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Steering Renewable Energy Investments in Favor of Energy System Reliability: A Call for a Hybrid Model

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Abstract: The global increase in electricity supply volatility due to the growing share of intermittent renewable energy sources together with recent extreme weather events draws attention to energy system reliability issues and the role of renewable energy sources within these systems. Renewable energy deployment strategies have already become a key element in debates on future global energy systems. At the same time, more extensive use of renewable energy sources implies a higher dependence on intermittent power, which puts the reliability of the electricity system at risk. Policymakers are introducing measures to increase the reliability of energy systems. Paradoxically, support for renewable energy and analyses of energy system reliability have been dealt with by two different and rarely overlapping research approaches. As a result, renewable energy promotion has often been designed without accounting for system reliability. To our knowledge, a model that captures those investment incentives and allows for tuning such financial support does not exist. This paper introduces a hybrid model that can potentially steer renewable energy investments in favor of energy system reliability. We demonstrate the idea of reliability-based support for renewable energy sources in action using a stylized case. Depending on the complementarity of different renewable energy power outputs available in the system, such reliability-based support can substantially reduce the necessity for greater backup capacity, can cut the overall costs of the energy system, and can reduce its environmental footprint.

Keywords: renewable energy support; energy modeling; sustainability; energy system design; generation profile; environmental footprint

1. Introduction

Striving to reduce their carbon footprints, governments worldwide have been introducing renewable energy policies to decarbonize power sectors. Even the COVID-19 pandemic has not slowed down the growth in the global renewable power capacity, reaching a record share of almost 30% of the global energy mix in 2020 [1]. However, such development poses challenges for energy systems. Electricity generation from many types of renewable energy sources is intermittent. However, the overall electricity supply should match the demand at every moment to avoid costly blackouts. Thus, the extensive deployment of renewable energy may threaten the reliability of energy systems. In response, various flexibility measures have been developed. They include storage technologies, such as batteries and hydrogen solutions (the latter possesses a potential for electricity transmission [2,3] and sector coupling with transportation [4]); demand-side management; smart grids; and regulatory measures to ensure reliability [5], so-called capacity mechanisms [6,7].

Recent extreme weather events have drawn the attention of policymakers and researchers towards the reliability of the power systems, with implications for widespread renewable energy adoption as well. Extreme weather events and weather variations affect both the energy demand and the reliability of energy systems. Numerous global cases of extreme weather events, such as heatwaves or severe winter storms, forced interruptions in the power generation, and even blackouts have been reported [8,9]. Perera et al. [10]
estimated that future extreme weather events induced by climate change might lead to a drop in power supply reliability by up to 16%. Uncertainty in the power supply associated with weather variations may slow down the implementation of intermittent renewable energy technologies and may increase the dependence on fossil-based power generation. However, Perera et al. [10] demonstrated that further adoption of renewable energies is possible without compromising the resilience of energy supply systems if potential risks are appropriately quantified. In this regard, financial mechanisms, which promote the implementation of renewable energy while ensuring the energy system reliability, should be introduced. The idea of enabling market signals by channeling the system reliability needs in subsidies for renewable energy, advocated in the paper, was highlighted in previous studies as well [11].

Intermittent renewable energy is often mentioned as one of the causes of problems with energy system reliability in Europe [12]. Norway has the highest cost for maintaining electricity supply security in Europe partly because of their high share of small-scale intermittent hydrogeneration in the system [13]. In the academic literature, renewable energy sources are often treated as a threat to energy system reliability as well [14–16]. Such research normally inquires about what types of capacity mechanisms can better tackle the problem. For example, Bhafgwat et al. [15,16] ran simulations to determine what type of capacity mechanism would better protect against a high share of renewable energy sources. Lara-Arango et al. [14] came to the conclusion that no capacity mechanism can sufficiently tackle the issue because of the uncertainty in the electricity supply from renewable energy sources.

An emerging research direction reconsiders the adverse role of renewable energy sources for energy system reliability. Mastropietro et al. [17] demonstrated that some countries choose to include renewable energy sources into their capacity mechanisms because they do contribute to system reliability. In the same vein, Söder et al. [18] made an argument for including renewable energy power plants into capacity mechanisms. Peter and Wagner [19] showed that wind power generation in Europe is characterized by spatial and temporal heterogeneity. Thus, if wind farms are built in places better for system reliability instead of the most profitable locations, excessive amounts of backup capacity could be avoided. At the same time, existing energy models are often wired to add a fixed amount of backup capacity for every new unit of renewable energy [20], which makes it impossible to capture the complementarity effects of renewable energy sources and their subsequent benefits.

However, obtaining a model that accounts for those complementarities of renewable energy sources is insufficient. The value of renewable energy sources for system reliability needs to be translated into investment incentives. Such incentives would steer investments towards creating an optimal mix of technologies for system reliability and towards avoiding considerable costs for unnecessary backup capacity provisions. Thus, we need a different type of renewable energy support mechanism that can take system reliability into account. Such support can only be designed with the help of a model that can do both: capture the complementarity of renewable energy sources and simulate investors’ behavior.

