

Inclusion of Innovation in Simulation of Offshore Power Grids

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Abstract: The European offshore grid is a barrier and an enabler to the sustainability transitions of power systems. Its social and technical elements shape the development pathway, one strongly influenced by innovations. Simulation can help on pathway management, but its application is non-existent, and the consideration of innovation in simulation is scarce. Therefore, we analyse relevant features of socio-technical systems, innovations and the offshore grid, and different simulation approaches. ABM and myopic optimization represent better multiple transition phases, individual actors and the technical subsystem. By complementing qualitative and quantitative methods, simulation can support the offshore grid sustainability transition and innovations.

Keywords: Offshore grid, innovation studies, sustainability transitions, simulation, modelling

JEL codes: C000, O210, O380

1. Introduction

Infrastructures are physically networked socio-technical systems providing essential services to society [1], [2]. As such, infrastructures have social and technical subsystems. While the technical subsystem comprises the technical components forming a network with nodes and links, the social subsystem components are the actors and institutions of the system, which are also interconnected (albeit not physically). Also, as a socio-technical system infrastructures are a complex system, where no single viewpoint can completely describe the system [3].

Society currently faces many challenges such as climate change, resource depletion, market reforms and technological development [4]. These challenges are driving change in infrastructures, which also face specific challenges such as the adoption of ICT technologies, uncertain demand and change of uses, increasing renewable energy sources integration needs, and balancing public and private participation [5]. Hence due to internal and external challenges infrastructures face changes which in the long-run will have to be substantial, therefore composing transitions [6], [7]. In the context of climate change and resource depletion, we may refer to this as the sustainability transition of infrastructures.

A particular infrastructure type is the Northern Seas offshore grid. This grid performs two functions: it interconnects the Northern European power systems of the British Isles, Scandinavia and Continental Europe; and it connects offshore wind farms in the Northern Seas to those systems. What more, while one may state that this grid is already a reality, it will significantly develop in the future, though a wide range of possible development pathways exist. The latter range from typologies with separated assets to

perform the two functions (e.g. separate offshore wind farm connector and a NO-UK interconnector) to typologies with significant asset integration [1], [8]

One important aspect for addressing sustainability transitions in infrastructures are technological and social innovations. These enable new organizational structures, institutions and technologies addressing the challenges energy systems are confronted with. When analyzing innovations for sustainability transitions, one must be aware of the system components (technical elements, actors and institutions), its characteristics affecting the development, the diffusion and use of innovations and system change, the system boundaries, the knowledge forms, and any interactions with policy [9].

The importance of innovation to sustainability transitions also applies to the offshore grid. The grid involves two main technologies, offshore wind power and high-voltage direct current (HVDC) transmission, both of which still present innovation challenges and potential. As an example, the offshore grid requires the development of high-capacity HVDC breakers, flow control devices, control strategies, wide band and DC/DC converters, and the standardization and interoperability between manufacturers [10]. The future development of offshore wind which impacts this grid depends on its turn on significant performance improvements and cost reductions, especially in turbines, competition within the industry and the cost of equity [11]. Moreover, the offshore grid itself requires new governance solutions addressing issues such as planning, coordination with generation investments and financing [1]. These examples demonstrate the importance of both technological and social innovations for the offshore grid.

Therefore on the one hand there are innovation challenges for the offshore grid. On the other hand, it can contribute significantly to advance the sustainability transitions of the European energy system. First, by integrating offshore wind power into the system the grid develops a renewable energy resource poised to contribute with up to 15% of the European electricity demand by 2050 [12]. Second, the grid adds flexibility to the system by connecting partly uncorrelated loads, generation and storage. This increased flexibility facilitates the integration of variable renewable resources, which includes but is not limited to offshore wind power. Third, the interconnection of different European power systems may facilitate the integration of distributed energy resources (DER), for though these are applied at the distribution level they still interact with the transmission system. Last but not least, the offshore grid improves the economic efficiency of power systems, which improves its legitimation and indirectly affects its sustainability transition (e.g. by freeing up funds for investment in future energy technologies).

