Universal Journal of Renewable Energy 2 (2014), 45-66
www.papersciences.com

Innovation Effects of Support Schemes for Renewable Electricity

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Abstract
The aim of the current research is twofold: 1) to provide a conceptual framework to analyze and classify the innovation effects of instruments to support electricity from renewable energy sources (RES-E) by considering different analytical perspectives and, 2) based on a thorough review of the empirical literature, to compare the innovation effects of different RES-E support instruments, with respect to the different innovation dimensions resulting from those perspectives (technological diversity; research, development and demonstration (RD&D) investments; learning effects and technological competition). No instrument scores well in all innovation dimensions, although feed-in tariffs (FITs) score highly in a majority of them. In particular, FITs are more likely to feed back into previous stages of the innovation process than other deployment support schemes, mostly due to their proven capacity to create markets for renewable energy technologies, which activates all the innovation dimensions. Our results do not support the usual claim of a combination of deployment instruments for technologies with different maturity levels. Indeed, the evidence suggests that we should use FITs for technologies with different maturity levels, combined with public RD&D support for the least mature. The impact of deployment instruments on private RD&D investments calls for a better coordination and integration between public RD&D and deployment support. However, the evidence of the impact of support schemes on some of those dimensions is scarce and, thus, more research is required.

Key Word and Phrases
Renewable Electricity, Innovation, Support Policies.

1. Introduction.

This paper focuses on the "innovation effects" or "innovation dimensions" of the innovation effects of instruments to support electricity from renewable energy sources (RES-E)[1]. We picture the "innovation process" [1] or "innovation cycle" [2] in a broad sense, encompassing invention, adoption and diffusion, with feedbacks between stages[2].

The innovation effects of RES-E support schemes is a very relevant topic. The long-term nature of policy challenges such as climate change makes it all the more important that we improve our understanding of those effects. Renewable energy technologies are expected to be a key technology leading to significant emissions reductions (see, among others, [5]). Therefore, encouraging and improving renewable energy technologies is a prerequisite for surmounting these challenges timely and cost-effectively.

Furthermore, given ambitious targets in the renewable energy realm in many regions, a great deal of focus has been placed on the role of innovation in lowering the cost of these energy sources [6]. It is widely acknowledged that innovation has the potential to significantly decrease the costs of attaining societal goals for climate change mitigation [7], [8]. Finally, some countries (i.e., Germany), stress that a main goal of its RES-E support scheme is to achieve technology cost reductions[9].

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[1] Throughout this paper the terms "innovation effects" and "innovation dimensions" are used interchangeably.

[2] "An invention is an idea, sketch, or model for a new device, process or system" [3]. "Adoption" is the first commercial implementation of a new invention. "Diffusion" refers to the widespread use of a commercial innovation, and is often studied as a communication process between current and potential users of a technology [4].

Traditionally, the literature on RES-E support schemes has paid attention to two main criteria: effectiveness and static efficiency (see, among others, [10]-[13]). In contrast, the innovation effects have received much less attention[3]. Although a few contributions have focused on the innovation effects of deployment support in general vs. support for research, development and demonstration (RD&D) support, specific deployment instruments have not been considered [18], [19]. Furthermore, RES-E support schemes have been analysed without due regard to the theoretical contributions of the systems of innovation (SI) literature. In contrast, this paper focuses on the innovation effects of different deployment support instruments using the insights from the SI approach.

The aim of this paper is twofold: 1) to provide a conceptual framework to analyze and classify the innovation effects of RES-E support schemes by considering different analytical perspectives and, 2) based on a thorough review of the literature, to compare the innovation effects of different RES-E support instruments, taking into account the different innovation dimensions resulting from those perspectives.

The paper is structured as follows. Section 2 compares and relates relevant approaches to the analysis of the innovation effects of RES-E support schemes, while section 3 discusses the different innovation effects resulting from those policies. An overview of RES-E support instruments is provided in section 4. The empirical analysis of the impact of those instruments on those dimensions is carried out in sections 5. Section 6 concludes.

2. Theoretical Approaches for the Analysis of the Innovation Effects of RES-E Support Instruments.

Several approaches have different conceptualisations of the sources, barriers and drivers of technological change. Thus, the innovation effects of RES-E support instruments can be analysed with several perspectives.

The traditional environmental economics perspective[4]

Several perspectives are based on the lineal model of innovation, for which technologies subsequently go through sequential stages, but without major interactions between them. In environmental economics (see [21] for a review) innovation is regarded as a "black box" and the effects on the different stages of innovation are analysed separately. Technological changes are assumed to respond automatically to changes in relative prices as a result of exogenous developments (such as policies).

Several papers in this tradition analyse the cost-effectiveness of RES-E deployment [22], [6]. However, a main problem with this view is that the time horizon considered is usually too short and the mitigation targets considered are very moderate. This plays against capital-intensive technologies (with a large cost-reduction potential), like renewables [23]. The framework adopted is usually static, disregarding dynamics and the interdependencies between institutions, actors and technologies in complex systems leading to inertia and lock-in. Furthermore, competitive pressure is regarded as the main (or exclusive) mechanism to reduce the costs of technologies, disregarding other dimensions of dynamic efficiency such as diversity. Generally, "technology-neutral" instruments are advocated.

The systems of innovation (SI) perspective

This approach focuses on the importance and interdependencies of actors, networks, institutions, cumulative learning processes and spatial and technological characteristics [24] and deals with phenomena such as path dependency, lock-in, interdependence, non-linearity, co-evolution and reinforcing effects [25] – [27].

[3] Notable exceptions are [14,15,16,17].

[4] By traditional economics, we refer to the Walrasian model of welfare economics, which can be defined as the theoretical synthesis of the Marshallian approach with marginal production theory and the rigorous precision of mechanical mathematics [20].

An innovation system consists of three elements [28], [29]: technology and related knowledge, networks of actors and institutions. Networks of actors develop and implement new knowledge and technology, within their institutional context. For an innovation system to be successful in developing and implementing technologies, these three coevolving building blocks need to be aligned. Recently, a functional perspective of the SI approach has been developed, whereby "success" is related to the fulfillment of system functions [30].