This paper aims to design a conceptual model that allows for bridging these two detached phenomena: renewable energy support and energy system reliability. With such a model, we can see whether, where, and under which conditions the support for renewable energy sources is better to be designed based on the system reliability needs. In future studies, when the model introduced here is expanded, we will be able to observe whether the capacity mechanisms steer the mix of renewable energy technologies well after their support is withdrawn, whether any modifications are required, and what the effects of the development of storage solutions are. Overall, such a model would provide in-depth insight for modern energy policymaking.

The remainder of the paper is structured as follows. First, we provide a short overview of existing energy modeling approaches for: (i) renewable energy support design and (ii) energy system reliability studies. Furthermore, we present the conceptual idea and
design of the model, illustrate it in action with a stylized case, and describe the modifications required for the model to be applied to a real-world analysis. We conclude with an in-depth discussion of the model’s applicability and possible policy implications.

2. Background

2.1. Modeling for Renewable Energy Support

Renewable energy support is meant to foster investments in renewable energy. In order to understand what investment incentives a policy creates, one needs to take the investor’s perspective and to analyze the investment profitability and how the policy affects it. Traditionally, such an investment analysis is conducted with a cost–benefit approach and in particular real options framework [21]. The real options framework, apart from plain profitability, recognizes uncertainty connected to the project implementation and possible flexibilities that allow the benefits to be captured or the shortfalls of unfolding uncertainties to be avoided [22]. Therefore, the real options framework becomes especially useful in understanding the effects of policies since a policy aims to reduce uncertainty for investors that otherwise hinders technology diffusion.

A considerable share of renewable energy valuation studies specifically focused on the analysis of policy effects [23]. The majority of such studies recognize uncertainty coming from volatile electricity market prices, and the main type of flexibility is to postpone investment. Such a study design allows for addressing the question of whether one or another policy sufficiently shields investors from uncertainty to incentivize investments sooner rather than later. Especially beneficial for policymaking are comparative studies, where the performance of different types of support instruments is analyzed [24,25]. Methodologically, real options research encompasses both analytical and numerical methods, including standard methods such as dynamic programming, Monte Carlo simulation, and various trees and lattices [23,26]. However, the majority of studies take an individual investor’s perspective.

System-level energy models rarely come down to the policy details [27]. One prominent exception is the Green-X model [28], which intentionally recognizes different types of support for renewable energy and analyzes their performance and costs on the system level. However, GREEN-X lacks modeling of realistic investment behavior. The decisions to invest are based on a plain cost–benefit analysis and investors, for example, are not given a right to postpone their investments.

Meanwhile, in the real world, professional investors and utilities behave in accordance with the real options logic [29], even if they do not use real options models for decision-making [30]. To the best of our knowledge, the only model, so far, that integrates real options logic into the energy system level is the one by Rios et al. [31]. However, it does not focus on renewable energy sources or their support policies. Instead, the aim of this model is to capture the fluctuations in investments in new power generation after electricity market liberalization. The cyclic behavior of these new capacity additions makes it possible to simulate the flexibility in postponing an investment in the model. Thus, this finer detail of investment behavior—flexibility under uncertainty—is a must-have in system-level energy models if the aim is to estimate policy effects on investments.

2.2. Modeling for System Reliability

Often in the literature, the terms security of electricity supply, power system reliability, and power system adequacy are used interchangeably. Heylen et al. [32], in their comprehensive review of reliability indicators, provided a classification where system reliability is composed of system adequacy and system security. System adequacy refers to the ability of the supply to meet the demand in regular circumstances. System security refers to the ability of the system to accommodate disturbances. Many different indicators exist in both categories and, often, they are related to each other to different extents.

Peter and Wagner [19] utilize a commonly used approach with respect to the measure of system reliability in their hybrid model. The reliability measure expected energy unserved
(EEU) characterizes the overall system reliability. It is, essentially, the expected load level that cannot be served over a time span and is defined based on loss of load probability (LOLP), a common system adequacy indicator. The contribution of individual technologies to the system reliability or their capacity value can be defined via equivalent firm capacity (EFC), where the term ‘firm’ refers to only the amount of capacity that actually contributes to electricity generation. Thus, the capacity of an individual technology is practically a share of its overall installed capacity that contributes to the decrease in the loss of load probability and, thus, improves system reliability.

System reliability is a system-level issue and, thus, should be studied by system-level models. The reliability of electricity supply depends on all power plants, storage solutions, and demand flexibility available in the system, and all of these actors should be taken into account. Typically, long-term energy system optimization models have been used for this matter. In such models, the evolution of the power-generation technology mix can be traced, and its reliability can be assessed, usually on a year-by-year basis and sometimes while taking into account seasonal, weekly, or day/night variations in the supply and demand. However, with the increasing share of renewable energy sources, in which the power output varies from hour to hour and from day to day, a necessity for integrating more fine resolutions into those models arose [20]. Operational power system models match the supply and demand on an hourly basis and are commonly utilized by system operators to balance the system. Such models, however, do not have room for new investments and long-term technology mix evolution [33]. Thus, policymakers call for hybrid models that are able to combine short-term power variations and long-term technology development [34].

