simulation tools to study the role of communication architectures in load-generation and distribution-transmission control systems [87].

In Figure 9, we offer a general picture of the stated problem in this study. The Sankey diagram presents a general sight of the trending of surveyed techno-economic tools for the integrated T&D systems. The diagram shows in overview the covered topics and approaches which have been a matter of focus for researchers.

The roadmap is very extensive. For instance, market processes are barely explored by previous studies; therefore, in an integrated T&D context, network-constrained market simulators that can provide recommendations for specific network operation and market management and design should be implemented in the co-simulation problem. In addition, modelling and simulation modules to address the interactions between different regulatory frameworks need to be studied.

It is not yet considered the integration of other energy markets (e.g., heat and cold, gas, etc.) in the co-simulation studies. These energy markets can also provide flexibility to the network, which in turn opens the pathway to further research of flexibility markets by using co-simulation and determining how profitable these markets can be under different congestion scenarios.

A more in deep analysis of the joint activities between TSO and DSO (e.g., congestion relief and flexibility options from the distribution side) is also required for integrating into the co-simulation problem. In this context, developing new tools to support TSO and DSO to improve their reliability is required.

There are still several distributed energy resources and flexibility technologies to be considered in both transmission and distribution systems that should be included in a co-simulation tool to have a more complete view. The potential use of DERs to support system-wide grid operations requires the development of models that bridges the traditionally different domains of transmission and distribution systems, analyzing not only the physical components but capturing the market, the ICT components, and end-use dynamics.

It is clear that there is a growing demand for load-based services at the distribution level. However, the widespread of such services implementation is being limited by the lack of opportunities and visibility and design of the market with appropriate tools for their evaluation. For instance, the potential impacts of the large-scale introduction of P2P energy trading mechanisms on the distribution system and planning are very unclear yet. Moreover, the co-simulation of P2P energy trading frameworks and distribution systems has not been studied in the literature.

On the other hand, a new tool for economic assessment of technology impacts and unlocking of decentralized flexibility should provide several benefits compared with pre-existing studies [11–14] by taking into account:

- The value of flexible solutions for all services that they can provide to the power system (congestion management, economic dispatch, short-term balancing requirement). For instance, if no flexibility is introduced (i.e., the existing approach to balancing is maintained), the potential wind generation curtailment in the United Kingdom as a function of installed wind capacity will move from 2.5% to above 25% in 2030 [12], although proactive curtailment strategies of excess renewable is not necessarily a bad economic policy [116].
- The effects of competition between alternative options. As some different smart grid flexibility solutions can provide similar services to the power system (security of supply, reserves and ancillary services, congestion management, etc.), the deployment of one of them could lead to pushing the other ones out of the market.
- The effect of the scale of deployment of flexibility solutions on their added value. The performed analyses factor in the effects of (i) increases in costs as the capacities deployed/mobilized are increased (this applies to demand response/load modulation in particular, residential PV/storage [117], and EV charging [118]); (ii) decreases in benefits based on each solution's level of introduction and the deployment of potentially competing solutions.

**Figure 9.** Trending overview of surveyed techno-economic tools for integrated T&D systems.

In the long-term planning, the concern arises at how far open-source tools are from commercial ones (e.g., PLEXOS) in terms of interoperability and integration with other software when co-simulating. Several desired functionalities should include generation dispatch and unit commitment, integrated transmission and generation planning on a techno-economic basis, stochastic scenarios, tougher climate policies, storage management, generation primary source management, multi-energy systems [23,119], HVDC lines, network constraints (power flow), N−k analysis; all of these within the time domain and in addition to the development of graphical user-interfaces and data consistency checking [120]. Open models are becoming more important as most current models are not open source, and therefore, it is not possible to manipulate or replicate the code.

## 6. Conclusions and Future Research Directions

A literature review of existing simulation tools to assess the techno-economic benefits of smart grid technologies in integrated T&D systems is presented. The survey includes novel frameworks available in the literature. They are classified on their multiple characteristics, including smart grid-related dimensions. More than 40 studies were surveyed, and 36 different frameworks for the analysis of integrated T&D systems were identified.

The study of integrated T&D simulation is a relatively new area of research. Nonetheless, a large amount of work is available. We aimed to review the most relevant approaches which may be claimed as a definitive solution. Despite the novelty of the research area, we have found various promising candidates to properly simulate integrated T&D systems. Nonetheless, there is not yet a consensus on a specific framework that should be adopted by researchers in academia and industry. Moreover, as the power system is evolving rapidly towards a smart grid system, novel technologies and flexibility solutions are still under study to be integrated on a large scale. In a later stage, these smart grid solutions should be included in the study of integrated T&D systems.

As an imperative need for future energy systems analysis, this article aims to contribute and to feed the discussion about which pathway the scientific community should focus on for a successful shift toward environmentally friendly energy systems. The ultimate intention of this review is not to recommend a specific integrated T&D systems framework but to offer researchers more extensive instruments to identify the gaps and focus the research on successfully decarbonized energy systems.

The roadmap is very extensive. Market processes are barely explored in an integrated T&D context; network-constrained market simulators that can provide recommendations of specific network operation and market management and design should be implemented in the co-simulation problem. In addition, modelling and simulation modules to address the interactions between different regulatory frameworks need to be studied. It is not yet considered the integration of multi-energy markets (e.g., heat and cold, gas, etc.) in the co-simulation analysis. Developing new tools to support TSO and DSO to improve their reliability is also required. On the other hand, a new tool for economic assessment of technology impacts and unlocking decentralized flexibility may provide several benefits compared with pre-existing studies. In the long-term planning, the concern arises at how far open-source tools are from commercial ones (e.g., PLEXOS) in terms of interoperability and integration with other software when co-simulating.

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