The few studies applying this approach to analyse renewable energy systems [31] – [36] stress that a shift to renewable energy technologies is a complex process that involves changes in those elements. The SI perspective acknowledges that barriers to renewable technologies are systemic. These systemic barriers lead to lock-in through a path-dependent process driven by technological and institutional increasing returns to scale. The diffusion of renewable energy technologies into the incumbent energy system requires vicious circles to be established between the different functions of an innovation system [37], [30]. These may take place in a niche, which allows technologies to progress and create a supportive institutional environment around it. Niches can be created through RES-E support.

A coalition of forces has been shown to be crucial in the success of RES-E support schemes and coalitions result from the sequential interaction between support, market creation, stages of technological change and actors [38][5]. Stimulating RES-E will create cumulative causation processes and virtuous cycles between actors and stages of technological change, providing further investment and learning opportunities and expanding the market for key technologies [41][6]. These coalition of forces/actors and cumulative causation processes are mostly disregarded by the traditional approach.

The literature on learning effects

Learning effects refer to many mechanisms which are considered to contribute to the costs reductions of renewable energy technologies (box 1). This literature is not isolated from 2.1 and 2.2. Some papers have analysed the diffusion of RES-E (induced by policy), relying on learning curves [42]. Many energy-economy models that incorporate induced technological change include some learning effects and the SI literature stresses the importance of these effects. The extent to which instruments and design elements encourage those learning effects is a main aspect of RES-E support. While mainstream economics has stressed learning-by-doing, other learning effects have been neglected, particularly learning-by-using and learning-by-interacting). These are considered in this paper. Learning effects (as included in a learning curve), however, have been criticised for being a black box because it is not entirely clear what mechanisms induce innovation [43]-[45].

Box 1. Learning mechanisms.

Source: [46], [47].

-Learning-by-doing. The repetitious manufacturing of a product leads to improvements in the production process -Learning-by-using. Improvements in the technologies as a result of feedback from user experiences into the innovation process. -Learning-by-interacting takes place as a result of the network interactions between actors. -Upsizing (or downsizing) a technology may lead to lower specific unit costs (e.g. the costs per unit of capacity). -Economies of scale. Standardization of the product allows upscaling of production plants, and producing the same product in large numbers. -Learning-by-searching refers to improvements due to RD&D.

[5] For example, the German case of wind power reveals how feedback loops may be generated from early market formation, via early entrants, to changes in the institutional framework beyond the formative. phase [32, 35]. Jacobsson and Johnson [39] provide similar conclusions for wind energy in Denmark, Astrand and Neij [31] for Sweden and Del Río [40] for Spain.

[6] However, while a coalition of forces is necessary in the take-off stage, it may have negative implications in the long-term if it leads to regulatory capture and rent seeking by renewable energy firms, making support instruments difficult to change or even remove when they are no longer justified.

Combining different perspectives

Those approaches miss some important phenomena underlying the complexity of technological change. System changes and interdependencies are disregarded by environmental economics [48]. The energy-related SI studies do not analyse the specific impact of environmental regulations on the innovation system, they downplay the role of competition as a source of cost-reductions and technological improvements and have been criticised for not generating sufficient practical policy advice [30], [48], [29]. Therefore, those perspectives are complementary and should be integrated in order to consider all the relevant innovation effects resulting from RES-E promotion. To fully develop a combined framework represents an endeavour that exceeds the scope of this paper, however. Instead, the aim is to provide some bridges connecting different approaches.

We propose that this integration is built on a SI approach, which provides a broader and richer picture of the innovation process in renewable energy and, thus, offers a guiding heuristic on how RES-E support policies may influence this process.

Learning effects have points of connection with two main aspects of the SI approach: the interaction between learning and RD&D and the close relationship between technological and institutional learning. Regarding this second aspect, an important learning effect is "learning by interacting". During the diffusion of the technology, the network interactions between actors such as research institutes, industry, end-users and policy makers generally improve [49]. Astrand and Neij [31] empirically showed how subsidies in the early 1990s in Sweden increased the diversity of actors involved in the development of wind turbines and how this improved the learning in using wind turbines, suggesting a link between diversity of actors and learning effects. Indeed, the SI approach provides a broader perspective on learning, "systemic learning", which refers to learning that is not only about specific technologies but it is regarded as a systemic phenomenon which includes a complex set of dynamic processes [50], leading to systemic improvements[7], including changes in different surrounding systems through positive feedback mechanisms [27].

Learning effects are a market failure in the sense of the traditional approach: market outcomes for technologies exhibiting these features may be inefficient [52]. This provides a link between 2.1 and 2.3. The modelling literature on endogenous low-carbon technical change has shown that learning effects can be introduced in traditional models without much frictions [53].

The link between 2.1 and 2.2 may be compatible on different time frames. The policy implications that can be drawn from SI studies are long-term and, thus, complementary to neoclassical policy insights that apply well to well defined, short-term problems [54].

Some points of disagreement are worth highlighting. While the conventional approach emphasises competition between technologies, the SI approach stresses the relevance of the diversity of innovations, learning effects and feedbacks from deployment to RD&D. In contrast, competition between innovators as a source of cost reductions and improvements in technologies has probably been downplayed by the SI approach. While some insights/hypotheses from the traditional approach are compatible with the SI (i.e., technological competition), others are certainly not (i.e., the lineal approach).

Therefore, while traditional environmental economics see the benefits of market creation in terms of competition among players and technology selection, the SI takes a broader perspective and considers the market as a learning arena, which creates variety in the system. Market creation has elements of supply-push dynamics, whereby learning effects and RD&D investments are encouraged and feedback loops between the technological and the institutional realms are developed. Institution building is a major aspect of policies leading to the development and diffusion of technologies which, in turn, create an institutional environment around them, in a process termed "co-evolution" [26]. Both perspectives can thus be regarded as complementary and, on this front, the SI perspective with its relevance attached to learning would embed the mainstream approach with its focus on competition.

3. The Innovation Effects of RES-E Support

[7] An example of systemic learning would be the institutional evolution that allows lowering of costs of projects in which new technologies are used [44]. See also [51] and [43].

The above perspectives suggest the existence of several innovation effects of RES-E support[8]. An integrated perspective requires that these effects are singled out but also that their interrelationships and interactions are considered. We do not claim that these effects or dimensions are isolated from each other. On the contrary, they overlap[9].