A handful of studies attempted to integrate the finer details of operational power system models into long-term energy system models [19,35]. Peter and Wagner [19] specifically focused their modeling efforts on accounting for the complementarity of renewable energy. The operational detail of the model allows for capturing the temporal and spatial heterogeneity of renewable energy power generation. When available in the region, the anti-correlation of wind speeds is translated into a reliability value for the energy system. The more nonsynchronous the power-generation profiles of wind farms, the larger their overall contribution to the energy system adequacy and the less backup capacity needed to support such a system. The authors estimate that such a wise investment approach into renewable energy would allow for avoiding 66 GW of unnecessary backup capacities at an annual cost of 3.8 billion euros by 2050 in Europe [19].

Methodologically wise, energy system models and operational power system models are often simulation-based and often embody analytical and hybrid approaches [20,36]. Critical design decisions in these models include the scope and resolution of temporal, technical, and spatial representation [20].

2.3. Summary of Models

A summary of the approaches for energy modeling is presented in Table 1. For the purposes of this research, we distinguish three conceptual levels for all energy models. The first one looks into the operational routines of power systems dealing with balancing supply and demand on an hourly (or even finer) basis. The second one reviews the development of long-term energy systems, mostly focusing on the technology mix and its implications for system reliability, environment, economics, and so forth. Both types of model take the system perspective. The third type is real options models, which take the investor’s perspective to understand the effects of policies.
Table 1. Overview of different model types in energy studies and their usual design choices.

| Conceptual Level | (i) Operational Power System Models | (ii) Long-Term Energy System Models | (iii) Investment Behavior, Real Options |
|------------------|------------------------------------|------------------------------------|----------------------------------------|
| Perspective      | System perspective                 | Investor’s perspective             |                                        |
| Focus            | Unit commitment and economic dispatch | Evolution of installed generation capacity | Investment profitability and policy effects |
| Time horizon     | 1 day–1 year                       | Decades                           | Investment lifetime                     |
| Time resolution  | 5 minutes–1 hour                   | Year                              | Year                                   |
| Technical resolution | Unit by unit               | Technology type                     | Single investment                       |
| Geographic scope | Power system                      |                                    |                                        |
| Methods          | Mixed-integer linear programming   | Bottom-up (technology-rich)        |                                        |
|                  |                                    | • Partial equilibrium               |                                        |
|                  |                                    | • Optimization                      |                                        |
|                  |                                    | • Simulation                        |                                        |
|                  |                                    | • Multi-agent modeling              |                                        |
|                  |                                    | Top-down (macroeconomic)            |                                        |
|                  |                                    | • Input–output                       |                                        |
|                  |                                    | • Econometric                       |                                        |
|                  |                                    | • Computable general equilibrium    |                                        |
|                  |                                    | • System dynamics                   |                                        |
|                  |                                    | • Simulation                        |                                        |
|                  |                                    | • Differential equations            |                                        |
|                  |                                    | • Trees and lattices                |                                        |
|                  |                                    | • Game theory                       |                                        |
|                  |                                    | • Fuzzy logic methods               |                                        |
| References to reviews of models | [20,33]                    | [20,27,33]                         | [23,27]                                |
| Key examples of hybrid models | [19]                          | x                                  | [31]                                   |

We highlight the importance of hybrid models that combine several conceptual levels to reveal new insights and to capture new phenomena. Peter and Wagner [19] were able to note and quantify the benefits of an anti-correlation of power generation from renewable energy by integrating the fine resolution of operational power system models into a long-term energy system model. In contrast, Rios et al. [31] were able to comprehensively capture realistic investment behavior on an energy system level by embedding the real options logic into a long-term energy system model. However, for the purpose of designing a support instrument for renewable energy sources to steer their deployment in favor of system reliability, we need a model that combines all three levels: operational detail, system-level evolution and realistic investment behavior—a hybrid three-tier model.

2.4. Solutions for System Reliability

Before discussing whether and how renewable energy sources can alleviate system reliability issues, it is imperative to consider current measures and those deemed effective in the future. In this section, we draw our attention to storage, sector coupling, and regulatory solutions to support energy system reliability.

Storage solutions introduce flexibility to energy systems and allow for higher shares of renewable energy and, thus, contribute to both system reliability and decarbonization [37,38]. Pumped storage hydro (PSH) is currently dominating the global energy storage market (with a share of about 94% of the installed energy storage capacity and over 99% of the energy stored [39]), which is a commercially mature technology with 160 GW of installed capacity and 9000 GWh in energy storage capacity worldwide [37]. Other storage solutions with considerable use worldwide include thermal storage (mainly molten salt thermal storage), electro-chemical storage (batteries and electro-chemical capacitors), and mechanical storage technologies (compressed air storage and flywheel). The produc-
tion of electro–chemical storage (batteries) is one of the most rapidly growing industries nowadays [38], although battery capacities accounted for only 17 GW globally in 2020 (5 GW of storage capacity was added only in 2020) [40]. Currently, the most commercially available battery storage technologies include lithium–ion iron phosphate (LFP) batteries, lithium–ion nickel manganese cobalt (NMC) batteries, lead–acid batteries, and vanadium redox flow batteries (RFBs) [41], with lithium–ion batteries being most widely used (accounting for 93% of the global battery storage capacity in 2020 [40]). Benefitting from the economic scale of lithium–ion battery production for transport applications, the cost of stationary lithium–ion batteries is expected to decrease by 54–61% by 2030 to about 145–480 USD/kWh depending on the battery chemistry, while the number of full cycles may grow by 90%, according to IRENA projections [38].

