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A B S T R A C T

To expand intermittent renewable electricity sources (RESs), worldwide energy policy makers have introduced fixed feed-in tariffs (FITs). However, FITs typically expire after a limited time period. Due to the intermittent electricity supply of RES, market distortions, and insufficient flexibility options, exclusive participation in wholesale electricity markets might not be a viable business model for RES that no longer receive a FIT. Thus, it remains unclear which RES business models (RBMs) ensure a viable operation of RES in the post FIT era. To close this research gap, we present a typology encompassing five RBM archetypes: *wholesale electricity market* (1), *physical power purchase agreements* (2), *nonphysical power purchase agreements* (3), *self-consumption* (4), and *on-site power-2-X* (5). The typology includes three additional service layers, which may enhance the profitability of RBM archetypes by opening up additional revenue streams: *infrastructure services* (1), *electricity storage services* (2), and *ancillary services* (3). We highlight the need for new approaches to quantify the viability of RBM archetypes and services layers under different regulatory, technological, and market conditions. To prevent the imminent decommissioning of existing RESs, policy makers must shape the next era of the energy transition, weighting the implications of market-based and intervention-based energy policy approaches.

1. Introduction

In a world exposed to the fundamental threat of climate change, the reduction of greenhouse gas emissions induced by electricity generation is an inevitable challenge. Energy transition via the integration of intermittent renewable electricity sources (RESs) provides a means of reducing the use of fossil energy sources, which is an immensely complex endeavor [1,2]. To accelerate the energy transition, the expansion of RES capacities became a subject of energy policy nearly two decades ago. In hindsight, countries spearheading progress (e.g., Denmark in 1992, Spain in 1998, and Germany in 2000) initiated energy policy measures encompassing extensive financial support for the expansion of RES [3–5]. When designed effectively, fixed feed-in tariffs (FITs) have been demonstrated to be highly successful in stimulating technological progress and investor adaption [6–8], making FITs the most prevalent form of financial guarantees for RES [9]. Alongside falling investments for RES-related technologies, the extensive intervention-based policy approach of FITs significantly increased the development of RES in electricity markets. Today, electricity from RES accounts for a substantial share of electricity generation in the first moving countries, such as Denmark with 50% [10], Spain with 37% in [11], and Germany with 42% in 2019 [12].

With an increasing share of renewable energies, however, the financing of FITs requires reallocation via levies on electricity consumers, thus yielding an increasing financial burden [13]. Furthermore, electricity market price signals are distorted by RES receiving a FIT, which may hinder the expansion of flexibility technologies required for a successful energy transition over time [14]. As a result, the intervention-based policy approach of FITs is discussed and challenged [13,15] causing policy makers to consider completely terminating FIT programs [16].

For individual RESs, a FIT expires after an ex-ante known period of time. A FIT expiration leaves existing RES owners uncertain about their economically viable business operation in a corresponding transition phase to a post FIT era. From an RES owner's perspective,

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List of abbreviations (in order of appearance)

RES	renewable electricity source
FIT	fixed feed-in tariff
RBM	renewable electricity business model
CES	conventional electricity source
PPA	power purchase agreement

capital investments are recovered by the time FITs expire. However, besides operational costs, for instance maintenance costs must be continuously recovered to ensure a profitable operation in an era post FITs. Overall, there are three options after the expiration of FITs: (i) continued operation of a plant if RES owners identify an economically viable business opportunity; (ii) decommissioning of a plant if RES owners fail to identify an economically viable business opportunity; or (iii) additional investment in the repowering of existing plants. To not further lose pace in the transition to a low-carbon energy system, policy makers must ensure that the majority of RES owners chooses options (i) or (iii). As an increasing number of RES will be affected by such an expiration, option (ii) bears a substantial risk for high shares of today's RESs being shut down.

Without granted FIT, one traditional business model is based on revenues from selling generated electricity in wholesale electricity markets. However, the high penetration of intermittent RES and missing flexibility strongly affects the established wholesale electricity market price dynamics [17,18] in such a way that in periods of high electricity generation from intermittent RESs, wholesale electricity prices vastly decline due to temporal oversupply [19,20]. The coexistence of RESs that still receive a FIT and RESs whose FIT already expired may lead to a situation where the latter are not able to cover a minimum of operational costs necessary for a viable operation. Currently, the necessity for new approaches to these economic challenges associated with the forthcoming expiration of FITs has led to a rise in lobbying, calling for fall-arrest energy policy interventions to prevent RESs from being shut down, as can be observed in Germany [21]. While the economic viability of RESs with FIT is well understood in the literature (for example refer to Karakaya et al. [22], Burger and Luke [23], and Yu et al. [24]), and challenges associated with the FIT expiration are partially addressed by Huijben and Verbong [25], Djørup et al. [26], and Blazquez et al. [27], a profound understanding of the consequences for the economic viability of RES business models (RBMs) in a phase where RESs with FIT and RESs without FIT compete is lacking. However, RBMs might even open-up opportunities for option (iii), which would not only avoid to stall, but to accelerate the energy transition by repowering amortized RES with new technical components as renewable electricity technologies made significant progress in output per RES over time. Therefore, with this study we aim to contribute to closing this research gap by answering the following research questions: *Which business opportunities for RES exist in a post FIT era, and how can they be structured in RBM archetypes?*

To answer this research question, we developed a typology encompassing five archetypes of RBMs as well as three service layers that may support each RBM archetype by creating additional revenue streams. Building on this RBM typology, we discuss implications for the forthcoming energy transition from two perspectives: the RES owner perspective on viable business models, and the policy maker perspective on policy implications for different intervention- or market-based approaches.

This article is structured as follows: Section 2 presents the existing literature relevant to the research question stated. In Section 3, we illustrate the challenges associated with the expiration of FITs using a stylized academic example. Section 4 presents our research approach of developing a typology of RBMs alongside the business model canvas [28]. The main results are presented in Section 5, and policy implications are highlighted in Section 6. Finally, we draw conclusions in Section 7.

2. Related literature on FITs, wholesale electricity market dynamics, and RBMs

This section provides an overview of existing literature concerned with (1) the conception of FITs, (2) effects of such RES support policies on wholesale electricity market prices, (3) associated risks for existing RES, and (4) approaches including the business model canvas to develop and characterize business models in the energy sector.

2.1. FITs are effective support policies for the integration of RES.

Studies by Menanteau et al. [29], Lesser and Su [7], Held et al. [6], and Pahle et al. [30] concluded that if effectively designed, FIT programs are most successful in stimulating technological progress and investors' adaption to RESs at the lowest cost to society compared to other RES support policies. Being applied in 83 countries [31] across the globe, FITs are the most frequently adopted form of financial guarantee and the dominant support policy for simulating the integration of RESs in energy systems. Alizada [9] provided a review of the global adoption of FIT programs and investigated policy diffusion mechanisms (emulation, suasion, learning, and competition) that facilitate the widespread application of FITs on a national government level. As the design and implementation of FIT programs differ considerably between countries and depend on specific conditions/requirements of an energy system, Couture and Gagnon [32], and Pyrgou et al. [15] outlined the evolution of FITs. They also provided a comprehensive overview and characterization of FIT design options together with corresponding remuneration schemes and discussed the advantages and disadvantages of different FIT program designs. Furthermore, by elucidating the interactions among design options, program parameters, and FIT program performance, Kim and Lee [3] proposed a quantitative model to evaluate and optimize FIT programs focusing on four different payoff structures. Analyzing the experiences from a number of first moving countries in Europe, Fouquet and Johansson [33] suggested that the specific design and stability of the remuneration scheme is essential to achieve high innovation incentives and simultaneously mitigate investor risks to safeguard further RES development.