Diversity

Both the "options approach" [55] and model simulations [56], [57] have shown that ambitious RES-E deployment targets can only be attained cost-effectively from an intertemporal perspective by simultaneously (not sequentially) promoting different technologies [58], [23], [59]. The SI approach has also stressed the need to invest in a broad variety of technological options in order to avoid lock-in to technologies with limited potential or negative consequences [25]. Lack of support for immature technologies with a large cost-reduction potential would lead to higher costs in the long term because these technologies will not be sufficiently developed when they will be needed to comply with more ambitious targets.

Diversity is about supporting different technologies and different actors, since vested interests are a barrier to a transition to renewable energy technology systems [60]. New energy technologies are often developed outside the established energy systems and engage non-traditional energy actors [61], [31]. Actors, networks and institutions involved in radical innovation processes are not identical to those performing activities that sustain an established system [25][10]. The SI approach has stressed the need for new firms into an emerging technological system (see [29], [30], [26], [25], [31] among others).

Building a coalition of forces is crucial to support technological diversity, gradually break the institutional lock-in which is required for the emergence of a new technoeconomic system [32] and build the social acceptability and political feasibility of RES-E promotion [63]-[65][11]. Therefore, RES-E support should contribute to this variety by promoting technologies with different maturity levels, i.e., through niche creation. Increasing actors' diversity reduces long-term policy risks (i.e., risks created by policy) since the wider the types of actors and technologies participating, the greater the social and political legitimacy of public support which ensure the continuation of public support[12].

Risks related to public support are problematic for diversity. The costs of renewable energy technologies are highly dependent on the cost of capital and affected by price, volume, and balancing risks. In turn, they are all affected by policy risk [67], [34]. Given their greater capital intensity and reliance on public support, immature technologies are more affected by risks. In turn, it is more difficult for small generators to cope with greater risks. Different design elements result in different degrees of policy risk.

Finally, although diversity of technologies should be favoured, this should be balanced by the fact that that, if many technologies are supported, available funds may be spread on too many alternatives at the same time without significant progress in any technology.

RD&D investments

[8] Rogge and Hoffmann [48] suggest an alternative structure for the analysis of the innovation effects of renewable energy policies. They consider the impact of the European Union Emission Trading Scheme (EU ETS) on four building blocks: "knowledge and technologies", "actors and networks", "institutions" and "demand". Our classification is not incompatible with theirs, however. While their focus is on the "intermediate" of those building blocks, ours looks more closely to the final impacts of one of the "institutions" (RES-E support) on the other building blocks and renewable energy technologies. However, our dimensions also encompass the insights contained in those building blocks.

[9] One of the "sources" of technological change (spillovers from activities undertaken in unrelated sectors) is not included in this paper because, as argued by Clarke et al. [8], a substantial component of spillover effects is exogenous from the perspective of the home industry. Thus, RES-E support instruments are largely ineffective to trigger these effects.

[10] However, Genus [62] argues that, in relation to future industry development, the role of larger incumbent companies entering or taking a larger interest in the renewable energy sector is of critical importance.

[11] For example, in the German wind case, new entrants (manufacturers and generators) increased the political power of the advocates of wind energy so that they could defend a favourable institutional framework [30].

[12] An example is Germany, where one-third of wind power is owned by over 200,000 local landowners and residents, i.e., 45 percent of wind projects in Germany are locally owned. In Denmark, 83 percent of wind projects are owned by individuals or local cooperatives [66].

As with other technologies, energy technology innovation is characterised by research, development, demonstration and deployment and the presence of multiple dynamic feedbacks between these phases. RD&D is one of the basic driving forces of technological progress [43]. Empirical studies have shown that private RD&D investments are an important side-effect of deployment policies [68], [41], [69], [70], in a context of relatively modest and stagnant direct public RD&D support in renewable energy technologies [71], [72][13]. Indeed, private RD&D seems to be a main share of total RD&D in the RES-E sectors[14]. Deployment support is no substitute for public RD&D support, however. They are rather complements and should be coordinated [76]. Both they may also compete as well. Hoppmann et al [77] suggest that the FIT incentivized German firms to shift resources towards investments in new production capacities and away from long-term RD&D.

Deployment feeds back into RD&D as a result of two interrelated factors: the existence of a stable market for renewable energy technologies (demand-pull) and the existence of a surplus for RES-E generators which they can share with RES-E manufacturers and which allows the later to invest in RD&D (supply-push). Note that investors in RD&D are technology providers (equipment suppliers) and, to a lesser extent, power generators themselves[15]. The supply push influence is argued by [14] on theoretical grounds and empirically shown by [80] for the U.K. and German cases. However, the surpluses that are likely to be reinvested in RD&D are those obtained by investors in immature technologies, since the scope for improvements is greater for these technologies. In contrast, greater profits for mature technologies are unlikely to be reinvested in radical technologies and more likely to lead to windfall profits [81]. Obviously, policy risks negatively affect this dimension since both the aforementioned demand-pull and supply-push influences are constrained.

Economies of scale and learning effects

Diffusion allows cost reductions and improvements in the technologies over time through learning effects (box 1). Instruments can contribute to learning effects by creating niches, especially for immature technologies. Only a reliable and stable mass market would allow technologies to advance along their learning curves. Thus, policy risks have negative effects on the effectiveness of support, and, thus, on learning effects.

Learning effects suggests that it might be cheaper to provide significant investment early on in order to drive renewable technologies rapidly down their experience curves and reduce costs quickly, rather than to reduce the costs of technologies slowly through more gradual introduction [82]. This is supported by model simulations [56], [57].

The SI literature stresses that, particularly, the interaction of the actors involved should be supported (learning by interacting)[16]. When the connectivity and interactions between elements of the innovation system are poor, fruitful cycles of learning and innovation are prevented [29]. Learning mechanisms are largely based on the networking of suppliers and users [83]. In particular, the competitiveness of generators is dependent to a large extent on their collaboration with equipment suppliers, with whom they have formed long-lasting networks of technological interaction and interdependence. This is confirmed by analysis of the Danish wind energy support scheme [84], [31].

Technological competition

[13] In the last 35 years, total public sector energy RD&D budgets have declined in real terms while the relative share of energy in total RD&D has also declined from 12% in 1981 to 4% in 2008 [73]. According to OECD [74], public spending in renewable energy-related RD&D in OECD countries represented 25% of total public energy technology RD&D in 2007 and was at the same level than in 2000.