Sector coupling broadly refers to integrating different energy sectors in order to achieve more flexibility in the energy system and allows for higher shares of intermittent renewable energy sources [42]. The classical example often studied in the academic literature is deeming wide-spread electric vehicle usage as a storage capacity for solar power [43]. However, the sector coupling concept is broader and can include even information systems for better balancing and control of cross-sectoral energy flows [44].

While the technological progress offers promising prospects in the future, its current state is not sufficient to fully resolve energy system reliability issues. Therefore, governments around the world have been introducing regulatory measures to support the security of electricity supply [5]. Five countries in the world maintain strategic reserve (selected power plants that are kept away from the market and switched on in scarcity conditions), eight countries implemented capacity payments (similar to strategic reserves but power plants operate on the regular market as well), and sixteen jurisdictions operate some kind of capacity markets (arranged in parallel with electricity market and open to the majority or all of market participants) [7]. Capacity mechanisms are only ‘useful’ for a power capacity that can actually contribute to electricity generation. Approaches to calculating this contribution vary, and some of them are covered in Section 2.2.

With or without a capacity mechanism, we argue that a different approach to support for renewable energy sources can substantially alleviate the burden of intermittent electricity generation on energy system reliability.

3. Hybrid Three-Tier Model

In this section, we propose a hybrid three-tier model to tackle the issue of steering renewable energy in favor of energy system reliability. First, we present the conceptual design of such a model. Then, we demonstrate the model’s power with an abstract and highly stylized example. Finally, we discuss what needs to be accounted for when the model is transformed from a concept to application in a real case.

3.1. Conceptual Design

The proposed hybrid three-tier model combines all three types of energy models reviewed earlier. Its concept is depicted in Figure 1. Block A is composed of an operational power system model. This block contains hourly demand load curves and power generation profiles of different technologies; projects hourly electricity prices; and comprises weather and other uncertainties with relevant diurnal, weekly, and seasonal variations in demand and supply. With hourly projections, this block is responsible for computing system reliability measures at every hour. Block A feeds its information to Block B, where investment incentives are created and investment decisions are made. Here, the support instrument for renewable energy sources is based on system reliability and can be designed and tested. If the amount of remuneration from renewable energy sources is calculated based on their contribution to system reliability, it affects the profitability of the renewable energy technology with different power generation profiles differently. Thus, the investment incentives are created and translated based on the investors’ behavior. The resultant investment decisions affect the composition of the system’s technology mix, which is cap-
tured using a long-term energy system model component, Block C. The technology mix, in turn, affects the hourly power generation modeled in Block A. Thus, the cycle repeats. The environmental footprint of the system is calculated within Block A based on the simulated data of the system operations.

Figure 1. Concept of the hybrid three-tier model.

The model should be run for two main scenarios:
1. Conventional/existing renewable energy support (as a reference scenario);
2. Renewable energy support via the reliability-based instrument.

The difference in technology mix evolution for these two scenarios showcase the relevance of renewable energy support via a reliability-based instrument for a particular region. If a region possesses spatial and temporal complementarity of its renewable energy sources, then new investments in renewable energy sources can be optimized to favor system reliability. This, in turn, results in a reduced overall backup capacity or storage solutions needed. Overall, such a system would cover its peak demand with a smaller installed capacity and, thus, less incurred costs, compared with scenario #2, where renewable energy sources are supported in a conventional way.

Continuing the list of scenarios, the model can analyze the effects of different policy mix arrangements and technological solutions available, though not considered in this paper:
3. Only capacity market with no support for renewable energy sources at all;
4. Capacity markets with no support for renewable energy sources, and penalties for new investments that do not contribute to system reliability;
5. Infrastructure expansion (i.e., interconnectors to harvest complementarity of renewable energy sources) effects for scenarios #1–4; and
6. Storage and demand-response development effects for scenarios #1–4.