Therefore, the offshore grid acts as both an enabler and a barrier to the sustainability transition of European energy systems. This characteristic is in fact common to multiple infrastructure types and is identified by Frantzeskaki et al. [7] as the dual roles of infrastructures. The authors nonetheless stress that “based on their characteristics, [infrastructures] have a tendency to promote incremental change”, as opposed to radical change. This dual role is similar to the concept of the duality of infrastructures, which

opposes the closed aspects of infrastructures in the short run against its open, dynamic aspects in the long-run [1].

One can see therefore that the dual roles of infrastructures manifest themselves in different time horizons, and that these systems are subject to considerable inertia. The importance of dynamics in infrastructure studies manifests itself not only through this inertia, but also through their path dependence. Path dependence implies that given certain initial conditions, contingency (random events) and/or self-reinforcement mechanisms, a system cannot escape a given pathway (i.e. pathway lock-in) without external influence [13].

The dual role and the path dependence of infrastructures reinforce the argument to manage their transition, to which innovations will play a major part. Hence, it is relevant to study innovations in infrastructures. The stated aim of this paper is to address explicitly innovation in the simulation of offshore grids for sustainability transitions. It analyzes the possible approaches, considering the advantages and disadvantages of each of them. Therefore, the research question is “how can we consider innovation when simulating the sustainability transitions of offshore grids and what are the advantages and disadvantages of the different approaches?”

Besides developing a framework for considering innovation in the simulation of offshore grids, this framework can be of use for other infrastructures, and for the simulation of offshore grids in general, a field with scarce research, as discussed below. This framework is of interest to academics active in innovation studies and energy systems modelling, and to policy makers working with infrastructure management or the offshore grid itself.

The study scope is defined as follows. First, the system of focus is the offshore grid, and consequently other systems such as the offshore oil & gas infrastructure are not discussed, except in the conclusion. Second, evolutionary computation models are not analyzed, for even though these may lead only to local optima they still strive for global optima and can be classified as perfect foresight (meta)-heuristics optimization models, which are out of the study scope. Qualitative models are also excluded, which leaves out notably accounting approaches, sometimes classified as simulation models [14]. Lastly, the simulation level of interest is the offshore grid, and not individual actors in it. Hence, the detailed modelling of the actors composing the offshore grid is not discussed (e.g., the interest is the modelling of the firm as a system component, and not as the focus itself).

This article is organized as follows. The next section discusses modelling approaches for the offshore grid and details the research gap of applying simulation to study this particular infrastructure, with a complementary literature review. Then, Section 3 presents the methodology, the modelling approaches considered, and the features these should be compared against. Section 4 presents the comparison results, and finally conclusions and future research recommendations are drawn.

2. Modelling the offshore grid

For studying energy systems one can use several methodologies. A first classification can be made between qualitative and quantitative approaches, with modelling composing an important subcategory of quantitative approaches. Modelling can itself be subdivided into top-down (e.g. general equilibrium economic models) and bottom-up (e.g. optimization or simulation models) as presented in Figure 1 [15].