[14] Criqui et al [75] report that over the last 25 years (1974–1999) private RD&D expenditures for wind energy might have been approximately 75% higher than public RD&D expenditures. IEA [71] notes that private-sector RD&D spending on energy technologies today is at 40 to 60 $billion a year, about four to six times the amount of government RD&D.

[15] For example, in a survey of the German RES-E sector, 38% and 77% of power generators and equipment suppliers, respectively, invested in RD&D activities [78].

[16] Lundvall [49] stressed that the development of new technologies requires a close interaction between the users and producers of a technology. REIs can promote innovation in so far as they facilitate those interactions.

A wealth of literature exists attesting to the positive relationship between the market competition and cost-reducing innovation [85] – [87], among others. During the diffusion period, increased competition between supplying firms leads to cost efficiencies in the production of products [88]. This innovation dimension stresses competition between RES-E generators and between equipment manufacturers as a source of innovation. Strong incentives are passed from RES-E generators to equipment suppliers to seek revenue-enhancing or cost-reducing innovations. RES-E generators may increase their profits by purchasing more efficient (greater revenues) or cheaper technologies (lower costs) from equipment manufacturers.

Competition depends on an attractive investment climate, which in turn is contingent on policy stability. However, a guarantee of total revenue certainty eliminates the incentive to improve efficiency [89] and reduces competitive pressures. Some instruments may have enhanced this competition more than others (see section 5).

Note that, since the relevant competition is that between equipment producers, an instrument should promote competition at this level (i.e., favour new entrants)[17], although Renewable Energy Instruments (REIs) are targeted directly at RES-E generators and only indirectly affect equipment suppliers.

Lower investment risks

Uncertainty (and risks) are one of the core mechanisms of technological change [43]. By improving the effectiveness of support, reducing investment risks is instrumental in triggering the previous innovation effects. This reduction is particularly important for renewable energy technologies, given their relatively high capital-intensity. Since policy-related risks are a major risk factor, RES-E support instruments can be evaluated according to the extent to which they minimise investment risks. Indeed, the long-term predictability of support may be more important than the economic level of the incentive itself [91]. The greater stability of the revenue stream is even more relevant for immature technologies, which can not absorb the fluctuations in project revenues as easily as well-established technologies [92].

Discussion

The relevance of the mechanisms leading to innovation effects changes along the technological change pipeline (i.e., for technologies with different maturity levels), since each phase faces distinct requirements and barriers. Technological diversity and RD&D investments are more important in the first stages, whereas learning effects are more relevant in the transition from the pre-commercial to the commercial stages. At the end of the innovation process, competition between RES-E generators becomes crucial, whereas competition between equipment suppliers is important in all stages.

However, the matter at hand is not simply which dimensions are most important along the technological change process, but how they interact with each another. Innovation dimensions are interrelated, with synergies and conflicts between them. One example of those interactions is between RD&D and learning effects (learning-by-doing) which are usually regarded as isolated from each other in the literature. RD&D leads to cost reductions and facilitates the advancement of technologies along their learning curves [69], [93]. On the other hand, learning effects reduce costs and promote diffusion. In turn, market creation makes RD&D investments in those technologies more attractive[18]. RD&D investments are encouraged by a greater market and producer surplus. Learning effects positively affect both. Lessons learned on the production line or in the use of a technology can feedback the RD&D process and can help to set RD&D priorities [95].

A strong link between diversity and learning can also be observed. Since immature technologies have the greatest cost-reduction potentials due to learning effects, promotion of different

[17] Since new entry results in intensified competition and rivalry [90].

[18] For example, Gillingham et al. [94] and Ek and Söderholm [72] note that if production costs fall, the potential competitiveness of the technology increases, increasing also the return on additional private RD&D efforts. This will induce more RD&D expenses on the part of private market actors, something which in turn implies lower costs and higher market penetration rates for the technology.

technologies increases aggregated learning benefits compared to the promotion of one technology. On the other hand, selection pressure triggers learning effects and RD&D investments.

Thus, capturing those interactions is key to identify the overall innovation effects or innovation dimensions of different policies. A policy affecting one of those innovation dimensions also influences others.

4. RES-E Support Instruments

RES-E promotion has traditionally been based on three main instruments, which are the focus of this paper: feed-in tariffs (FITs), quotas with tradable green certificates (TGCs) and bidding/tendering schemes [96], [12], [97], [91]. In addition, there are a wide array of "secondary" instruments, including investment subsidies and fiscal incentives.

FITs are subsidies per kWh generated, combined with a purchase obligation by the utilities. Quotas with TGCs (called Renewable Portfolio Standards (RPS) in the US) are certificates issued for every MWh of RES-E, allowing generators to obtain additional revenue to the sale of electricity (i.e., two streams of revenue). Demand for TGCs originates from an obligation on electricity distributors to surrender a number of TGCs as a share of their annual consumption (quota). Otherwise, they would pay a penalty. The TGC price strongly depends on the interaction of supply and demand and other factors.

Tendering/bidding systems. The government invites RES-E generators to compete for either a financial budget or RES-E generation capacity. Within each technology band, the cheapest bids per kWh are awarded contracts and receive the subsidy (i.e., bid price per kWh).

RES-E support (all instruments) is generally funded by electricity consumers in their bills.

5. Assessing the Innovation Effects of RES-E Support Schemes

The innovation effects of different RES-E support schemes are identified according to the empirical literature, using the innovation dimensions discussed in section 3.

Methodology

A systematic review of the empirical literature on national RES-E support schemes was undertaken. All issues of the most relevant journals in the 2000 to 2011 period were revised[19]. This was complemented with other documents (i.e., reports). The titles and abstracts that appeared to tackle the innovation effects were examined. Only those articles which empirically analyse at least one of the innovation effects of the three instruments, albeit with different methodologies (case studies, econometric modelling and simulations), were selected. Only effects on domestic innovators have been considered in the literature (with the exception of [18] and [98]).

Main results

Table 1 summarises the results of our assessment of the empirical literature on RES-E support regarding the contribution of each instrument to the innovation dimensions.

