Strategic capacity choice in renewable energy technologies under uncertainty

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Abstract

In this paper we discuss optimal renewable energy investment (in wind and solar technology) under uncertainty in a real options approach framework. We consider the combined impact of uncertain production volumes associated with renewable energy power output, policy uncertainty via uncertain remuneration of surplus power and stochastic technological learning, which – in expectation – decreases future costs of solar technology. An energy manager who determines the optimal dynamic investment strategy aims at minimizing expected power procurement costs, which consist of investment costs in renewable energy technologies, expected shortfall costs and expected benefits from selling surplus power to the grid. This results in non-linear costs of power procurement and introduces – similar to classical portfolio theory – a diversification effect between wind and solar technology. Concerning the optimal timing of the investment, we show that a staged investment strategy can reduce expected power procurement costs compared to a lumpy investment strategy. Therefore, if technological innovations in solar technology are expected, an early investment in wind technology and keeping the option to expand the energy park can be the optimal strategic renewable portfolio choice.

Keywords: Feed-in tariff; Renewable energy policy; Renewable energy investment under uncertainty

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1. Introduction

Nowadays energy managers of industrial firms are facing investment decision in power generation facilities in a risky environment, where multiple potential sources of uncertainty arise. On the one hand renewable energy sources (RES) are more sustainable investment choices from an environmental point of view. On the other hand they are capital intensive and exposed to uncertain production volumes, a fact that increases the shortfall risk in the power supply. Therefore, in order to overcome the investment burden in RES, remuneration policies that promote environmentally friendly power technologies are put into place. However, the level of the remuneration is uncertain and is expected to decrease in the future. Therefore, besides facing uncertain production volumes, the energy manager is also exposed to policy uncertainty. In a competitive environment technology manufacturers of RES decrease the prices of the investment goods by active research and development. These technological innovation shocks occur randomly over time and thus the prices of the investment goods are also considered as uncertain. This illustrates that the energy manager is exposed to various sources of uncertainties which increases the complexity of the investment decision.

The scope of the paper is to consider an investment project in RES (wind and solar technology), where the timing of the investment decision is not exogenously fixed but can be chosen by the energy manager. In such a dynamic optimization framework the opportunity to postpone the investment decision to acquire knowledge over time and perform better-informed investment decisions at some time in the future is explicitly included in the model. We analyze the optimal investment decision in RES in a real options framework, where uncertainty associated with the investment opportunity in RES not only arises due to stochastic production volumes of RES, but also due to policy risk (uncertain remuneration of surplus energy that can be delivered to the grid) and investment price risk (uncertain prices of the investment goods). Since all of these uncertain parameters potentially affect the optimal investment decision, we analyze their combined impact.[1]

The bulk of the real options literature focuses on optimal timing of the investment (Dixit and Pindyck, 1994; Trigeorgis et al., 1996). A general result of applications of real options theory to investment models is that the option to defer the investment decision to later periods introduces managerial flexibility, which constitutes potentially significant economic value – the value of the real option. Investment, i.e., the exercise of the real option, is inevitably associated with a loss in flexibility and hence the value of the real option has to be considered in the investment decision. On the one hand, by investing a large amount in RES the firm takes the risk that if ex-post a significant innovation occurs, deferring the investment would have yielded higher profits or lower costs. On the other hand, postponing the investment decision to later periods not only waives potential cashflows but waiting for technological innovations bears the risk of a decreased remuneration policy which reduces expected benefits from selling surplus power. Therefore, in this setup the two sources of uncertainty drive the timing of the investment towards opposite directions, i.e., a high subsidy retraction rate implies that immediate investment is beneficial, whereas uncertain investment prices imply that the investment should be postponed to later periods.