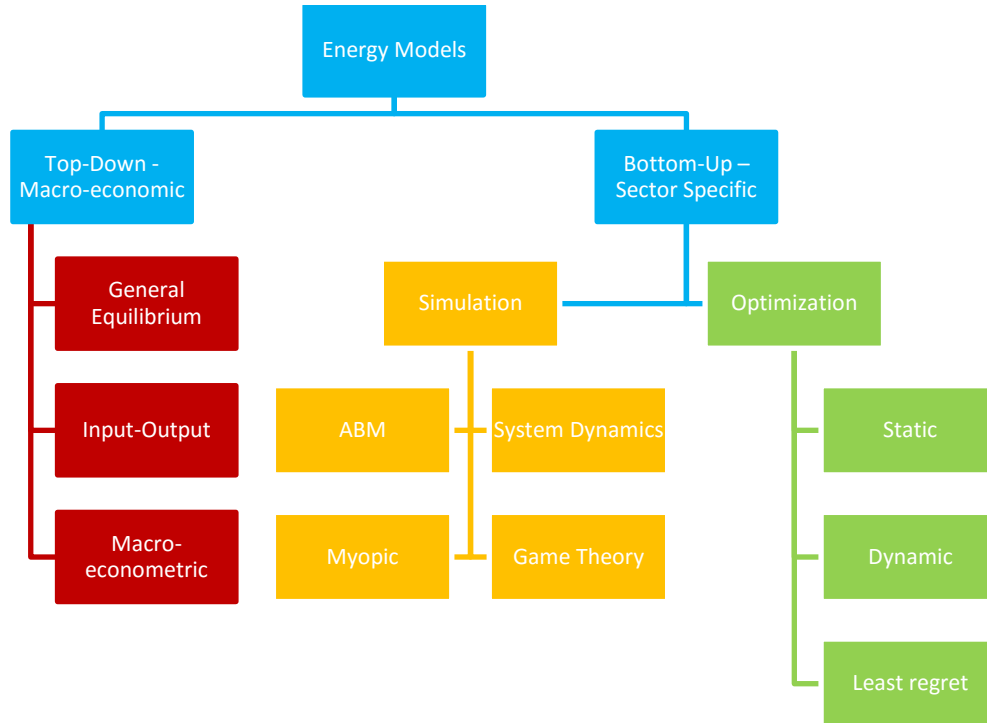


Figure 1: Modelling approaches adapted from [15]

Top-down models consider multiple economic sectors of the system of interest and their interaction. In this way, they are capable of representing feedbacks between those sectors and other phenomena, such as the rebound effect (where increased consumption partly or completely cancels out energy efficiency gains). However, top-down models do so at the cost of a simplified representation of each sector. Bottom-up modelling on its turn focuses on a specific economic or technological sector. By doing this it represents details of that sector in a manner that would be too complex for top-down models, and thus provides technology-dependent insights into those systems in a way that top-down modelling is unable to [14], [16], [17].

Simulation models are a sub-category of bottom-up models, having several advantages: detailed and explicit modelling of complex technical and social system components, and their interaction and timing; multiple alternative scenarios exploration with retroductive analysis of past transitions in a context of policy urgency; surpassing human cognition limits; system boundaries exploration without an *a priori* limitation; and facilitation of the analysis of transition management mechanisms [16].

On the other hand, simulation models have drawbacks. First, the application to future scenarios cannot be compared to existing ones [18]. In addition, the modelling of individual system components must also be validated. This is crucial, since detailed modelling does not imply an adequate representation of reality, e.g. actor decision-making heuristics leading to bounded rationality do not mean necessarily a more accurate representation of reality just because the decision-making heuristics are not optimal [19]. Third, the accuracy of simulations is lesser because of the required modelling assumptions [16]. Finally transparency is essential as in other modelling approaches, since simulation is not an accurate depiction of reality but a representation of possible scenarios while simultaneously supporting decisions on relevant and real issues [18].

As for infrastructures, conceptual research analyzing them as socio-technical systems is diverse [2], [6], [7], [20]–[26]. However, despite recent research developments the affirmation of Loorbach et al. [5] that “the role of infrasystems has received relatively little attention in transition research” is still valid. Moreover, despite the aforementioned advantages of simulation, research applying it to infrastructures transitions is much more limited. Hence, to the author’s best knowledge there are no examples of published simulation approaches to sustainability transitions of the offshore grid [8]. What more, despite the importance of innovation to sustainability transitions, simulations of the existing offshore grid and other infrastructures do not consider explicit innovation or the impact of the innovation modelling choices.

Beyond the literature addressed previously, two structured searches were conducted on Scopus to identify further research on the simulation and innovation of infrastructure transitions and of the offshore grid. The search concepts and alternative terms are indicated in Table 1. The first search resulted in 97 results, the majority of which does not focus on physical infrastructures, but rather consider infrastructures as one of many components of innovation systems. Moreover, no article specifically addresses all main search concepts (i.e. infrastructure, transition, simulation and innovation). Nonetheless, 9 articles relating in varying degrees to the topic were identified [1], [27]–[34]. The second search topic is even more specific and hence provided only 16 search results, where the only relevant reference is Kern et al. [35], which nonetheless does not use simulation modelling.

In this way, there is simultaneously the need to address explicitly innovation in the simulation of infrastructures for sustainability transitions, and the lack of any such research, thus supporting the research objective of this paper.