Table 1. Empirical findings of the literature on RES-E support with respect to different innovation dimensions

[19] The journals revised were (classified by types of theme): 1) Energy-related journals (Energy Economics, Energy and Environment, Energy Policy, Climate Policy, Renewable and Sustainable Energy Reviews, Energy Journal, Renewable Energy, Energy, Applied Energy and Electricity Journal; 2) Environmental and Ecological Economics journals: Ecological Economics, JEEM, ERE and Resource and Energy Economics; 3) Technology and innovation journals: TFSC, Research Policy, Technology Analysis and Strategic Management, Journal of Cleaner Production and Technovation.

Instrument	Diversity	RD&D investments	Learning effects
FITs	*Technological diversity. FITs have led to a diversified renewable energy technology portfolio in Spain, Denmark and Germany [99, 40]. FITs are easily differentiated by maturity level, costs, project size, location and resource quality. *Diversity of project sizes in the above countries. FITs have caused a fast shift towards distributed resources and smaller-scale systems installed by smaller firm [100]. *Diversity of actors. As project revenue streams were certain under the German FIT, project developers engaged the affected community early in the process [80]. The majority of investments by large incumbents have been earmarked for conventional technologies [68]. FITs set no restrictions on eligibility or capacity, meaning that both large-scale investor-owned utilities and smaller businesses and individual homeowners can take advantage of them [101]. FITs in Germany have provided an incentive to build renewable energy “all over the country, in varying sizes and configurations, owned by a variety of people and institutions, even in low resource areas”. FITs promote diversification of technologies, locations and ownership. More than 90% of the 430,000 solar panels installed under the German FIT, for example, are owned by homeowners and cooperatives instead of electric utilities and independent power providers [101].	The greater effectiveness of FITs in spurring diffusion is likely to feed-back positively into RD&D investments, as shown by Rogge et al. [68] for Germany. The creation of a local RES-E market encourages a local industrial base and, in turn, facilitates RD&D investments by local manufacturers. A lower risk for investors is translated to equipment/technology manufacturers [102]. Most manufacturers of renewable technologies are from countries with FITs (Denmark, Germany and Spain). These countries have been the most successful at creating sizable, stable markets for wind power [103, 104, 105]. In 2000-2002, they were home to eight of the ten biggest wind turbine manufacturers in the world. In contrast, a competitive renewable energy industry was not developed in the UK [15]. Johnstone et al. [70] show that FITs encourage RD&D investments in immature, high-cost technologies (solar), while TGCs encourage RD&D investments in more mature technologies (wind). Jänicke [2] shows that FITs in Germany led to a large increase in renewable technology patents after 1998. Lee et al. [41] argue that renewable technology patenting by country is also a response to shifts in market conditions and the timing of their take-off may also reflect the impact of policy incentives such as feed-in tariffs in key wind markets. However, these authors do not show a clear relationship between the patent assignees and the type of support scheme implemented in the countries.	FITs have shown generally effective to increase renewable capacity, both in the EU and Canadian provinces [99, 106, 107, 108, 175, 14, 109, 58, 91, 110]. Nevertheless, RES-E capacity expansion has been modest in Greece and Italy (before adopting TGCs) [111]. Papineau [112] shows large and (statistically) significant estimates for learning effects in wind and solar technologies in countries with FITs (Denmark and Germany). Similar findings from [42].
Quotas with TGCs	a) Technology diversity. The cheapest technologies are privileged over expensive ones (solar, off-shore wind, wave and tidal) [119, 99, 108, 80, 120, 121, 58, 91, 70, 113]. * U.K.: only wind on-shore, landfill-gas and some biomass have been promoted [80, Mitchel et al 2006, 122, 123]. * Sweden: Investments in new plants restricted to on-shore wind and biomass cogeneration [124,125]. Of the electricity production that received TGCs in 2008, 64% was from biofuel-fired plants, 5.5% from CHP plants burning peat, 13% from wind and 17% from hydro. The other technologies did not receive any TGCs at all [126]. The current quota obligation in 2016 will probably be fully met by biomass and on-shore wind [93]. * In Flanders, most of the RES-E was delivered from bio-waste and biomass exploited by incumbents [124, 64]. * Texas: only deployment of wind energy has been encouraged [127,128]. * California. A greater technological diversity than in other RPS. Of the 7000MW of contracts for renewable generation between 2002 and 2007: 53% (wind), 23% (solar), 12% (geothermal), 7% (biomass) and 1% (hydro and ocean) [128].	Producer surpluses are not directed to innovation in immature technologies. Significant rents are reaped in TGC schemes by investors in mature technologies (U.K., Flanders and Sweden) [124, 93, 64]. But these rents have not rewarded successful entrepreneurs developing and applying immature technologies [93]. Little demand has not stimulated industry creation in immature technologies in the U.K., Sweden and Flanders [124]. Patent analysis suggests that FITs encourage private RD&D investments in immature, high-cost technologies (solar), while TGCs encourage RD&D investments in mature technologies (wind) [70]. However, Lee et al [41] do not show a clear relationship between the patent assignees in wind and solar and the type of support scheme.	In the EU, TGCs have been less effective than FITs [114, 91]. Some studies have compared the UK (TGC) and the German (FIT) models, showing a lower effectiveness of the former [80, 99, 102]. The UK ROC has not delivered deployment at expected levels [136]. The data shows a low effectiveness of the Swedish TGC scheme both in terms of installed capacity and generation [125,124]. In 2007, the target was 25.6 TWh and actual generation reached 15.9 TWh [124]. Ineffectiveness in Australia and Japan. In Australia, the annual target of 14,400 GWh in 2011 only consists of 1900 GWh of new generation [130], although the MRET may have been successful at arresting a long-term decline in RES-E [55]. In 2007, Japan was only half its national target of 2010 [138].