2.2. RES and FITs lead to a decline in wholesale electricity market prices.

The literature advocates that FIT programs entail substantial effects on wholesale electricity market price dynamics. Sensfuβ et al. [34] provided a detailed analysis of the effects of privileged RES feed-in on spot market prices in Germany. Their results demonstrated that in the short-run, market prices decline as RES generation increases. This implies reduced profits for electricity generators. De Miera et al. [35] found similar results induced by RES support schemes for the Spanish market region. Summarizing previous studies on the effects of an increasing RES supply on traditional wholesale electricity market mechanisms, Würzburg et al. [19] presented a comprehensive review of simulation-based and empirical research and conducted an empirical analysis on the price effect of RES supply for the Austrian-German-Luxembourgish market region. The results confirm a temporal decrease in electricity prices in the day-ahead market caused by the intermittent feed-in of the RES electricity supply. Furthermore, Ballester and Furió [18] performed a detailed review and analysis of the effects of RES supply on electricity prices and found that a high share of RESs on electricity supply not only leads to temporarily low or even negative wholesale electricity prices but also to an increased price volatility due to the intermittency of RES supply. De Vos [36] found negative wholesale electricity prices in periods of peak RES electricity generation to be a consequence of (1) renewable support mechanisms causing market distortion and (2) the system's scarcity of downward flexibility to temporarily reduce RES feed-in to prevent a market situation of electricity oversupply. Therefore, De Vos [36] called for new flexibility services to enter the market on the supply or demand side. More specifically, Paraschiv et al. [20] discussed the implications of a FIT policy intervention on day-ahead electricity prices and confirmed that the expansion of RESs stimulated by FIT programs foster extreme price changes and a temporal decrease in prices that pose new challenges for the successful marketing of electricity.

2.3. RES without FITs on wholesale electricity markets risk falling victim to their own success.

Linking the effects of RES electricity supply on wholesale electricity market prices with the operation of current RESs, Djørup et al. [26] analyzed the extent to which a wholesale electricity market design can support a strong increase in RES capacities. The results of their study reveal that traditional market designs may hinder the increased marketing of RESs without upholding FIT programs due to declining revenue prospects for existing RESs; they conclude that wholesale markets must be redesigned when FITs expire. Based on the finding of negative wholesale electricity prices in periods of high electricity generation from RESs, Blazquez et al. [27] stressed the fact that RESs capture a high share of electricity supply in liberalized electricity markets, which may lead to declining revenue prospects for already existing RESs and decreasing investment incentives for candidate RES plants. Therefore, the authors argue that without FIT, renewables could fall victim to their own success. Although the issue of shrinking revenue prospects due to declining wholesale electricity market prices due to high RES feed-in is widely addressed in the current literature, none of the existing studies address how RES owners and future investors can identify alternative opportunities to market electricity besides participating in traditional wholesale electricity markets against the background of expiring FITs.

2.4. Existing literature lacks an overview of RMBs from an RES owner's perspective.

The imminent development of economically viable business models is a prerequisite for future sustainable energy systems that are capable of uphold and further increase the share of RES. Applying the business model canvas [28], multiple studies have proposed business models for utilities in the past. Bryant et al. [37] analyzed 50 Asian and European energy utilities and identified 4 emerging energy utility business model typologies addressing the strong need for innovation and new value propositions for today's energy utilities to deal with changing conditions in energy markets. Richter [38] conducted a review of business model literature for utilities and identified two fundamental approaches for traditional utilities to reformulate their business model with respect to the inherent logic of value creation to remain competitive in the future energy landscape. Investigating the status quo of utility business models for renewable energies in Germany, Richter [39] found that utilities have developed viable business models for large-scale utility-side renewable energy generation but lack viable business models to commercialize small-scale customer-side renewable energy technologies. By collecting and analyzing data from company websites, Chasin et al. [40] derived eight smart energy business model archetypes for utilities that either place the provision of services or tangible products to end consumers at the heart of value creation. However, although highly relevant for the future operation of the electricity system on a holistic level, business models for standalone RES remain unexplored in these studies.

Engelken et al. [41] systematically reviewed existing research on business models for renewable energies in more general and provided a structured overview of corresponding drivers, barriers, and opportunities. Burger and Luke [23] identified a set of business model archetypes by classifying 144 empirical business models in the energy sector. However, the scope of their study is restricted to an empirical analysis of the current business model landscape of demand response and energy management systems, electricity and thermal storage, and solar PV resources. The authors present specific business model archetypes for each resource category. However, the study does not provide a generic conceptualization of business model archetypes that can be applied to RES in general but rather focuses on specific service categories or technologies.

A plethora of research contributions have studied business models for particular RES technologies. The most relevant studies are the following: Horváth and Szabó [42] investigated the evolution of business models based on solar photovoltaic technology and review main inhibiting factors of a corresponding distributed energy deployment. Considering citizens and communities as potential RES owners, Nolden et al. [43] analyzed three past to present community energy business models for solar photovoltaic. They conclude that following the expiration of subsidies, which previously supported the adoption of renewable energy projects on a community level, new emerging intermediaries will play a key role in reviving increasingly complex energy business models. Focusing on wind power producers, González-Aparicio et al. [44] proposed a joint business model that combines selling electricity from wind power generation on wholesale electricity markets with carbon dioxide utilization by producing methanol to be sold to third parties. Several scenarios for market participation are tested within the proposed business model to define conditions for an optimal business model operation. Based on a literature review, Kooshknow and Davis [45] addressed the challenges associated with the intermittent nature of RES electricity generation, providing a conceptual framework for the design of electricity storage business models. Focusing on a specific business model, Proka et al. [46] analyzed the collaborative neighborhood battery concept for electricity storage focusing on the collaboration between a network operator and renewable energy initiatives on local energy storage. Focusing on the decentralization of the energy system, Brinker and Satchwell [47] analyzed municipal energy business models, revealed energy decentralization dynamics, and concluded that energy policy plays a critical role in energy decentralization. Focusing on peer-to-peer energy communities, Plewnia and Guetnher [48] presented a multiple case study to investigate respective value propositions to stakeholders and the overall energy system. Closest to the research question of this paper, Leisen et al. [49] identified six sustainable business models found along the electricity value chain, including electricity consumption, generation, procurement, and grid balancing. The authors analyzed the respective economic logic using the business model canvas. However, their study does not provide an overview or detailed characterization of viable business models that can generally be applied from an RES owners' perspective and is rather dedicated to investigating the risk profile of each identified business model with respect to the risk of regulatory changes.