Table 1: Literature search on infrastructure transitions simulation

| Infrastructure Transitions Simulation | | | | |
|---------------------------------------|-----------------|------------|-----------------|------------|
| | Term 1 | Term 2 | Term 3 | Term 4 |
| Main term | Infra*structure | Transition | Simulation | Innovation |
| Alternative terms | Infra*system | Change | Model* | |
| | | Evolution | System dynamics | |
| | | | Agent-based | |
| | | | ABM | |

| Offshore Grids Simulation and Innovation | | | | |
|--|-----------------|------------|-----------------|------------|
| | Term 2 | Term 3 | Term 4 | Term 5 |
| Main term | Infra*structure | Transition | Simulation | Innovation |
| Alternative terms | Infra*system | Change | Model* | |
| | Grid | Evolution | System dynamics | |
| | Network | | Agent-based | |
| | | | ABM | |

3. Framework for comparison

3.1. Methodology

To address the research question this study compares the approaches to include innovation in simulation models according to identified features. First, the principal simulation modelling approaches for the offshore grid are briefly described. Secondly, the relevant features are identified and divided into the main categories of socio-technical systems, innovation and the offshore grid, as in Table 2. Finally, the advantages and disadvantages of each approach can be analyzed according to the features, providing the main framework of this study.

3.2. Simulation modelling approaches

As see, different energy model classifications are possible, e.g. [14], [18]. Here, simulation approaches comprise game theory, agent-based modelling (ABM), system dynamics (SD) and myopic optimization. **Game theory** calculates the individual strategies of (possibly rationally bounded) actors by iterating to an equilibrium (e.g. evolutionary game theory) or through an equation system (e.g. Cournot equilibria) [14], [36]. **Agent-based modelling** defines individual actors' perceptions, heuristics and networks in order to simulate their actions and arrive at non-optimal system states, usually stochastically. On its turn, components in **system dynamics** interaction and behavior are defined by differential equations, whose simulation in time also lead to non-optimal system states. Finally, **myopic optimization** defines an optimization problem with a restricted horizon, therefore leading to sub-optimal solutions when considering the full problem horizon (e.g. a single-period optimization in a dynamic, multi-period problem).

3.3. Features for innovation and the offshore grid modelling

To address the research question this study deals with three different concepts as levels for the framework. These concepts are socio-technical systems, innovation and the offshore grid. Each of the concepts has defining characteristics as in Table 2 (with the accompanying references) that need to be considered in the chosen simulation model, with the principal ones being presented next.

As indicated socio-technical systems are systems comprising “two deeply interconnected subsystems: a social network of actors and a physical network of technical artefacts” [3]. Hence, the components of such a system are actors, institutions and technical elements. The **multiplicity** (of actors, levels, objectives and phases) is a central characteristic of socio-technical systems and increases the challenge of setting **system boundaries**. This because socio-technical systems are open systems interacting with the environment, so defining which components belong or not to the system may not be a clear-cut issue [3]. As seen **path dependence**, **lock-in** and **co-evolution** are central to transition studies, but also to studying socio-technical systems, and are hence a central feature in the simulation of sustainability transitions of such systems [13], [37]. Then, social components deserve particular attention for sustainability transition studies, given the management of transitions is often a central objective, so **institutions** and particularly **policies** are necessary features [9]. Finally, **bounded rationality**, **learning** and **networks** all revolve around actors and affect the system and innovation pathways [36]–[38].

Innovation on its turn may be defined as “technologically novel or improved material goods, intangible services or ways of producing goods and services”, and may be social or technological, and product- or process-related [9], [39]. How the simulation models addresses the **degree** and **type of innovation** is crucial to the system and innovation pathways. However, independently of the degree and type the task of modelling innovation is made more difficult by the **environmental uncertainty**, the **technology complexity** and the **innovation diversity** [40]. These features lead to multiple and uncertain innovations interacting with each other and the system components. However, these features already warrant the use of the socio-technical system concept and simulation. This because the former addresses this complexity arising from the features, and the latter allows the detailed modelling of the system, innovations and the offshore grid.

Following the Northern Seas example, offshore grids are “offshore high-voltage transmission system connecting offshore wind power (OWP) and onshore power systems ... composed of transmission assets (interconnectors and generation connectors), without a predefined transmission technology or topology of the grid” [8]. The offshore grid characteristics can be classified in the categories of **technology**, **implementation** and **system** [8]. These characteristics exhibit some overlap with the **governance** aspects

of planning, financing, ownership, pricing and operation reported by Mekonnen et al. [41], [42], but the latter covers nonetheless new governance functions.