	* Other US states. Wind is the dominant renewable technology deployed. State experience in supporting solar energy with RPS programs is mixed [174]. *Japan: The RPS has not promoted technological diversity [130,131]. The dominant technology has been low-cost waste-fired power from existing power plants, with wind power also a significant fraction. Ineffective to support solar PV [131]. * Australia. Only the most mature technologies (hydro, on-shore wind and bagasse) have been promoted [132, 55]. Solar electricity: only 1.4% of the 35,484,013 TGCs created by 2008 [55]. Apart from case studies, other methodologies (i.e., modelling simulations) point in the same direction. Voogt and Uyterlinde [133] and Nogee et al [134] show, respectively that an EU-wide and a US federal RPS would not promote technological diversity (particularly solar technologies) and that wind and biomass would dominate. b) Diversity of actors. A diversity of actors is not promoted: large utilities and incumbents have been favoured and small actors are discouraged from participating in Flanders [64], Sweden [124, 93] and the UK [102, 64, 135,136]. This is partly a result of the larger investment risks and transaction costs of the instrument for small actors. The three largest producers accounted for 21% of certificate-entitled production in Sweden [126]. The TGC scheme in the UK poses price, volume and balancing risks that only large, integrated energy companies have overcome [102]. In the US, RPS have been found to favour vertically integrated generating companies and big electric utilities that can handle large-scale investments [101]. Small renewable energy producers may face barriers under an RPS due to the significant transaction and administrative costs and risks involved in participating in the TGC market [137,100].		In contrast, the effectiveness of RPS in the U.S. is unclear. Yin and Powers [139] find that US state RPS programs have had a statistically significant and positive impact on in-state renewable energy development. Menz and Vachón [140] show that states with an RPS exhibited larger expansion in wind capacity between 1998 and 2003 than states without an RPS. The Texas RPS target for 2005 was met several years early [80]. Several case studies show that RPS can be effective in promoting wind capacity additions (e.g., [141, 142, 143, 127, 128]. In contrast, Carley [144] shows that RPS policies do not increase the share of RES-E generation. States with RPS do not have statistically higher rates of RES-E share than states without RPS policies, holding all else constant. Kneifel [145] finds that RPS policies do not lead to an increase in renewable capacity in a state. Sovacool [101] shows that RPS have been responsible for only one-fifth of renewables growth in the US from 1978 to 2006.
Tendering/ bidding	a) Technological diversity. U.K.: the most expensive technologies were not promoted. Landfill gas, waste-to-energy and on-shore wind dominated [119, 99, 149]. b) Diversity of actors The intense price competition favoured large incumbent RES-E developers and suppliers in the UK, Ireland and France, at the expense of independent providers and small firms [100, 101]. Bias of the NFFO towards big industrial players. Lack of creation The priority granted by NFFO has been unable to create a big renewable lobby group in the U.K. [150].	Producer surplus: In the U.K. NFFO, the fierce competition among project developers kept producers surpluses to a minimum, limited the budgets of developers and manufacturers, encouraged producers to adopt foreign best available technologies and did not enable them to invest major resources in RD&D [15, 103]. Market creation. NFFO: tenders did not draw domestic manufacturing interest to the country [119]. This also occurred in France and Ireland [15]. In contrast, the tendering scheme in Quebec attracted local manufacturing, due to stringent local content requirements, labour tax incentives and a large project tender that established a sizable market [103]. Countries with tendering have not been those with greater or lower patents [41].	The NFFO failed to deliver the quantities of renewable energy generation that it had aimed for [99, 80, 151,152,153]. The incentive to bid low and the absence of an obligation to carry out the projects led to low profitability levels and discouraged the realisation of projects. Planning restrictions were also a barrier. From the 1st to the 5th round of the NFFO, the projects generating decreased and the non-completed projects increased [150]. By 2003, only 30% of MW contracted were actually installed [80]. France's EOLE saw just 70 MW built out of 300MW contracted with 30MW were operating in 2005 [80]. Manitoba's tendering scheme shows a similar ineffectiveness [110]. There is also evidence of ineffectiveness (regarding projects actually being built) in Portugal [154], Peru [155] and Brazil [156].

Source: Own elaboration.

Table 2 summarises the impact of each instrument on the different innovation dimensions/effects. It also reports the degree of evidence and agreement in the literature on the impact of a given instrument.

Table 2. Summary assessment of the impact on the innovation dimensions.

	Diversity	RD&D	Learning*	Competition	Risks
FITs	(HI, HE, HA)	(HI, LE, LA)	(HI, LE, HA)	(LI, LE, LA)	(HI, HE, HA)
Quotas with TGCs	(LI, HE, HA)	(LI, LE, LA)	(LI, LE, HA)	(HI, LE, LA)	(LI, HE, HA)
Tendering/ Bidding	(MI, HE, HA)	(LI, LE, LA)	(LI, LE, HA)	(HI, LE, LA)	(MI, LE, LA)

Source: Own elaboration. Note: HI/MI/LI= High/Medium/Low impact; HE/LE = High/Low evidence. HA/LA = high/low agreement. * Indirectly (HE on effectiveness).

It can be observed that: 1) no instrument scores well in all innovation dimensions, although FITs score highly in a majority of them, followed by tenders and TGCs, 2) the degree of evidence/agreement is quite unbalanced across these effects/dimensions, suggesting that further research is needed in the future.

Discussion

Both the SI and the RES-E support literature acknowledge that niche creation is very relevant for technological diversity. Furthermore, the SI approach stresses that diffusion and innovation are coupled processes and that both influence each other. The analysis reveals that TGCs are unlikely to provide niches for immature and expensive mature technologies, negatively affecting diversity (technologies and actors) but also RD&D and learning effects. In contrast, since technology-specific support can be provided by FITs, they have created niches for different technologies. For example, while technological niches for photovoltaics have been created by FITs in the EU [25, 40], TGCs have been unsuccessful in this regard in the US [174]. Diversity is all the more important as a high RES-E world is likely to rely on a broader portfolio of technologies with different maturity levels [166]. Notwithstanding, variety should not only be promoted at the deployment policy level (i.e., demand-pull), but through public RD&D (supply-push). Regarding the diversity of actors, the evidence shows that TGCs restrict the role of small generators and new entrants. In contrast, FITs tend to encourage a greater amount of RES generation capacity to be installed by a broader range of players.

FITs would tend to positively affect RD&D in immature technologies, since they have been more successful in creating a large market (demand-pull) and generating sufficient profit margins to finance RD&D (supply-push). For example, under the German and Danish FIT, the capital goods suppliers benefited from the creation of a domestic market and the transfer of some of the support to the capital goods suppliers through high equipment prices, which to a large part were used for technology development [158], [74]. This suggests that support schemes for RES-E and especially FITs are not only an instrument of demand-pull, but they have important supply-push properties.