As current research demonstrates, a standalone participation in traditional wholesale electricity markets may not represent a viable business opportunity after the expiration of FITs any longer, leaving current RES owners with uncertainty about the future operation of their existing RESs. However, the scope of existing studies on business models in the energy sector is limited to the application of single technologies, case studies, or the characteristics of specific stakeholders along the electricity value chain, for example, community networks or utilities. To the best of the authors' knowledge, none of the reviewed studies provides a conceptualization of renewable energy business models that generally entail the potential to open up future perspectives for today's RES owners. Therefore, we aim to analyze the economic implications for existing RBMs associated with the individual expiration and the general termination of FITs and identify archetypes of RBMs that may serve as future pathways for RES owners to create, deliver, and capture value.

3. RES in a post FIT era: A stylized example of traditional wholesale marketing

In this section, we provide an understanding of the main challenges associated with the viable operation of RESs in the post FIT era. In particular, we consider an economic situation where RESs with FIT and RESs without FIT compete against each other on the same wholesale electricity market. Using a stylized, illustrative example, we demonstrate that, especially in scenarios with high RES supply, RESs without FIT may systematically be driven out of the wholesale electricity market. Related findings were found by Haas et al. [17], Blazquez et al. [27], and Djørup et al. [26] in the scientific literature. Wallasch et al. [50,51] and Quentin et al. [52] derive related results in a more practical context.

Following the standard of relevant economic literature, we consider a linear decreasing electricity demand function [53,54,101,102]. For the electricity supply side, we assume that existing RES and existing conventional electricity sources (CESs) feature a given maximum generation capacity and (constant) positive variable marginal generation costs. While the capacity of a CES is determined by an ex-ante undertaken investment, the actual generation capacity of an RES depends on current weather conditions in addition to its nominal capacity. Further, we assume that all RES that still receive a FIT obtain a FIT that exceeds their marginal electricity generation costs. In accordance with the technological characteristics of RES, we assumed that RES features short-term marginal electricity generation costs close to zero [18]. In the following, we present our analysis and comparison of three different market scenarios.

3.1. Wholesale electricity market scenario 1: Low supply of RESs and all RESs receive a FIT

First, we consider a market scenario with a low RES supply. All RESs receive a FIT. As illustrated in Fig. 1, the merit order of RESs and CESs constitutes the aggregated stepwise market supply function. This function gives the short-term marginal costs of electricity generation in ascending order. The intersection point of the electricity demand and supply function yields the equilibrium price *p**. Assuming a situation with low RES supply, the equilibrium price is determined by the most expensive CESs that still successfully participates in the market. All RESs successfully sell their available generation capacity and receive the guaranteed FIT. The levy-financed RES premium compensates for the difference between the equilibrium price *p** and guaranteed FIT.

3.2. Wholesale electricity market scenario 2: High supply of RESs and all RESs receive a FIT.

Electricity systems that extensively adopt FITs are now typically characterized by a growing installed generation capacity of RES. This implies that in an increasing number of market scenarios, electricity demand is entirely satisfied by RES. The wholesale electricity market scenario with a high RES supply is depicted in Fig. 2. As per the assumption that all RESs receive a FIT, there is no price incentive for RES owners to reduce electricity supply in such a scenario [27]. Ultimately, the high RES supply leads to a reduced equilibrium price, which is negative in the present case. Even if we do not expect permanently negative equilibrium prices to represent a long-run wholesale electricity market scenario, short-term negative prices are expected to occur at least in the transition towards a complete integration of RESs and are driven by both the system's lack of flexibility and the market distortion caused by the renewable support mechanisms, that is, a FIT offers no incentive to reduce feed-in of an RES [36]. Similar to the first scenario, all RES

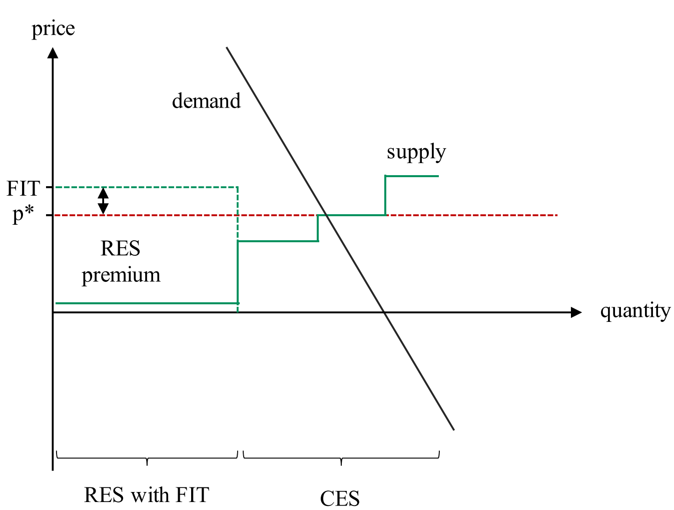

Fig. 1. Wholesale electricity market scenario 1: low supply of RESs and all RESs receive a FIT.

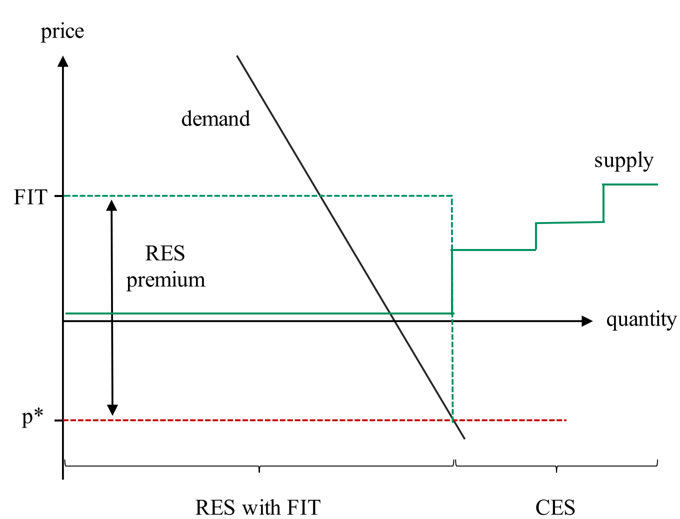

Fig. 2. Wholesale electricity market scenario 2: high supply of RESs and all RESs receive a FIT.

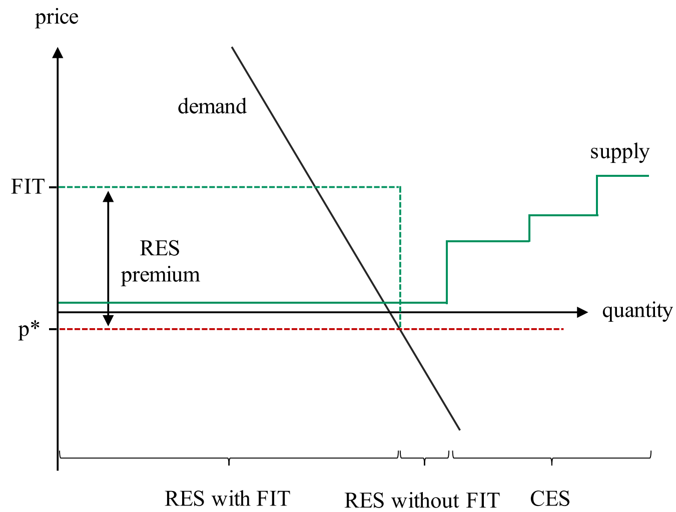

Fig. 3. Wholesale electricity market scenario 3: high supply of RESs and partially expired FITs.

generation capacities successfully participate in the market. However, FITs are now the driver for a viable RES operation, as in the present scenario with a high RES supply, it would hardly be possible to obtain any revenue on the market without a FIT.