Balcer and Lippman (1984) analyze the optimal timing problem associated with adopting a new technology when innovations are uncertain and show that the current best practice technology will be adopted if the technological lag exceeds a certain threshold. Grenadier and Weiss (1997) consider an option pricing model to evaluate technological innovations, which are assumed to be stochastic in their arrival times as well as their profitability and show that depending on the structure of the innovations the firm might adopt the initial technology, even if potentially more valuable innovations might occur

[1] Policy risk arises due to the uncertain remuneration policy of surplus power, where the level of the FIT is assumed to be subject to multiplicative geometric Brownian shocks and is expected to decrease over time. Investment price risk is due to stochastic technological learning and diffusion which decreases the prices of the investment goods. Therefore, the prices of the investment goods are assumed to be subject to exogenous technological innovation shocks.

in the future.[2] (Sendstad and Chronopoulos, 2020) emphasizes that many studies ignore technological uncertainty. In their paper the authors compare different investment strategies under policy and technological uncertainty. The authors demonstrate that *"[...] the option to invest sequentially in improved technology raises the value of the investment opportunity"* (Sendstad and Chronopoulos, 2020). Boomsma et al. (2012) analyze different support schemes associated with renewable energy output and demonstrate in a use case, that feed-in tariffs encourage earlier investment. Ritzenhofen and Spinler (2016) show that under market-independent, fixed and sufficiently attractive FIT schemes investment projects in RES can be considered as "now-or-never" decisions. Nagy et al. (2021) analyze the effect of subsidy withdrawal on the optimal investment decision under demand uncertainty and show that increasing probability of subsidy withdrawal accelerates the investment, however, at a smaller size. Dalby et al. (2018) propose a real options model that incorporates Bayesian learning, through which the investor updates his or her subjective beliefs on subsidy retraction. The authors demonstrate that *"[...] investors are less likely to invest when the arrival rate of a policy change increases"* (Dalby et al., 2018).

In our investment model, the optimal renewable energy portfolio choice, as well as the optimal timing of the investment have to be determined simultaneously. In several applications of standard real options theory the investment opportunity is assumed to be of a given size. Dangl (1999) was among the first to consider optimal timing and optimal capacity choice in a monopolistic setup simultaneously and shows that with increasing uncertainty the investment decision occurs later in a higher capacity, which highlights the effect of uncertainty in the investment decision. Huisman and Kort (2015) extend this approach by considering a duopoly setting and found that under an entry deterrence policy the first investor overinvests in capacity and that the entrant invests in less capacity.

Generally, the energy manager of a firm has available a bundle of different investment

[2] This is also due to benefits from learning and the resulting easy adaption to technologies arising in the future, which makes them better able to benefit from future innovations.

opportunities in renewable energy technologies (we focus on wind and solar technology). Dixit (1993) evaluates investment opportunities in a general setting under output price uncertainty, when a menu of different projects exist. He argues, that each project should be evaluated separately, and that the optimal solution is the one with the highest option value, see also Décamps et al. (2006). Therefore, the analysis in Dixit (1993) can be considered as the multi-project extension of the single project case discussed in McDonald and Siegel (1986). In our paper – where the energy manager faces the opportunity to invest in wind and solar technology – we adopt a different view and do not consider the investment opportunity in different renewable energy technologies as mutually exclusive, but highlight the diversification effect arising from investment in a mix of different generation technologies.

This portfolio diversification effect is due to the nonlinear pricing relation of the expected power procurement costs which have to be minimized. In the investment decision in renewable energy technologies the energy manager evaluates the total costs of the energy park by including investment costs, expected shortfall costs as well as expected remunerations from surplus power. Each technology included in the renewable energy portfolio exhibits different characteristics of the power output. Therefore, each technology contributes differently to the shortfall risk. By choosing the optimal technology portfolio, the energy manager can shape the risk distribution associated with a shortfall in the power supply (Ondra and Dangl, 2020). Due to the existence of a portfolio diversification effect we do not consider investment opportunities in different RES technologies as mutually exclusive but as interrelated projects, where the synergy gains result from risk shaping associated with the renewable energy portfolio selection.[3]

Due to the fact, that the timing of the investment is not exogenously fixed, the investment model basically allows for different investment strategies: (i) a lumpy investment

[3] Childs et al. (1998) discuss the effect of project interrelationships on investment decisions, where there is a development and implementation stage and projects are considered as complements in the sense that implementing projects together yields synergy gains.