TGCs and tendering have probably been less successful in triggering private RD&D investments in immature technologies due to their focus on the lowest cost solutions and, in the case of TGCs, the greater revenue risks for investors due to volatile TGC prices. Although profit margins have been greater under TGCs (see [114], [159]), it is investors in mature technologies who have benefited from these margins. They are less likely to invest in RD&D in immature technologies. However, relatively large producer surpluses for investors in immature technologies do not guarantee that those will be reinvested in RD&D. There is some evidence that rapid growth of solar PV deployment under FITs in some EU countries (Spain, Germany and Czech Republic) has not led to higher private RD&D investments. Hoppmann et al. [77] and Peters et al. [18] report that FITs in Germany have shifted resources towards investments in new production capacities and away from long-term RD&D. Thus, the statement that FITs are superior in this dimension generally holds if fast deployment is avoided, which can be done with the appropriate design elements (i.e., flexible degression and capacity caps, see [160]).

FITs also score better regarding learning effects, which depend on the diffusion of technologies. Given their ineffectiveness in inducing technological diversity, TGCs have not created a space for learning in immature technologies. The conceptualisation of learning effects by the SI approach is broader and, in addition to learning-by-doing, it encompasses learning-by-using and learning-by-interacting. By encouraging diversity of technologies and actors, FITs are more capable than TGCs to build up new networks to enhance learning effects, particularly learning-by-interacting. Furthermore, since FITs are more likely to activate the innovation-policy cycles, by shaping a favourable institutional context for the new technology and triggering the coevolution of technological and institutional change, it is likely to result in a higher degree of systemic learning.

Regarding technological competition, TGCs are often assumed to provide a stronger competitive pressure and incentive for cost-reducing innovation. [161], [85], [162], [163], among others, claim that, as FITs are not based on direct competition between electricity generators, the incentive for innovations is less pronounced than under TGCs and tendering[20].

These claims contrast with the paucity of evidence supporting this superiority. Indeed, the empirical literature suggests that TGCs do not lead to greater competition among equipment/technology suppliers [80]. Even though FITs do not promote direct competition between generators, technical progress increases the producers' surplus and encourages them to innovate (or purchase innovative products from equipment suppliers). In tendering and TGC schemes, however, the surplus for RES-E generators with immature technologies is, if any, much more limited [14], [42]. Therefore, the capacity to purchase innovative products is modest and a strong equipment supplier sector is unlikely to emerge under these conditions. Without a market for immature technologies, there is no competition. FITs have proven more effective at market creation and also encourage competition between equipment suppliers to provide cheaper technologies in order for RES-E generators to increase their surplus.

While the discussion on the comparison between RES-E support schemes has focused on the TGC/FIT dichotomy, tendering/bidding schemes have some interesting features regarding innovation effects. In theory, they allow the promotion of technologies with different maturity levels (through banding), promote competition and provide stable low-risk incentives once bids are awarded.

However, they have not been effective in promoting neither mature nor immature technologies, probably due to the low profitability allowed by the instrument, leading to negative impacts on diversity, learning effects and RD&D investments. A priori, the instrument would score highly in the competition dimension. By allocating contracts on the basis of competitive bidding, providers have an incentive to cut costs to make their bids more attractive. But Butler and Neuhoff [80] show that competition among equipment suppliers in the U.K. Non-Fossil Fuel Obligation (NFFO) tendering scheme was lower than under the German FIT. Nothwithstanding, the evidence is very tiny on this dimension.

Given that no instrument fulfils all the innovation dimensions and that the literature argues in favour of instrument combinations to support technologies with different maturity levels, with FITs for the immature, more expensive technologies, and TGCs for the mature ones [91], [165], [17], we may ask whether a combination of deployment instruments is desirable from the perspective of innovation effects.

If TGCs were superior regarding competition between RES-E generators (something only supported by the theoretical literature), then a TGC scheme for the most mature technologies could be combined with another instrument for the immature (FIT). However, the proven superiority of FITs with respect to diversity and the (unsupported) claim that TGCs are better concerning competition suggests that TGCs should never be used in isolation, but combined with other

[20] For example, Sweden chose a TGC scheme because it was thought of better reducing costs through competition between different renewable energy sources and leading to technological development [164].

instruments. This has been recognised by some governments using TGC schemes. For example, in Italy, solar photovoltaics (PV) is promoted with a FIT and, in the U.K., FITs apply to small renewable energy projects (<5MW).

In contrast, our results show that, since FITs are the most appropriate RES-E promotion instrument to trigger innovation effects, this instrument should be chosen for all technologies, whether mature or immature.

Previous research has shown that a combination of demand-pull (deployment instruments) and supply-push policies (public RD&D) are more effective in promoting innovation than just one type of policy on its own [167]. Thus, public RD&D investments are needed in addition to a RES-E support policy since the former generate variety in the system while the later help to select among the different options [168], [26]. Even FITs are no substitutes for public RD&D investments, given existing market failures in RD&D investments. In particular, although deployment policies induce private RD&D generally, they are unlikely to promote basic and applied science. They are likely to promote incremental innovation. Only technology-push support (public RD&D support) is able to incentivise non-incremental innovation [18], [19]. Thus, the relevant combination of instruments is between public RD&D and deployment incentives, not between different types of deployment incentives. When the technologies are truly mature and competitive if the CO2 externality is internalised, we do not need a technology-neutral RES-E support scheme (such as TGCs) at all, but a technology-neutral CO2 price signal, i.e., either an emission trading scheme or a carbon tax.

Some of the drawbacks of the instruments with respect to specific innovation effects/dimensions can be mitigated with the use of different design elements, not different instruments. Indeed, only looking at instruments is not enough to analyse the innovation effects of RES-E support, since their impact is mediated by their design elements. Both the RES-E literature [91] and the innovation literature [68] have argued so. However, space limitations prevent us from discussing the innovation effects of FIT and TGC design elements. This is a fruitful area for future research. An initial attempt has been made by Del Río[169].

Finally, there is evidence on interrelationships between different innovation effects/dimensions and instruments. Although synergies are likely to occur (i.e., between diversity and learning in FITs), there is much evidence on conflicts, especially between diversity and competition in TGC schemes.