3.2. A Stylized Example
3.2.1. Assumptions

A stylized example is used to demonstrate the model’s functioning on a high level of abstraction in an intuitively understandable way. We chose a region with high potentials for solar energy resources; therefore, the numbers for technology-specific estimates, such as the capacity factor and levelized cost of electricity, are taken based on California’s data for 2018 [45], and as the lifetime of flexible generation, we use the estimated lifetime of gas-fired power plants [46] (Table 2).
Table 2. Technology-specific assumptions.

| Technology Type                  | Capacity Factor | Total LCOE, USD/MWh | Lifetime, Years |
|----------------------------------|-----------------|---------------------|-----------------|
| Flexible generation (combined cycle) | 71%             | USD 114             | 34              |
| Solar PV (standalone)            | 26%             | USD 49              | 25              |
| Wind (onshore)                   | 40%             | USD 54              | 25              |

In the system, 20 GW-based load facilities and 5 GW flexible generation are assumed to exist. The intraday load profile is a classic textbook example with two consumption peaks: morning and evening. It is assumed to vary between 20 and 45 GW (Figure 2a). Such demand levels correspond to a region with electricity consumption similar to California [47]. The one-day profile is assumed to be representative of the whole year. The day-ahead electricity market prices are set proportional to the demand (Figure 2a). The missing supply is deemed to be covered by renewable energy sources, solar and wind power, and extra flexible generation, if needed, is auctioned by the regulator. The solar and wind power generation profiles are sketched to resemble the most common situation, with the sun peaking during the day and winds prevailing at nighttime (Figure 2b). The power profiles are presented for 1 MWh generation per day overall for each technology.

![Figure 2](image-url). Initial load profile, available power, and hourly day-ahead market prices (a) and assumed solar and wind power profiles (b).

An investment decision is based on profitability by comparing the cost (LCOE) per megawatt hour and revenue per megawatt hour comparison. If the revenue exceeds the cost, the decision to invest is made. The model is entirely deterministic; therefore, there is no uncertainty and, hence, value to postpone investment. That is why profitability is defined by the deterministic net present value (benefits minus costs) rather than real options. However, industrial players behave in accordance with the real options theory [30]; therefore, it is imperative to integrate the real options framework when uncertainty is included into the model, as in the hybrid model discussed above [31]. The LCOE assumptions are presented in Table 2. The revenue is composed of the market sales (with prices depicted in Figure 2b) and a premium.

A premium is modeled in two different scenarios. The YELLOW scenario is modeled with a classic fixed premium of 20 USD/MWh on top of electricity prices. The premium remains constant and does not depend on the hour of the day or any other factors. In the GREEN scenario, we present an experimental reliability-based premium. At the core of many reliability indicators is a probability of lost load (electricity supply not meeting demand) [32]. Since our conceptual model is entirely deterministic, no probabilities. Thus,
our lost load $LL$ is calculated simply as the demand $D$ minus the available supply $S$ for each hour of the day $h$.

$$LL_h = D_h - S_h.$$ (1)

Then, we set the ceiling of the premium $P_{max}$ at 40 USD/MWh. We compute the hourly premium as a fraction of the maximum premium corresponding to the hourly lost load compared with the maximum lost load of the day.

$$P_h = P_{max} \frac{LL_h}{LL_{max}}.$$ (2)

Thus, when the need for power at a particular hour is greater, the reliability premium is higher. The hourly profile of the reliability premium, in turn, defines the profitability of technologies with different generation profiles. The need for reliability is translated into an investment incentive.

This is a simplified calculation of the reliability-based premium for the current stylized case with a fully deterministic model. In reality, many variable and stochastic factors should be taken into account, including weather, electricity demand, operating profiles of power plants, etc. With those factors taken into account, the premium should be based not on a deterministic indicator but on one of the proper indicators for a ‘useful’ capacity, for example, based on the loss of load probability, as discussed in Section 2.2. A detailed analysis of existing approaches to calculating the contribution of renewable energy sources to system reliability is presented in [17].

For the GREEN scenario, the auction is run in two phases. First, the reliability premium is calculated based on the current reliability situation (Figure 2a), and the most profitable technology type is selected. Then, the reliability indicator $LL_h$ is recalculated, taking into account the generation profile of the selected technology. The reliability premium $P_h$ is recalculated as well, taking into account the updated reliability indicator. The updated premium then may change the profitability of different technologies.

### 3.2.2. Results

#### Power System

The resultant economics per unit of generation for wind and solar power are presented in Table 3. LCOE (column 2) corresponds to the assumptions presented in Table 2. Market revenue (column 3) is calculated as the technology generation profile (Figure 2b) multiplied by the market price (Figure 2a). Wind power makes 2 USD/MWh more revenue from the market during the day, 34 USD/MWh, than solar power. However, it offsets the difference in their LCOE: 5 USD/MWh. Therefore, together with the fixed equal feed-in premium in the YELLOW scenario (column 4), solar power becomes the more profitable technology while wind power does not generate profit (column 7). Therefore, in the YELLOW scenario, only solar technology is auctioned.

| Technology | LCOE | Market Revenue | Feed-In Premium (FP) | Reliability Premium (RP) | Profitability |
|------------|------|----------------|----------------------|--------------------------|---------------|
|            |      |                | Phase I | Phase II | FP | RP I | RP II |
| **YELLOW** |      |                |         |          |    |      |       |
| Solar      | 49   | 32              | 20      | 27       | 3  | 11   | -13   |
| Wind       | 54   | 34              | 20      | 27       | 24 | -0   | 6     |

For the first round of the auction, in the GREEN scenario, the revenue from the reliability premium for solar and wind (Table 3, column 5) is the same, resulting from the average hourly reliability premium multiplied by the hourly generation. Due to the
difference in costs, though, solar power is still more profitable than wind power (column 8). Thus, solar power is selected in the first phase. The reliability premium profile is recalculated after the first phase to reflect the added solar generation in the system. Now, the premium is zero during solar power peak and higher during mornings and evenings. The premium revenue is thus substantially lower for solar power and comparatively better for wind power (column 6). Overall, however, the need for power is reduced; thus, the possible revenue from the reliability premium is lower than in the first round. With this change in premium revenue, wind power becomes more profitable than solar power (column 9). Thus, wind technology is auctioned in the second phase.