Table 2: Features for the comparative analysis of models

| Category | Feature | Reference | Description |
|------------------------|---|------------------|--|
| Socio-technical System | Multiplicity | [3], [36] | Of actors, levels, objectives and phases |
| | System boundaries | [9] | Defining components belonging to the environment or system |
| | Path dependence and lock-in | [13], [37] | Initial conditions, contingency and/or self-reinforcement constrain pathways in absence of external influence |
| | Formal and informal institutions and policies | [9] | Unwritten conventions, habits and rules and written laws, regulations and relationships governing the interaction of actors; Policies: Objectives of policy makers and the mechanisms for their execution |
| | Bounded rationality and learning | [36]–[38] | Bounded rationality: Actors have cognitive limitations on information and decision making; Learning: Individual (past experiences) and social (interaction with actors) learning leading to changes in heuristics |
| | Co-evolution and network dynamics | [9], [37], [38] | Co-evolution: Interaction of system components and resulting change; Network dynamics: Change of networks among actors |
| Innovation | Degree and type | [40] | Degree: Disruptive, radical or incremental innovation; Type: Process, product or service |
| | Environmental uncertainty and technology complexity | [40] | Environmental uncertainty: "Function of the rate of change of technologies and product-markets"; Technological complexity: "Function of technological and organizational interdependencies" |
| | Diversity, selection and diffusion | [37], [38], [43] | Diversity: Range of innovations possible; Selection: Individual (natural and subset selection) and group (based on characteristics of groups of actors) selection; Diffusion: "The pace of adoption of particular technologies, goods and behaviors that have been already adopted (selected) by a fraction of the population" |
| | Scale and resources change | [38], [44] | System scale change and investment |
| Offshore Grid | Technology | [8] | Power systems and HVDC technology |
| | Implementation | [8] | Asset- and project-related characteristics |
| | System | [8] | Systemness and decentralization |
| | Governance | [41], [42] | Planning, financing, ownership, pricing and operation |

4. Comparison of simulation approaches

Table 2 summarizes the capabilities of each approach to address the features of interest to modelling innovations in the offshore grid as a socio-technical system. A preliminary analysis indicates that the methods that adequately address the most features are agent-based modelling and myopic optimization. This is due to them sharing three principal characteristics: the easier representation of individual actors, of multiple phases in the sustainability transition of infrastructures, and of the technical subsystem of an offshore grid.

Regarding the first characteristic, the requirement of system dynamics to describe components by differential equations hinders actors, institutions and innovation diversity and change. This burden is not shared by the other approaches, especially ABM and myopic optimization. Changing these components may be difficult in an equation-based game theoretic approach, though not so in an evolutionary one.

As for representing multiple phases in sustainability transitions, game theory is the less adequate methodology. Game theory (whether evolutionary or equation-based) defines stable strategies for each actor. A changing system implied by a sustainability transition will require changing strategies as opposed to stable ones. Although the need for changing strategies can be addressed by modifying the conventional applications of game theory models, these would increasingly resemble agent-based methods.

Finally, the technology and implementation features of the offshore grid require the detailed modelling of the technical subsystem with individual assets such as transmission lines and generators, and their joint operation. Game theory and to a certain extent system dynamics face obstacles in representing a large number of such assets and the physical laws governing the technical subsystem operation. Since these features are crucial to determine the system state this means agent-based modelling and myopic optimization more adequately reflect the technical subsystem.

Table 3: Features comparison of simulation approaches

| Category | Feature | Game theory | ABM | System dynamics | Myopic optimization |
|------------------------|---|-------------|-----|-----------------|---------------------|
| Socio-technical System | Multiplicity | + | ++ | ++ | ++ |
| | System boundaries | | | | |
| | Path dependence and lock-in | | + | + | + |
| | Institutions and policies | | + | + | + |
| | Bounded rationality and learning | + | ++ | + | + |
| | Co-evolution and network dynamics | | + | | + |
| Innovation | Degree and type | | + | + | + |
| | Environmental uncertainty and technology complexity | + | + | + | + |
| | Diversity, selection and diffusion | ++ | ++ | | |
| | Scale and resources change | | + | + | + |
| Offshore Grid | Technology | | + | | + |
| | Implementation | | + | + | + |
| | System | + | + | + | + |
| | Governance | + | + | | + |