6. Conclusions

This paper has provided an integrated framework to assess the innovation effects/dimensions of RES-E support schemes and, based on a review of the empirical RES-E support literature, it has compared the impact of different RES-E support instruments according to different dimensions. Authors generally focus on only one dimension and, thus, disregard relevant impacts on innovation. This paper has tried to fill this gap in the literature.

Contrary to the belief that TGCs provide a better spur to innovation, it is shown that FITs score better on most innovation dimensions. They are more likely to feed back into previous stages of the innovation process than other deployment support schemes, mostly due to their proven capacity to create markets for renewable energy technologies. Thus, the topical call for instrument combinations for technologies with different maturity levels (FITs for the immature and TGCs for the mature) does not stand empirical scrutiny when the innovation effects of instruments are considered. Indeed, the evidence suggests that we should use FITs for technologies with different maturity levels, combined with public RD&D support for the least mature. In addition, the impact of deployment instruments on private RD&D investments calls for a better coordination and integration between public RD&D and deployment support.

The relevance of the innovation dimensions differs for technologies with different maturity levels. For the more expensive technologies (such as solar PV), supporting diversity (to avoid the risks of picking the wrong winners), triggering RD&D investments and stimulating learning effects is particularly important, whereas competition between RES-E generators is more valuable at later stages (i.e., for mature technologies). Competition between equipment suppliers is important in all the stages and critical in the initial stages.

FITs generate technological diversity and are more effective in activating (private) RD&D investments and learning effects. It is generally argued that TGCs are more appropriate to encourage competition between manufacturers, although the empirical evidence of this claim is non-existing. Competition exists when markets for the technologies are created. This is more likely under FITs. Deployment of immature technologies provides incentives for RES-E generators and equipment suppliers to reinvest profits towards RD&D and encourages competition between different actors. In contrast, under TGC schemes, markets for the immature are less likely to be created and thus, no competition at the level of equipment suppliers and no RD&D investments can be expected. In addition, FITs are more likely to encourage a broad participation of actors, which more likely leads to competition [166]. However, the excessive growth of deployment under FITs may have reduced the incentives to dedicate funds for private RD&D.

We propose nine avenues for further research regarding the assessment of the innovation effects/dimensions of RES-E support,.

First, the impact of different RES-E support schemes on private RD&D investments and competition should be assessed by carrying out comparative surveys among equipment suppliers in countries with different instruments (as done by [80] for U.K. and Germany).

Second, further empirical research should explore how different innovation effects/dimensions interact between each other. The analytical framework has been based on the assumption that different dimensions are separated from each other. Although this is appropriate in order to illustrate the most relevant direct effects, it rules out the existence of indirect effects, i.e., the impact on one dimension may also affect other dimensions.

Third, the implications of applying a SI approach for the analysis of the innovation effects of RES-E instruments should be further explored. In particular, applying the functional perspective of the SI approach can be very useful in this regard, identifying how different instruments contribute to different innovation functions.

Fourth, a quantitative and qualitative analysis on the innovation effects of the different design elements of RES-E support instruments is missing in the literature. Instruments are generally compared between each other, abstracting from their design elements. However, a major finding of the literature is that the success of RES-E promotion depends as much on the instrument chosen as on the specific design elements of those instruments.

Fifth, the complementarities of public RD&D support and deployment instruments (which trigger private RD&D investments) should be analysed beyond the general conclusion that public RD&D is mostly needed in the first stages of the innovation process and private RD&D is most appropriate for later stages. Trade-offs and interactions should be investigated further. Deployment and public RD&D do not only contribute to innovation, but feedback each other. Which deployment instrument is more synergistic (i.e., better integrated with public RD&D support) should be researched. Conflicts between private RD&D and deployment have been reported by Hoppmann et al. [77] and Peters et al. [18] for Germany (see also 5.3). The conditions and instruments under which these conflicts are more likely should be identified.

Sixth, an international dimension is crucial for this analysis since the innovation effects of RES-E deployment spill to other countries, while the costs fall on the country providing the support. This innovation externality suggests that greater coordination should be achieved between public RD&D and RES-E deployment policies and between different countries. A supranational RES-E support scheme would balance the effects of innovation spillovers and mitigate disincentives for the creation of demand-pull policies. Which instrument is better in this regard, i.e., which one would facilitate a better coordination or harmonisation of support schemes in Europe, is worth analysing. How different support schemes influence innovators abroad is also a crucial issue, allowing the identification of the “spillover rate”, i.e., how much of the innovation effects from deployment support can be accrued by the country making the financial effort.

Seventh, while demand-pull instruments in general are argued to lead to incremental innovation rather than radical innovation [170,171,18], it should be empirically analysed which deployment instrument (and design elements) provide a stronger incentive for radical innovation. The tiny evidence suggests that FITs are more successful in triggering innovation in less mature technologies [70][21].

Eight, there are hardly any empirical analyses available on spillovers from learning in renewable energy technologies across countries [172]. The IEA [45] argues that knowledge spillovers may be one explanation of the stronger learning effects in wind turbines in Germany compared to Denmark. Hansen et al [173] suggests the existence of learning spillovers between Danish firms.

Finally, the impacts of innovation on policy have been scarcely explored, a notable exception being Jänicke [2]. An ambitious RES-E policy will lead to innovation, technology improvements and cost reductions. In turn, this would allow even more ambitious policies and more stringent targets to be implemented [21]. The evidence suggests that these innovation-policy cycles are more likely to occur under FITs.

Acknowledgements

We are grateful to the National Research Council of Spain for financial support (Proyecto Intramural: Análisis de las interacciones entre instrumentos de promoción de las renovables y procedimientos de mitigación de las emisiones de gases de efecto invernadero). Also to the Beyond 2020 project (Design and impact of a harmonised policy for renewable electricity in Europe). This initiative could be established thanks to the financial and intellectual support offered by the "Intelligent Energy – Europe" (IEE) programme of the European Commission, operated by the Executive Agency for Competitiveness and Innovation. Cristina Peñasco gratefully acknowledges support from the Spanish Ministry of Education and CSIC through the JAE program.

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[21] In turn, the SI approach suggests that, by encouraging a diversity of actors and RES-E advocacy coalitions and the diffusion of immature technologies (which feeds back to innovation), FITs better create the conditions favourable for innovations of all sorts, including radical innovation.

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