strategy and (ii) a staged investment strategy. In the lumpy investment strategy the budget available for building the energy park is spent at one specific point in time. In contrast to that, it might be valuable to adopt a staged investment strategy and partially invest in a single technology at an early stage of the investment period and invest later in the lagged technology. This investment strategy corresponds to investing a fraction of the budget and to keep the option to expand the energy park alive. Sequential investment is investigated for example in Dixit and Pindyck (1998) and Bar-Ilan and Strange (1998). Applications of sequential investment models in the power sector can be found in Gollier et al. (2005), who discuss an investment model of nuclear power plants and evaluate the flexibility of investing in a sequence of small power plants in contrast to investing in a large scale power plant. The authors demonstrate that despite the presence of economies of scale, the option to invest in a modular project can have a higher value and therefore is able to outperform a lumpy investment strategy. Sendstad and Chronopoulos (2020) consider policy risk and technological uncertainty together and show that a greater likelihood of subsidy retraction lowers the incentive to invest. Moreover, the authors demonstrate how sequential investment facilitates earlier technology adoption compared to lumpy investment.

This paper aims at investigating the energy manager's investment decision in RES (specifically wind and solar technology) associated with uncertain production volumes, which are subsidized by a remuneration policy that is uncertain over time. Moreover, we consider the prices of the investment goods to be subject to random exogenous innovation shocks and therefore also consider technological uncertainty. The energy manager consequently faces the power procurement problem under multiple sources of uncertainty and has to determine whether an investment in RES is beneficial, or if power to cover the firm's demand should be purchased via pre-contracted energy at a fixed exogenous energy price. Therefore, we extend the real options literature in the field of energy economics by highlighting the optimal dynamic investment behavior in renewable energy technologies in the presence of a renewable portfolio diversification effect under policy and investment price uncertainty. The rest of the paper is organized as follows. Section 2 introduces the investment model. Section 3 values the investment decision and Section 4 derives the Bellman equation. Section 5 reports on the numerical results of the use case and Section 6 concludes the paper.

2. The investment model

We consider an energy manager who aims at minimizing the firm's costs of power supply by investing in renewable self generation facilities (wind and solar technology), where the firm is considered to be a price taker. Furthermore, we assume a regulatory framework promoting renewable energy such that surplus power from renewable self generation facilities can be sold to the grid at the level of the feed-in tariff (FIT). In case of a shortfall in the power supply of the energy park (or in the absence of an investment in renewable energy sources (RES)) there exists an outside option, where pre-contracted power can be purchased at a fixed exogenous energy price. Therefore, the expected costs of power supply of the firm are given by: (i) the investment costs in self generation facilities, where the budget that can be used to build the energy park is constrained by I_0, (ii) plus expected costs in case of a shortfall associated with the self generation facilities and (iii) minus expected remunerations for selling surplus power to the grid.

We consider a dynamic investment framework, where the timing of the investment opportunity is not exogeneously fixed but can be chosen by the energy manager. Therefore, the energy manager has to determine simultaneously: (i) optimally installed capacities in wind and solar technology subject to a budget constraint and (ii) the optimal timing of the investment. Moreover, the energy manager faces the decision in an uncertain environment, i.e., under multiple sources of uncertainties which potentially affect the optimal investment decision. Generally, the major sources of uncertainty associated with an investment in RES are: (i) uncertainty in the renewable energy output (uncertain production volumes) (ii) policy risk (uncertain levels of the remuneration of surplus power from renewable energy technologies) and (iii) technology risk (uncertain prices of the investment goods).

One of the most important aspects discussed in this paper arises from the fact, that power output from renewable energy technologies is uncertain. Wind and solar technology can be associated with different distributions of the power output per unit of installed capacity. A special characteristic of the power output distribution associated with wind technology is that due to the existence of a threshold wind speed below and above which no power output can be generated, the wind distribution exhibits the characteristics of a heavy-tailed distribution. Therefore, investment in wind technology comes along with a higher tail-risk of a power shortfall compared to an investment in solar technology. However, by choosing optimally installed capacities the energy manager is able to shape the underlying risk distribution of a shortfall in the power supply. Hence, by diversifying the energy portfolio the energy manager can lower the power shortfall risk which introduces the renewable energy portfolio effect. The histograms associated with the distribution of the power output are illustrated for a numerical example in Fig. 1 for the case of (a) a single energy investment in wind technology, (b) a single energy investment in solar technology and (c) a diversified energy portfolio with equal capital shares invested in wind and solar technology.