The resultant generation compositions are presented in Figure 3. In the YELLOW scenario (left), the investment incentive generated by the feed-in premium favors solar power. In the absence of other market signals or regulator’s intervention, only solar power is auctioned and built. Such a generation fleet leads to the peak generation exceeding demand during the day and insufficient generation during mornings and evenings, which is compensated for by the extra combined cycle generation.

![Figure 3](image-url)

**Figure 3.** Resultant power generation composition under the feed-in premium in the YELLOW scenario (a) and under the reliability premium in the GREEN scenario (b).

In the GREEN scenario (Figure 3b), due to changing reliability premium, solar power is produced during the first phase and wind power is produced during the second. Together, the two resources (assumed to be complementary in this stylized case) are sufficient to meet the demand almost entirely. The existing 5 GW of flexible generation is enough to cover minor discrepancies during the evening. Such a scenario results in a very different system (Table 4).

Table 4 first shows what is already visible in Figure 3. In the YELLOW scenario, a lot of solar power needs additional flexible backup capacities to cover mornings and evenings. In the GREEN scenario, the role of flexible generation is minimized, and complementary wind and solar together contribute to a major part of the overall power generation. The striking difference between the two scenarios, however, lies in their costs. The overall investment in renewable energy sources is clearly higher in the GREEN scenario. Thus, the costs for support policies are also higher. However, the costs of extra flexible generation are a significant setback of the YELLOW scenario, which overrides the lower costs for renewable energy sources.

In total, the GREEN scenario portrays a 30% more cost-effective system (not accounting for the baseload generation costs, which are equal in both scenarios), which is a 165 billion USD difference accumulated over 25 years, which translates to 7 billion USD saved annually. Of course, this holds only for this idealistic case with a relatively high anti-correlation of renewable power generation assumed. However, the lesson learned is that, if a system possesses some complementarity of renewable energy sources, it can be harvested by channeling the needs of system reliability into investment incentives.
Table 4. Characteristics of the resultant power systems in the two scenarios.

| Scenario | YELLOW | GREEN |
|----------|--------|-------|
| Support Type | Fixed Feed-In Premium | Reliability Premium |
| **Generation mix, GWh/year** | | |
| Base load | 175,200 | 47% | 175,200 | 45% |
| Flexible generation | 65,518 | 18% | 4015 | 1% |
| Solar PV | 131,948 | 35% | 87,965 | 23% |
| Wind | - | - | 117,895 | 31% |
| **Costs (25-year lifespan), billion USD** | | |
| Renewable energy fleet cost | 162 | 24% | 267 | 67% |
| New gas fleet cost | 457 | 67% | - | 0% |
| Support cost (premiums) | 66 | 10% | 132 | 33% |
| **Total** | 685 | 398 | |

Environmental Footprint

The implementation of renewable energy technologies primarily aims to reduce the harmful environmental footprint of the power sector. Hence, the next step of this study was to estimate and compare the potential environmental footprint of the power systems in the two scenarios. Since the composition of the baseload in both scenarios is unknown, we compare the footprint of the flexible generation (gas power plants) and renewable technologies (solar PV and wind plants).

The environmental footprint of the two power systems was investigated from the perspective of: (i) CO$_2$ emissions (both direct and lifecycle) and (ii) the direct water footprint (water consumption). In this context, direct emissions refer to the emissions that appeared during the power-generation process (e.g., from burning fuel), whereas lifecycle emissions encompass the emissions from the foreground process (the power-generation process) and all background processes (extraction, processing, and transportation of fuels; construction of the power plant; etc.).

While environmental studies typically consider only CO$_2$ emissions, the water footprint of power-generation facilities is often overlooked [48]. For instance, thermal power generation consumes water for cooling purposes, and solar PV generation requires water for the occasional cleaning of PV modules. During the process of power generation, this water is withdrawn from the immediate water environment, which may lead to the depletion of water resources, especially in regions already characterized by high water stress [49]. According to the Water Resource Institute, two-thirds of California face high or extremely high baseline water stress [50]. Hence, an assessment of the water footprint for California’s power sector is crucial.

The results of this analysis are shown in Table 5. The values were calculated for each generation type using the following formula

\[ \text{Lifecycle or direct emissions} \ [\text{gCO}_2\text{eq}] = \text{Annual generation} \ [\text{kWh}] \times \text{emission factor} \left[\frac{\text{g}}{\text{kWh}}\right] \]  (3)

for the annual lifecycle and direct emissions and

\[ \text{Direct water footprint} \ [\text{m}^3] = \text{Annual generation} \ [\text{MWh}] \times \text{water consumption factor} \left[\frac{\text{m}^3}{\text{MWh}}\right] \]  (4)

for the annual water footprint.