++ : Very adequately modelled

+ : Adequately modelled

| : Modelling possible

Given these considerations, each separate feature is then analysed. **Multiplicity** is pivotal to social-technical systems, where game theory is less adequate than the other approaches. Nonetheless, even this approach can represent multiple actors, levels and objectives, and hence be more adequate than non-simulation models. Approaches do not differ on addressing **system boundaries**, because setting adequate boundaries is a modelling challenge which all approaches face and which arises from the complexity of socio-technical systems. Differently, **path dependence and lock-in** are better addressed by approaches other than game theory, due to the aforementioned difficulty of the latter to represent the phase multiplicity. The **modelling of institutions and policies** is also more challenging with game theory, especially in equation-based methods where the simplifications required by the equations may hinder detailing such institutions. As for **bounded rationality and learning**, this is a common strong point of simulation in general. Finally, approaches with better representation of phase multiplicity (i.e. ABM and myopic optimization) perform better on **co-evolution and network dynamics**.

The **degree and type** is the first considered feature of the innovation concept level. Here degree implies different phases in the sustainability transition pathways, and hence game theory once again is the less adequate method, though it is not necessarily worse in representing type (product, service or

process). The **environmental uncertainty** of innovations can be adequately addressed by all approaches by exploring scenarios and using stochastic simulation. However, simulating the **technology complexity** (i.e. innovations and other system components interdependencies) is something new and which all approaches still need to improve. As for simulating the **diversity, selection and diffusion**, this is one of the core purposes of evolutionary game theory, and a feature where agent-based models are also strong due to their detailed representation of individual components. At last, simulating the system **scale and resources** change is done best with good phase multiplicity representation, i.e. by approaches other than game theory.

The greater adequacy of ABM and myopic optimization to model the technical subsystem of the offshore grid was discussed above, and affects the **technology and implementation** features. Simulation is especially adequate to represent the decentralization characteristics of the system feature, and hence here all considered approaches are equal. Nonetheless, modelling issues such as the transmission-generation coordination, internationality and regulatory differences are difficulty in any model. Finally, the different issues comprised in **governance** (planning, financing, ownership, pricing and operation) favour game theory on one hand and ABM and myopic optimization on the other, for different reasons. Game theory and its focus on defining stable actor strategies considering other actor strategies naturally leads to useful insights into governance questions (e.g. on the impact of redistribution of costs and benefits given certain strategies or adequate planning strategies). ABM and myopic optimization on their turn allow the detailed representation of actors, and since governance issues revolve around actors those methods provide the freedom to model the governance elements of interest.

5. Conclusions

While the use of simulation models in transmission expansion is rare but does occur, their application to the offshore grid is non-existent. Nonetheless, the features identified in this study indicate these models can contribute to our understanding of the sustainability transitions of the offshore grid, considering or not innovations. This applies especially to agent-based modelling and myopic optimization. These combine the general strengths of simulations models with a better handling of multiple individual actors, the phase multiplicity, and the representation of the technical subsystem.

Nonetheless, the *caveats* of validation, transparency and accuracy of simulation models remain when these are applied to offshore grids. While these potential pitfalls are common to all modelling approaches, validation is particularly relevant for simulation. Since alternative quantitative and qualitative approaches can compensate this and provide complementary insights, the study of sustainability transitions of the offshore grid should combine different methods. For example, a qualitative research of the innovation systems of the technologies affecting the grid can provide a detailed insight of them. Simultaneously, an optimization study may indicate the maximum potential benefits of an integrated grid, and simulation can support energy and innovation policies to strive for these benefits considering the interaction of all system components, modelled with the insights of the qualitative study. In conducting this, transparency of the methodologies and outputs is essential to ensure the coherency and verifiability of results which directly influence policy.

Simulation can in this way contribute to the transition management of offshore grids considering innovation, and while doing so contribute to the use of simulation for innovation studies in general. The next step for research is the actual development of simulation models for the grid, using not only the most adequate approaches identified but also game theory and system dynamics. In this way, practical difficulties of modelling the sustainability transitions and innovation of infrastructures will be clearer and strengthen further deployment. Also, considering and modelling the interactions with other systems is relevant, since these systems contribute to and interact with the offshore grid. This in a similar way the offshore oil & gas or onshore wind power sectors contributed to the offshore wind industry.

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