In classical portfolio theory, the risk diversification effect is due to maximizing expected utility of a risk-averse investor. In our approach, we don't maximize expected utility of wealth but minimize total expected power procurement costs, i.e., we consider a risk-neutral energy manager. In this scenario, risk diversification is formally introduced via the underlying non-linear pricing relation of expected surplus and expected shortfall costs. For the sake of tractability we consider 3 different types of renewable energy portfolios that reflect the characteristic features of the underlying shortfall risk distribution: (i) the

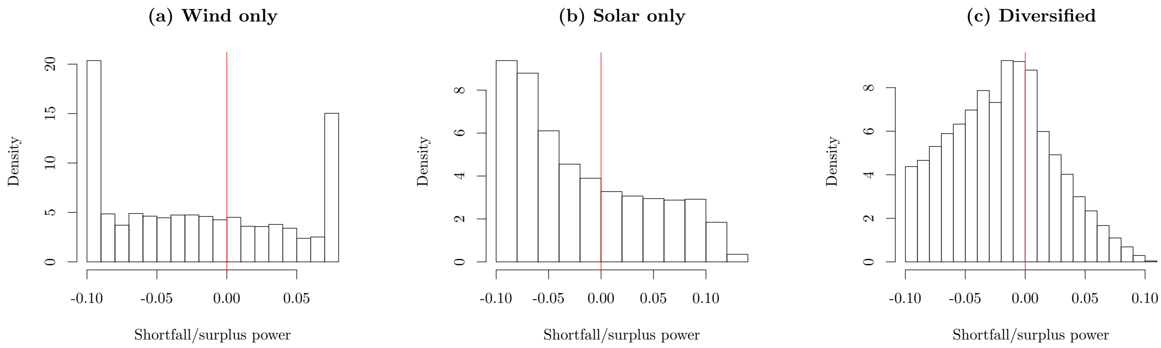

Figure 1: These figures show the empirical distribution of the shortfall/surplus power in case of: (a) single energy investment in wind technology, (b) single energy investment in solar technology and (c) a diversified energy portfolio with equal capital shares in wind and solar technology. The red line indicates demand and supply equality and separates the regions where a shortfall in the power supply occurs (left from the red line) from the region of surplus power (right from red line).

single energy investment in wind technology, (ii) the single energy investment in solar technology and (iii) a diversified portfolio consisting of equal capital shares in wind and solar technology. Of course, the portfolio consisting of equal shares of both technologies might not be the optimally diversified energy portfolio whenever the full range of possible capacity choices is considered, however, it demonstrates the characteristic feature of portfolio diversification and allows us to study conditions under which the diversified portfolio dominates the pure choices (i) and (ii).

To highlight the benefits of the portfolio diversification effect we consider an illustrative example. More specifically, we investigate the static problem (i.e., the "now-or-never" decision problem) where the exogenous parameters of the pre-contracted energy price and the prices of the investment goods are assumed to be deterministic, i.e., perfectly known. To do so, we determine the optimal portfolio choice as a function of the level of the feed-in tariff ξ_+ and the price for solar technology p_s in two scenarios. First, where the opportunity to invest either in wind or in solar exists (i.e., a diversified portfolio is not allowed). And second, where the opportunity to invest in wind, solar or a diversified portfolio exists. The optimal portfolio decision associated with the static problem is