The values presented in the table are the median estimates that were calculated using: (i) the lifecycle and direct emission factors obtained from IPCC [51]; and (ii) the water consumption factors for renewable and non-renewable technologies reported by Macknick et al. [52].

As shown in the table, the replacement of the gas capacities by solar and wind technologies in the GREEN scenario resulted in a considerable reduction in both the lifecycle and direct CO$_2$-eq emissions and in the direct water footprint compared with the YELLOW scenario. Assuming the same base load in both scenarios, the YELLOW scenario is associated with additional direct emissions of about 22.7 mln. tons of CO$_2$-eq annually.
compared with the GREEN scenario. To put this value into perspective, it is larger than the combined annual total CO$_2$ emissions of Latvia and Lithuania in 2019 [53]. The results also demonstrate that the GREEN scenario allows us to “save” approximately 30.4 mln. cubic meters of water annually. This is equivalent to 12'160 Olympic-size swimming pools. This “saved” water in the GREEN scenario can be conserved or reallocated for other purposes, for instance, food production.

Table 5. The environmental footprint of the power systems in the two scenarios.

| Scenario | YELLOW | GREEN |
|----------|--------|--------|
| Support Type | Fixed Feed-In | RELIABILITY PREMIUM |
| Base load | NA | NA |
| Flexible generation (gas-combined cycle) | 32.1 | 84% | 2.0 | 26% |
| Solar PV | 6.3 | 16% | 4.2 | 56% |
| Wind | - | - | 1.3 | 17% |
| Total | 38.4 | 7.5 |

The intention of this simple calculation was to demonstrate the potential environmental benefits of the GREEN scenario, which aims to minimize the role of flexible (commonly fossil-based) generation in the power generation mix.

3.3. From Concept to Realization

The model presented here is highly stylized and simplified for the purposes of showing the main principle for supporting renewable energy sources in favor of system reliability. For the model to be useful in analyzing a real-world system, several developments on top of the stylized example should be envisaged. Here, we list the critical aspects to be considered when transforming the concept into a sophisticated model for a real case:

1. An existing technology mix in the power system, with its technical and economic characteristics;
2. Realistic details for load profiles with seasonal and weekly variations. The design solutions for integrating fine temporal resolution into long-term energy models are well presented and discussed in [20], and the hybrid model [19] can be used as a guiding example;
3. A unit commitment and economic dispatch model of the system used to define which power plants generate electricity;
4. Uncertainty in the demand and supply of electricity should be introduced in order to realistically estimate the needs of system reliability and electricity prices. These and other uncertainties require stochasticity and simulations envisaged in the model;
5. Available investment options and possible potential of renewable energy anti-correlation in the region;
6. Uncertainties in the system bring complexity to the investment block of the model. With these uncertainties, deferral decisions are possible, for example, investments are considered real options, and thus, the policy effects can be modeled more realistically. An example of embedding real options logic into an energy system-level model can be found in [31];

7. Existing and potential flexibilities in the power system—storage, demand response, interconnections, and import/export of electricity; and

8. Existing and available policy scenarios.

4. Discussion and Conclusions

Some models integrate hourly fluctuations in the demand and supply of electricity into long-term generation technology mix planning. These models show that renewable energy sources possess a degree of complementarity that, if captured, can reduce the needed backup capacity and can ease the requirements on system flexibility. However, a complementary renewable energy power plant might be suboptimal in terms of profitability from an investor’s perspective. Thus, in order to steer renewable energy investments in favor of energy system reliability, different investment incentives need to be introduced. Such incentives need to capture the value of complementarity of a power plant to the existing power system. Numerous design choices are required to create such an incentive mechanism.

This paper introduces a conceptual model that can analyze the effects of different designs of support for reliability-based renewable energy on power system operations and development. In its simplest deterministic form, the model is applied to a stylized case, and the potential benefits in terms of power system reliability, overall technology, and policy costs and the environmental footprint are demonstrated. In contrast, currently, policymakers rely on models that are wired to calculate a fixed amount of backup capacity for every unit of newly built renewable energy source [20], hindering the very possibility to design a policy for a more efficient power system.

The hybrid model introduced in this paper allows us to redesign the support for renewable energy and to analyze whether a reliability-conditioned instrument makes sense for a particular system. The same model can be used to quantify the effects of different types of storage and demand response. With this model, one would be able to model the effects of different capacity mechanisms with or without separate support for renewable energy and to optimize the overall policy mix for the power system. The model will also be able to show the optimal limit of renewable energy adoption in a particular region. After such a limit, any more renewable energy of any type in any location would not provide any marginal contribution to the power capacity of the system. Pushing for the growth of renewable energy sources beyond this limit will become a futile attempt at decarbonization since more stable power output plants will be needed to offset the variability of renewable energy sources, which in turn would increase fossil fuel usage and jeopardize decarbonization. Instead, other sources of flexibility should be promoted in these system, such as storage, hydrogen and power-to-X solutions, and demand-response programs.