3.3. Wholesale electricity market scenario 3: High supply of RESs and partially expired FITs.

In Fig. 3, we consider a scenario with a high electricity supply from RESs but assume that FITs have already expired for some RESs. Consequently, RESs without FIT must now compete against RESs that still receive a FIT as well as against CESs. Even if the variable costs of electricity generation are close to zero for RESs, Fig. 3 illustrates that RESs without FIT are now driven out of the market given the artificial (i.e., policy-driven) competitive advantage of those RESs that still benefit from a FIT. This may pose severe challenges for the future operation of RESs without FITs.

We note that while CESs may still run profitably in scenarios with low RES supply and corresponding lower overall market competition, RESs without FIT must compete against other RESs due to the climatological induced correlation of electricity generation. Therefore, RESs without guaranteed FIT may suffer from an artificially imposed competitive disadvantage. Therefore, the traditional sale of electricity on wholesale electricity markets may not be economically viable from the viewpoint of an RES owner whose FIT has already expired. This is especially the case when the variable generation costs exceed attainable revenues [26,27]. Without developing alternative RBMs, owners of existing RESs may consider the decommissioning of their plants, and RES investors might be reluctant to implement new RESs projects without a sufficient financial guarantee for a viable operation. This may pose a severe threat to the energy transition, which could slow or entirely cease function.

4. Research approach to characterize RBM archetypes

Following an inductive research approach as proposed by Leisen et al. [49] and Burger and Luke [23] in the field of RBMs, our research approach consisted of three consecutive steps, which are presented in Fig. 4. In the first step, we identified an exhaustive set of instances of business models for RESs. For this reason, we conducted a structured literature review in this field. Additionally, we reviewed the German energy sector for empirical examples of established and developing RBMs. To identify further business models that are neither represented empirically nor in scientific literature, we conducted a half-day workshop with a group of 15 research experts with a high level of expertise in the field of energy-related research. In the second step, the authors characterized all instances identified in the first step of the research process individually and independently from each other by applying the business model canvas along the nine dimensions of (1) value proposition, (2) revenue stream, (3) cost structure, (4) key activities, (5) key partners, (6) key resources, (7) customer segments, (8) customer relationships, and (9) channels as proposed by Osterwalder and Pigneur [28]. After, the authors iteratively discussed their characterizations until they came to an agreement on the characterization for all instances. In the third step, we collectively derived RBM archetypes based on business model characterizations in the business model canvas such that instantiations with similar characteristics in the nine business model canvas dimensions were subsumed into an RBM archetype representing them. However, all RBM archetypes are mutually exclusive. In this step, supporting service layers, whose characteristics were not specific to a single RBM archetype but instead offered a possible extension of the economic success of an RBM archetype, were identified from the characterized instantiations. These supporting service layers can be seen as optional services that may enhance each of the RBM archetypes. The RBM archetypes together with the identified supporting services layers build the RBM typology.

5. Typology of renewable electricity business models

The derived typology encompasses five RBM archetypes for intermittent RESs, including the traditional *wholesale electricity market* as well as four alternative RBMs. Section 5.1 presents a detailed characterization of each RBM archetype. Furthermore, we elaborated how the success of each RBM archetype may be increased by additional supporting activities that we refer to as *service layers*. A comprehensive characterization of the supporting service layers is presented in Section 5.2.

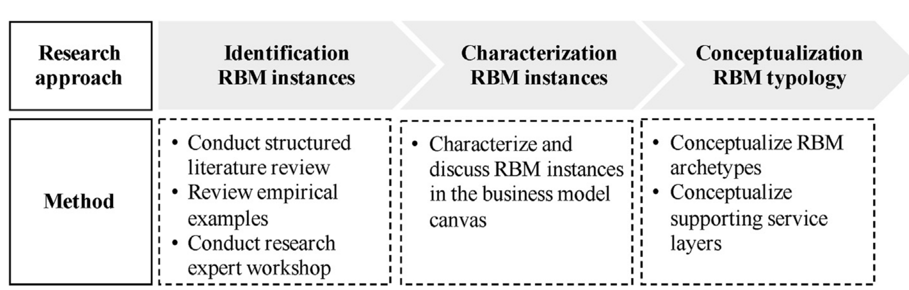

Fig. 4. Consecutive research approach.

Table 1
RBM archetype characterization along the business model canvas.

	Wholesale electricity market	Self-consumption	Physical power purchase agreements	Nonphysical power purchase agreements	On-site power-2-X
Value proposition	Provision of renewably generated electricity	Physical self-consumption of renewably generated electricity, mitigation of levies and taxes (e.g., grid tariffs), superiority of resource utilization (due to regional generation and use), and electricity prices per kWh (compared to purchasing electricity)	Physical provision of renewably generated electricity, long-term electricity price risk mitigation, mitigation of levies and taxes (e.g., grid tariffs), renewable and regional image	Provision of renewably generated electricity, long-term electricity price risk mitigation, renewable image	Renewably generated energy carrier or ubiquitous service, better resource utilization (due to regional generation and use), electricity prices per kWh (compared to purchasing electricity)
Revenue stream	Electricity sale per sold unit at the wholesale electricity market	Electricity bill savings, (electricity surpluses sale per generated unit in other RBMs)	Contractual determined remuneration scheme for electricity sales (e.g., discrete, continuous, indexed, capped, floored, per unit, per capacity) or per generated unit at a local market	Contractual determined remuneration scheme for electricity sales (e.g., discrete, continuous, indexed, capped, floored, per unit, per capacity)	Sale of renewably generated “to X″ medium (feed-in/-out control allows to exploit wholesale and medium price fluctuations, additional “to X″ services)
Cost structure	Renewables operation and maintenance, staff, information, and communication infrastructure	Renewables operation and maintenance, staff, information and communication infrastructure, additionally required local electricity grid, and smart meter	Renewables operation and maintenance, staff, information and communications infrastructure, additionally required local electricity grid	Renewables operation and maintenance, staff, and information and communication infrastructure	Renewables and electricity “to X″ conversion operation and maintenance, staff, information and communication infrastructure
Key activities	Renewable electricity generation and sale	Renewable electricity generation and sale, maximizing self-consumption	Renewable electricity generation and sale	Renewable electricity generation and sale	Renewable electricity generation and “to X″ medium sale, ongoing medium storage, feed-in/-out optimization
Key partners	Direct marketer, technical partners, grid operator, investor, and regulator	Direct marketer, electricity consumers, technical partners, grid operator, investor, and regulator	Energy service provider, electricity consumers, technical partners, grid operator, investor, regulator	Energy service provider, electricity consumers, technical partners, grid operator, investor, and regulator	Direct marketer, buyer of “to X″ medium, technical partners, grid operator, investor, regulator
Key resources	Renewable electricity generation infrastructure	Renewable electricity generation infrastructure, temporal flexible load	Renewable electricity generation infrastructure, local grid integration, interaction infrastructure	Renewable electricity generation infrastructure	Renewable electricity generation and “to X″ conversion, distribution infrastructure
Customer segments	Direct marketer	None	Electricity consumers (e.g., local smart/micro grid participants – residential/commercial/industrial), peer-2-peer networks	Electricity consumers (e.g., residential, commercial, industrial) or (municipal) utility companies	Depends on the commercialization of the medium
Customer relationship	Provision of renewably generated electricity, flexible relationship duration	None	Provision of renewably generated electricity, "ethically" superior alternative to the traditional utility, typically long-term relationship	Provision of renewably generated electricity, "ethically" superior alternative to the traditional utility, typically long-term relationship	Depends on the commercialization of the medium
Customer channels	Wholesale electricity market, direct B2B interaction	None	Direct B2B interaction, end consumer or peer interaction	Direct B2B interaction, end consumer interaction	Depends on the commercialization of the medium
Related literature	[18,36,55]	[56,57]	[58–67]	[60,61]	[68–73]
Empirical examples	Next Kraftwerke, Oxygen Technologies, traditional direct wholesale marketers (e.g., RWE Supply & Trading, Uniper)	Sonnen, Smart Home Products (e.g., Innogy, Magenta (Telekom) Smart Home, Google Nest Thermostat)	RWE Renewables, Anerscon, LO3Energy, Enyway, Level10Energy	RWE Renewable, Amerscon, Hanse Windkraft, Interconnector, Enyway, Lition Energie, Level10Energy	ExaMesh, MAN Energy Solutions, Interatec, Areva H2Gen, H2GO Power, GreenHydrogen, E-Energy

5.1. RBM archetypes

The first RBM archetype that we identified refers to the traditional marketing of electricity on the *wholesale electricity market* (1). Referring to the next two RBM archetypes, generated electricity may be marketed independent from an established marketplace in bilateral *physical* (2) or *nonphysical power purchase agreements* (3). Besides external marketing, electricity may also be used directly at the location of generation to cover present electricity demand or to transform electricity into another medium (e.g., hydrogen). Therefore, we identified *self-consumption* (4) and *on-site power-2-X* (5) as additional RBM archetypes. In the following, we describe the value propositions and outline examples for each RBM archetype. A full characterization of each archetype is given in Table 1.

5.1.1. Wholesale electricity market.

The first RBM archetype encompasses the sale of electricity on a *wholesale electricity market*. The value proposition is exclusively based on the sale of renewably generated electricity. An example is the traditional electricity sale via a direct marketer on a national electricity exchange, such as the European Energy Exchange or Nord Pool. As highlighted in Section 3, the *wholesale electricity market* is currently affected by the granted FITs and yields distorted electricity prices. Therefore, it is unclear whether and to what extent the *wholesale electricity market* serves as a standalone business model in the post FIT era. Nevertheless, a combination with supporting service layers may provide a basis for the viable operation of this traditional RBM in the future.

5.1.2. Physical power purchase agreement.

In a *physical power purchase agreement* (PPA), two parties agree on the physical supply of a predetermined electricity volume or capacity at a specified price or renumeration scheme over a certain contract period. A *physical PPA* may especially be useful if generation and consumption are geographically so close that a private, local grid can transmit electricity. Ultimately, for both contractual parties, *a physical PPA* allows a reduction in costs with respect to the use of the public infrastructure − at least in cases where the operation of a local, private electricity grid is less expensive. The actual value proposition of a *physical PPA* is three-sided. First, consumers may value the regional and renewable origin of the generated electricity. Second, when electricity is previously transmitted via public grids, the *physical PPA* may allow for possibly reduced electricity charges (e.g., grid charges or taxes), depending on the (future) regulatory environment. Thus, a *physical PPA* may contribute to lower overall electricity procurement costs for buyers, which allows them to (potentially) pay a higher renumeration than the *wholesale electricity market* offers without FIT. Third, *physical PPAs* represent a price risk mitigation instrument, as electricity prices can be negotiated individually between the two parties over a longer time period. However, a favorable specification of actual contract characteristics can be challenging for both parties, as the temporal availability of renewably generated electricity builds on forecasts and is subject to uncertainty. Nevertheless, current examples of physical local electricity alliances in smart- or micro-grids as well as peer-to-peer networks that match local electricity generation and consumption represent promising applications of *physical PPAs*.

5.1.3. Nonphysical power purchase agreement.

A *nonphysical PPA* is a (typically) bilateral long-term electricity supply contract. In contrast to a *physical PPA*, there is no physical connection between the electricity generation and consumption unit. Instead, there is a location-independent replication of feed-in and consumption profiles via a third party, such as an energy trading company. The value proposition encompasses the possibility of mitigating electricity price risks, whereby different remuneration schemes can be applied. Similar to a *physical PPA*, the renewable image of the supplied electricity may increase the value of electricity for end consumers. However, for *nonphysical PPAs*, contract design is a challenging task for all involved parties. Therefore, different forms of *nonphysical PPAs* can be observed in practice, for example, synthetic and sleeved PPAs where an energy service provider handles many of the associated tasks, such as load balancing or providing standard contracts.

5.1.4. Self-consumption.

The *self-consumption* RBM archetype refers to the consumption of generated electricity by RES owners themselves without the use of a public electricity grid that links generation and consumption units. Rather, electricity is generated and consumed by the same actor to cover its own electricity demand. The value proposition relies on electricity bill savings due to reduced electricity costs, for example, lower procurement costs, avoided or reduced grid fees, and possible tax exemptions depending on the regulatory environment. In this context, temporal flexibilization (e.g., by using supporting *electricity storage services*) may additionally contribute to an increase in electricity bill savings. A prominent example of this RBM is photovoltaic panels installed on roofs of residential, commercial, or industrial buildings, where owners or residents of respective buildings directly consume the generated electricity themselves.

5.1.5. On-site power-2-X.

In the last RBM archetype, generated electricity is transformed into another medium that can be another energy carrier or an electricity-consuming ubiquitous service. Recent examples include the conversion of generated electricity into heat for local use, hydrogen as a resource (e.g., used in industrial applications or for hydrogen-based mobility use cases), and the provision of computing power (for, e.g., cloud computing). The value proposition relies on the renewably produced X-medium supply and the direct local use of electricity without the need for a wholesale electricity purchase. *Self-consumption* also depends on the regulatory environment that affects and determines procurement costs, grid fees, and possible tax exemptions that may make the local use of electricity more attractive. Ultimately, the value proposition is not based on utilizing renewable and local electricity per se, but also on available marketing options for the transformed medium. The latter has its own 2-X transformation and marketing costs as well as risk and return characteristics that are different from those of electricity markets. Therefore, for the newly generated medium, business models relying on corresponding wholesale markets, self-consumption, and purchase agreements may represent possible sources of revenue.