The results of such a modeling exercise would heavily depend on region-specific characteristics. They include the technology mix currently in place; the electricity demand profile; its variability and projections; the transmission capabilities in a system and its connections to neighboring areas; the system flexibility, in particular the development and deployment levels of storage and demand response solutions; the availability of renewable energy resources; and their possible complementarity. Political, economic, and social factors clearly play their roles as well; however, their effects would depend on whether they are wired to the model.

The complementarity of renewable energy sources has been shown in multiple cases, such as the temporal and spatial heterogeneity of wind power among power used on the European continent [19] and the uncaptured value of southwest-oriented solar panels in California compared with commonly built south-oriented solar panels [47]. Some studies suggest that one way to discover the complementarity of renewable energy resources is...
to consider them over larger geographic areas. For instance, Grams et al. [54] suggested considering continent-scale wind patterns to implement pan-European collaborations for the development of renewable energies. Of course, capturing that complementarity value requires massive network investments, of which the economic viability can be thoroughly investigated using the proposed hybrid model.

One can argue that replacing the fossil-based flexible generation with renewable energy sources is not needed since synthetic fuels will soon replace fossil fuels. However, even according to very optimistic estimations, the adoption of power-to-X technologies and the corresponding massive production of synthetic fuels as well as massive installations of storage technologies (batteries) are expected to start worldwide not earlier than in the 2030s [55]. In this light, the introduction of policies, which aim to replace the currently used fossil-based flexible generation with the optimal mix of renewable energy technologies remains relevant.

Departing from modeling-related matters, actual policy implementation has numerous issues to consider as well. The transition from support for classical renewable energy to a reliability-based instrument might not be easy due to the associated paperwork, design, and arrangement burden. Although in the recent years, a trend has switched to more market-oriented mechanisms in supporting renewable energy, that is, from fixed feed-in tariffs to premiums, auctions and certificate trading [1], they still do not have a sufficient foundation for such a change since a power system perspective and procedures for calculating reliability are missing. However, some countries have introduced capacity markets, where calculations for the contribution of renewable energy to system reliability are already a routine procedure [7]. In these cases, the transition to reliability-based support for renewable energy sources would be much smoother. Countries that have capacity mechanisms in place and, most importantly, some procedures for calculating the contribution of renewable energy sources to reliability, are displayed in Figure 4.

While the idea of reliability premium is conceptually simple, in reality, it faces multiple design choices.

- Which reliability indicator should be used? The proposed model can compare the difference in effects of various reliability indicators. However, an important factor is the existing procedures for calculating reliability for a country. Different system operators adopt different practices in that respect [17], and implementing perhaps sub-efficient but already working solutions would create much less administrative burden, better transparency, and a faster transition. The same applies to the other design choices for the calculation of reliability and system modeling.

- Should projects be exposed to a dynamically changing premium, or should it be fixed for a project’s lifetime once calculated? The former has higher uncertainty and unpredictability for individual investors, computationally heavier systems, more room for administrative disorder, and more room for human mistakes. The latter allows for better order and provides more certainty for investors but might result in a less dynamic and responsive system.

- If the reliability premium is fixed, how often should it be recalculated? The recalculation can be carried out for each project, for each auction, or on an annual basis.

- If a capacity market is already in place and renewable energy sources can participate in it, how should the reliability-based premium be integrated? The two can co-exist or be merged. The former requires carefully accounting for the economic meaning of both types of support and prevents over-subsidization. In addition, a close collaboration would need to be established between the departments of system reliability and support for renewable energy sources. The latter creates a risk of distorting capacity prices and jeopardizing the effectiveness of the market by adversely affecting other categories of participants (non-renewable generation, storage, and demand response).
The question of which policy mix would potentially be able to steer the mix of renewable energy technologies was briefly discussed in the previous research devoted to international policy review [7]. The modeling exercise performed in this work sheds light onto and brings additional insight into this discussion. Naturally, if renewable energy sources are excluded from a capacity mechanism, the common types of renewable energy support alone would not provide investment incentives favoring system reliability. If participation in a capacity mechanism requires renewable energy sources to forgo the corresponding amount of support, the overall revenue from renewable energy sources stays the same, which again excludes incentives favoring system reliability. If, on the other hand, participation in a capacity mechanism entirely prohibits receiving other types of support, then such incentives come into the scene. The latter two points become clear with the modeling exercise performed in this paper, whereas in the previous qualitative-only analysis [7], these conjectures were made differently. Most importantly, however, is the conclusion that the incentive to steer a mix of renewable energy technologies in favor of energy system reliability can be implemented outside of a capacity mechanism and independently of its very presence. As we can see, the introduction of such a conceptual hybrid model with the hypothetical idea of supporting renewable energy sources via a reliability-conditioned instrument leads to a variety of consequent design and implementation choices. However, the authors believe that the direction is worth perusing for the sake of more reliable, cost-efficient, and environmentally friendly energy systems.

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