The identified RBM archetypes *wholesale electricity market* as well as *physical* and *nonphysical power purchase agreements* have the sale of electricity as a key value driver in common. In contrast, there is a significant difference in *self-consumption* and *on-site power-2-X*. *Self-consumption* relies on potential electricity bill savings, which mainly result from lower grid charges or taxes compared to the external purchase of electricity. *On-site power-2-X* revenue streams are based on the sale of the medium to which electricity is transformed. We note that given the different characteristics of the presented RBMs, a combination of the five archetypes is possible and may indeed offer additional value as an RES owner can optimize his individual risk and return profile. For example, in cases where own electricity demand is temporally satisfied by the locally generated electricity (*self-consumption*), surpluses may be sold via a *nonphysical PPA* to other consumers. Alternatively, the sale of a certain predetermined amount of electricity via a *physical PPA* may be combined with the use of remaining surpluses for an *on-site power-2-X* conversion, for example, the use of electricity to offer computing power. Another example is the combination of a *wholesale electricity market* with a wholesale *on-site power-2-X* market business model that reduces risks via participation in two different markets. However, renewable electricity generation by RES is the core of value creation in each RBM and therefore placed in the center of the typology. Fig. 5 visually summarizes the identified RBM typology as a whole. Allowing for different methods of marketing generated electricity, green arrows indicate marketing using a specific RBM archetype. Each RBM archetype may be complemented by the application of additional supporting activities as indicated in Fig. 5 and further elaborated in Section 5.2. In Fig. 5, plus and minus symbols represent the option to adjust the physical electricity flow by employing additional supporting activities.

As these examples show, the five archetypes generally differ with regard to their ability to mitigate individual price risks for the RES owner. While *PPAs* may generally have the highest potential to reduce return risk, in contrast the traditional sale of electricity on the *wholesale electricity market* is potentially associated with high risks in the post FIT era, as depicted in Fig. 5. Table 1 presents the characterization of each RBM archetypes along the nine dimensions of the business model canvas, including an overview of related literature and real-world examples that served as instances of the RBM archetypes.

5.2. Supporting service layers

When renewable electricity is marketed via a specific RBM archetype or a combination of the archetypes, it may additionally be complemented by three supporting service layers. This section will describe how the three layers *infrastructure services* (1), *electricity storage services* (2), and *ancillary services* (3) may reinforce the value creation of the different RBM archetypes. The three service layers are interdependent and may positively influence each other, which is why layers may be applied individually, but also in any combination. For example, while the storage layer may primarily support an RBM by intertemporally optimizing the sale, use, and purchase of electricity, it may also improve possibilities to offer more complex ancillary services.

5.2.1. Infrastructure services.

Infrastructure services refer to the use of the technical features of the RES plant and its infrastructure. For example, such technical characteristics and features primarily encompass the possibility of positioning PV panels toward the sun or aligning the rotor blades of a wind turbine to the current wind direction by adjusting the current feed-in. These characteristics shape the boundary conditions for each RBM because they influence electricity generation volumes. In addition, *infrastructure services* have the potential to support RBMs through non-electricity-related revenue streams, such as the sale of operational data of the RES plant, collected climatological data, or the use of the tower of a wind turbine for 5G antennas in rural areas.

5.2.2. Electricity storage services.

Electricity storage services increase the RBM by allowing for a temporal shift in electricity feed-in or consumption through the charging and discharging of electricity storage. Energy storage services may even support demand side management (e.g., load shifting of a power-to-X system). Such inter-temporal demand shifts may, in general, be supported by an ongoing decision support based on available information and optimization systems [74]. Electricity storage can increase revenues by exploiting inter-temporal electricity price differences in respective markets. Moreover, *electricity storage services* may also be deployed in RBMs that are based on *self-consumption* to increase self-sufficiency and reliability via self-generated electricity or to reduce costs, for example, in the form of saved supply or demand charges.

5.2.3. Ancillary services.

The provision of *ancillary services* to grid operators in the form of feed-in flexibility represents another possible source of additional revenue. Corresponding revenue schemes may be defined within a flexibility performance contract between a flexibility provider (the RES owner) and a flexibility aggregator and depend on actual markets for *ancillary services* [75]. The involved flexibility aggregators may pool several RESs and partially remotely control their electricity feed-in. Because RESs have a natural limitation when providing *ancillary services*, that is, RESs are only able to offer services in a negative direction (power reduction), a combination with an *electricity storage service* may significantly increase the added value of the ancillary services layer. Table 2 provides further examples of applications alongside the five RBM archetypes as well as an overview of related literature and real-world examples.

6. Discussion and policy implications

In the following subsections, we discuss the implications of our RBM typology from two perspectives: First, we consider the perspective of an RES owner facing the challenge of ensuring a viable operation in a post FIT era. We argue that RES owners may use the typology to identify and finally evaluate new business opportunities with respect to their risk and return profiles as well as the operational applicability of each RBM archetype. Second, we consider the perspective of a policy maker, discussing policy implications that arise from each of the identified RBM archetype and further discuss directions for market-based or intervention-based future energy policy approaches.

6.1. RES owner perspective post FITs

Along with the expiration of FITs, business models relying on the *wholesale electricity market* may not represent an economically viable prospect for RES owners, as discussed in Sections 2 and 3. In extreme cases, temporally negative electricity prices may occur as a consequence of (1) positively correlated feed-in of intermittent RESs in the wholesale electricity market, (2) missing incentives for RESs that still receive a FIT to vary electricity feed-in, and (3) missing demand and supply flexibilities.

Against this background, the proposed RBM typology provides new perspectives for RES owners to market electricity by implementing and combining different RBM archetypes, possibly together with additional services. Thereby, the RBM typology reveals new prospects for RES owners to discover, specify, and exploit new business opportunities beyond the traditional *wholesale electricity market.* RES owners may apply common methods [84–86] to evaluate the risk and return profiles of specific RBM archetypes.

From the perspective of an RES owner, a FIT guarantees a riskless RBM for an ex-ante known time. However, FITs typically expire abruptly on a cutoff date without a smooth transition phase, leaving RES owners without any guaranteed remuneration from one day to the next. Therefore, viable business model alternatives must be implemented immediately after the expiration of a FIT to ensure a seamless business model transition. Thus, RES owners search for business models that can be implemented in a short time frame. If RES owners perceive business model alternatives not to be economically viable or simply operationally not applicable shortly after the expiration date, they may decide to decommission existing RESs. This might highly endanger the future operation of RESs and consequently pose a risk to the energy transition itself.

Therefore, RES owners that face the expiration of FITs should not only account for characteristics such as risk and return profiles but also for the ability to operationalize a business model alternative. Although some business model alternatives may be very attractive from the risk and return point of view, they may face high technical complexity or even require changes in the regulatory environment.

6.2. Policy maker's perspective post FITs

FITs not only lead to distorted wholesale electricity market prices, but the reallocation of existing FITs via levies and charges to consumers also bears an increasing burden for the societal goal of affordable electricity. In recent years some policy makers switched from offering standardized fixed FITs to new approaches such as competitive bidding, where investors place bids for a fixed FIT. Undoubtedly, there is a need to look for other intervention-based or even market-based approaches for RES expansion. Competitive bidding may reduce the overall financial burden of FITs on the society as lower FITs can be achieved by competition between investors. However, such approach is particularly useful for deploying new, additional RES in the electricity system and not a solution for existing plants whose FIT expire. Hence, policy makers urgently need to answer the following question(s): how should stakeholders react to the expected changes induced by the expiration of FITs, which may ultimately impede the profitable operation of RESs, and how should the stage be set for alternative RBMs?

To answer the above question(s) in the transition phase towards a post FIT era and a potential full market integration of RESs, policy makers must form a regulatory framework for new viable business models. Without well-established answers, declining revenues for RESs on the *wholesale electricity market* yield to the threat that an active market participation with no state-guaranteed payments may result in a shutdown of existing RESs and a reluctance for future investments.

Confronted with expiring FITs, policy makers must choose a path of market-based or intervention-based policy approaches, leading to the next era of energy transition. Before choosing and implementing their policy approach, policy makers must acknowledge that a transition between both approaches may cause severe challenges and economic distortions, as we illustrated in Section 2. Intervention-based policy approaches that entail specific regulatory interventions appear to be conceivable when it comes to certain issues of fair cost or welfare distribution, the pricing of external costs such as emissions, or the promotion of new technologies [8,87]. In contrast, market-based policy approaches appear to create the most efficient outcomes, which is why there is a growing consensus that RESs should no longer be insulated from competitive market prices and associated risks; see Ref. [88–90]. However, policy makers must carefully design the transition phase to an era post FITs to avoid welfare losses and negative effects on the rents of both consumers and producers. As regulatory uncertainties are key factors that hamper private investments and negatively influence investors' decisions, energy policy must generally provide RES owners with security for planned (re-)investments in any case [6,14,89,91–93]. Ultimately, the selected energy policy approach must set the stage for a new era in which a stable environment fosters future RBM innovations and private investments in existing and new RESs. With respect to stable policy conditions, we highlight the following three avenues of policy implications for different RBM archetypes:

1) *Wholesale electricity market:* Develop new market-based approaches to solve structural challenges induced by intermittent RESs, for example, incorporating flexibility.

Given the threat of a non-viable operation of RESs in an era post FITs, on the one hand, we may observe an increased lobbying for new public interventions in the form of state subsidies and fall-arrest solutions, mitigating the risk of market distortions in the near future [21]. On the other hand, lobbying for RBMs relying on a full market-integration of RESs may occur simultaneously. We posit that it may not be advisable to select a further intervention strategy in the *wholesale electricity market* since it bears the risk of exacerbating market distortions in the long-term or delaying the structural challenges of intermittent supply. The transition into a post FIT era should therefore be accompanied by a transition and discussion of a new era of necessary electricity market designs. One

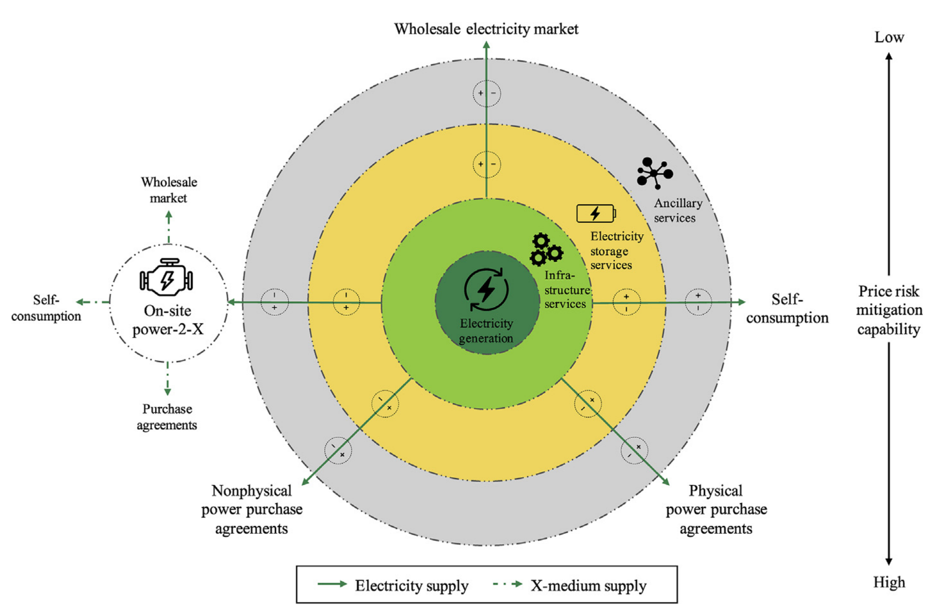

Fig. 5. Typology of RBM archetypes and supporting service layers.

Table 2
Supporting service layer characterization.

	Infrastructure services	Electricity storage services	Ancillary services
Illustrating examples of application	• Data provision and commercialization: When the RES is in service, operational data about the plant may be collected and offered to manufacturers or other service companies for plant improvement or maintenance business models. In addition, local weather data could be collected and marketed for research and other purposes. • Commercialization of the RES infrastructure: The infrastructure of the RES itself (e.g., the mast of a wind turbine) can add value for other services. As an example, the mast could be used in rural areas or near urban settlements as an antenna for the expansion of a 5G-infrastructure, thereby reducing the need to build new infrastructure. • Renewal/Repowering of the RES infrastructure: Due to enormous technological progress in recent years and decades, it may be worthwhile to renew RES components, Thus, electricity output may increase and/or costs of the plant per unit of generated electricity may decrease in order to support an RBM archetype.	• *Wholesale electricity market:* Refers to the use of feed-in flexibility to increase and stabilize wholesale electricity market revenues at a higher level. • *Self-consumption:* Increasing the share of own electricity consumption reduces the demand for external electricity supply and increases potential electricity bill savings. • *Physical power purchase agreements:* Use of feed-in flexibility increases revenues on the physical peer-to-peer market, as feed-in is possible at peak demand times. • *Nonphysical power purchase* agreements: Use of feed-in flexibility is integrated in the remuneration scheme of the PPA by, e.g., higher basic remuneration, since the feed-in profile is better adapted to the required load profile. • *On-site power-2-X:* Optimized utilization of the conversion facility through a more continuous inflow from the combination of storage and RES generation leads to further reduced electricity conversion costs. In addition, in any RBM archetype electricity can be purchased and stored via the electricity storage and, if necessary, resold or used to support the economic value of each RBM archetype.	• *Wholesale electricity market* Provision of negative balancing power capacities via temporal reduced RES feed-in through pooling by an energy service provider. • *Self-consumption:* Since this RBM archetype often involves flexible loads in order to maximize self-consumption, e.g., (positive/negative) balancing power can be provided through flexible loads and the RES in collaboration with an energy service provider. • *Physical power purchase agreements:* Provision of negative balancing power capacities via a temporal reduced RES feed-in through pooling by an energy service provider. • *Nonphysical power purchase* agreements: Provision of negative balancing power capacities via a temporal reduced RES feed-in through pooling by an energy service provider. • *On-site power-2-X:* The conversion plant itself may offer (positive/negative) balancing power. The offering of balancing power is only intended to serve as an example for *ancillary services* here. Depending on the energy system, other mechanisms may be suitable and useful. In addition, the supporting layer of the electricity storage offers an opportunity to expand *ancillary services* and support RBM archetypes.
Related literature	None	[45,60,76–80]	[81–83]
Empirical examples	ExaMesh	Sonnen, Innogy Smart Home Products, LO3Energy, Tesla, Powervault, Invenergy, Fluence	Next Kraftwerke, Sonnen, California Independent System Operator, Enerstorage

promising option is to develop electricity markets that value flexibility from the demand- and supply side in the energy system to structurally counteract and address the fundamental challenges of intermittent supply [36,94].

2) *Self-consumption, physical PPAs, and nonphysical PPAs:* Design interventions carefully based on long-term energy system goals alongside a long-term oriented legal RBM framework.

For RES owners, evolving RBMs have the potential to mitigate electricity price risks via pre-determined remuneration schemes. One possible intervention relates to the fact that the three corresponding RBMs often build on demand for “green-labelled”, i.e., low-carbon electricity. Strengthening the position of green electricity certificates poses a way to set the stage for these business models. In addition, the economic viability of the two RBMs *self-consumption* and *physical PPAs* relies on reduced grid fees. For example, *self-consumption* as a business model often requires no public grid because electricity is consumed on-site. Reduced grid fees and taxes may encourage *self-consumption* and *physical PPAs.* Concurrently, questions about a fair societal distribution of public infrastructure costs may arise. Promoting these RBMs fosters the decentralization of supply and demand. However, many countries are expanding their transmission grids to secure a supply of demand. As a result, reducing grid fees for *self-consumption* and *physical PPAs* affects the refinancing of electricity grid infrastructure and may counteract a socially fair distribution of associated costs. As market participants on the electricity supply or demand side may avoid grid fees, the financial burden due to infrastructure-related costs increases for the remaining market participants. Nonetheless, the question of fair social cost distribution depends on individual regulatory conditions in place or the adjustments made. Therefore, mechanisms to refinance public transmission grids may not solely rely on fees per transmitted electric work but on the absolute peak electric capacity transmitted within a predefined time period. Thus, in situations of peak transmission capacity utilization, high grid fees may arise. In any case, policy makers should decide on approaches that take a long-term perspective on the general development of the energy system. Instead of new technology-specific short-term funding in response to calls for strengthening (existing) renumeration schemes, RBMs require a reliable legal framework in the long-term. Creating such a legal foundation for RBMs must take interdependencies with the *wholesale electricity market* as well as technological and operational differences between the RBMs into account.

3) *On-site power-2-X:* Consider an integrated perspective on sector coupling with all its complexities between existing markets and interventions in other sectors when designing market-based or intervention-based policy approaches.

In the energy transition, where sector coupling might serve as a fundamental building block [95], the corresponding RBMs have the potential to opening-up new and indirect markets for RESs. Many technologies in the power-2-X sector require further improvements in efficiency before being economically viable. Therefore, policy makers need to support technology development to enable and accelerate their contribution to the energy transition.

With further technological progress, energy policy should take an integrated view on influences on the design of different energy markets as well as the interdependencies between them and emerging technologies [96], avoiding a slowdown by regulatory barriers that may ultimately stall sector coupling. In many countries, not only wholesale electricity markets but also other energy markets face distortions due to intervention-based policies. For example, tax cuts might distort a national fuel market. Instead of designing new interventions for electricity markets, policy makers should consider changing cross-market rules to foster the adoption of (on-site) power-2-X RBMs. Thereby, policy makers should reflect on and learn from successes and mistakes of past policy approaches.

As today's energy systems are increasingly interconnected across borders (e.g., the European integration or the Pan-Arabian power grid projects), we finally note that national climate and energy policy decisions should be coordinated between countries [97] to avoid unnecessary regulatory complexity that will create further uncertainty accompanied by increased costs for RES owners, for example, those in the form of complex legal consultancy. In this way, energy policy should set the stage for the next era of energy transition, including the development of flexibility options or power-trading products to ensure global energy transition goals to be realized through effective RES utilization [86,98,99,103].

7. Conclusion, limitations, and future research

The integration of RESs in energy systems has the potential to reduce greenhouse gas emissions. FITs have been introduced to foster the development of RESs. Their financing through levies has led to a financial burden for many electricity consumers. Furthermore, FITs and an associated higher share of RESs combined with insufficient system flexibility led to a distortion of wholesale market prices with declining, even negative, wholesale electricity prices in periods of high RES electricity generation. In the coming years, RESs without FIT will have to compete with RESs that still receive a FIT on the same wholesale electricity markets. As a result, RESs without FIT may be systematically driven out of wholesale electricity markets, leaving RES owners to uncertainty about operational viable business models without granted FIT.

Against this background, this article emphasizes the need for alternative RBMs that may enable a viable operation of RESs in the post FIT era. Therefore, this paper first contributes to an understanding of the challenges associated with the expiration of FITs. Second, a typology from the RES owner perspective is proposed that encompasses five RBM archetypes grounded on distinctive characteristics along the nine dimensions of the business model canvas [28]: *wholesale electricity market* (1), *physical power purchase agreements* (2), *nonphysical power purchase agreements* (3), *self-consumption* (4), and *on-site power-2-X* (5). Furthermore, three supporting service layers are introduced to enhance the profitability of the RBM archetypes via additional revenue streams: *infrastructure services* (1), *electricity storage services* (2), and *ancillary services* (3). Discussing energy policy implications, we present specific policy implications embedded per RBM archetype. In addition, we argue for stable conditions for private investments, the need for a clear decision on the character of future RES policy, and the urgent need to develop a corresponding long-term perspective for viable RES operation and energy system transition. This study extends the current literature by revealing new perspectives on business opportunities for RESs in the post FIT era and may contribute to the substitution of fossil energy sources by outlining strategies for sustainable business development, as proposed by Lund [100].

Further research may be needed to quantify the economic potential of each RBM archetype with respect to different regulatory, technological, and market conditions taking individual preferences of RES owners and investors toward risks into account. As the adoption of the proposed RBM archetypes may bear considerable operational complexity that is beyond the capabilities of RES owners, we emphasize research on (new) actors providing additional services to RES owners to enable the adoption of future business models.

With respect to policymaking, future work should further analyze how the regulatory environment could be designed to support RBMs that promise high greenhouse gas reductions. Future research should consider the individual energy policy goals of a country with respect to the energy trilemma. Thereby, it is essential to take the general electricity market design into account, as corresponding design elements will shape the environment in which new RBMs may evolve. In this context, we strongly encourage future studies to focus on attainable reductions of welfare losses and the "fair" distribution of producer and consumer surpluses. As such endeavors require an intense knowledge-sharing of natural scientists, engineers, economists, and lawyers, we appeal to employ interdisciplinary research approaches to accompany the complex development of future energy systems.

In summary, our RBM typology offers a deepened understanding of the challenges RES owners and policy makers encounter in the post FIT era. We present business models that may further increase the share of RESs and contribute to a low-carbon future electricity system.

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