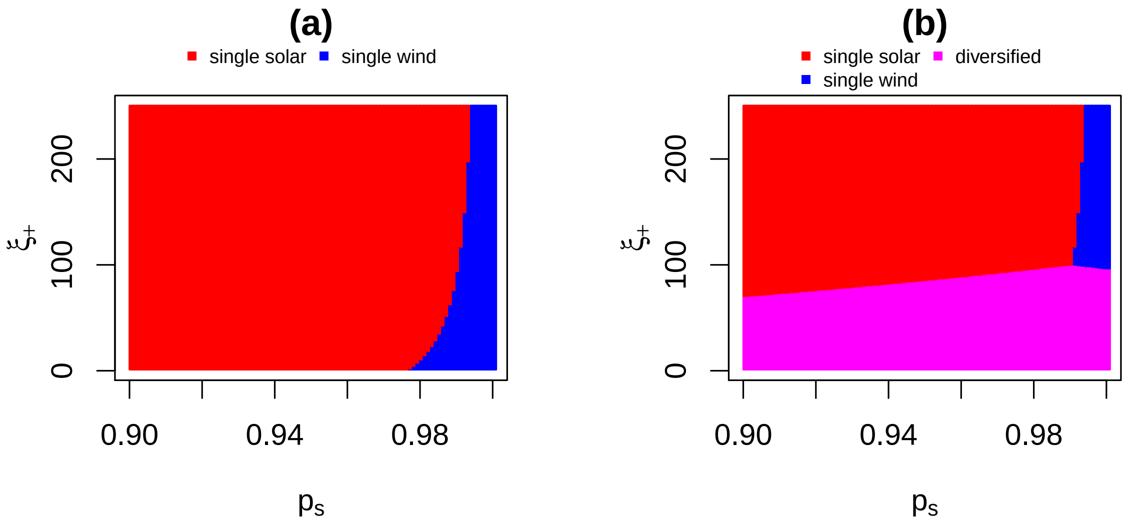

Figure 2: This figure illustrates the optimal renewable energy portfolio choice in a static framework (a) in case a diversified portfolio is not included and (b) in case a diversified portfolio is included. The price of wind technology is assumed to be $p_w = 1.4M€/MW$, the pre-contracted energy price is $\xi_- = 100€/MWh$ and the budget $I_0 = 0.25M€$.

illustrated in Fig. 2, where the type of renewable energy portfolio for different levels of the FIT and prices for solar technology (i.e., different levels of technological innovations) is plotted. Fig. 2(a) shows the optimal portfolio choice, whenever only the pure investment choices are considered, i.e., a diversified portfolio is not in the scope of the decision maker. Fig. 2(b) illustrates the situation when the diversified renewable energy portfolio is considered as a feasible investment opportunity. Despite the fact that the average power output per unit of installed capacity in wind technology is higher than the average power output per unit of installed capacity in solar technology,[4] the optimal investment is not necessarily to invest in wind technology, but depends on the level of the exogenous parameters. The optimal strategy might even be to reject investment in RES and purchase total power to cover the demand from outside. This occurs e.g., in the absence of a remuneration policy (or whenever the level of the FIT is exceptionally low) and when

[4]The average hourly power output per monetary unit of the investment are $0.317MW/M€$ for wind technology and $0.314MW/M€$ for solar technology, when daytime data are used.

the costs of purchasing total power to cover the demand are lower than the capital expenditures associated with the RES investment. However, we consider a situation where the investment in renewable energy technologies is affordable. Fig. 2 generally demonstrates that for lower levels of the FIT the cost-minimal choice is to invest in the diversified energy portfolio. This portfolio choice can be explained by taking into account the different shortfall/surplus power distributions of the underlying energy assets. A low level of FIT weakens the disadvantage of solar energy in terms of lower average energy output per unit of invested capital and puts more emphasis on avoiding large power shortages (the advantage of solar power as discussed earlier). In the case of very high levels of FIT, the optimal decision is in favor of a technology that maximizes energy output, i.e., wind energy. Higher risk of shortfalls associated with wind technology is less critical in this case. A diversified energy portfolio can balance out the expected costs in case of a shortfall in the power supply and the expected remunerations for selling surplus power to the grid.

This example illustrates that due to the stochastic production volumes of wind and solar technology, the investment decision in the optimal generation mix (or investment in RES at all) highly depends on the level of the exogenous parameters, i.e., the level of the FIT and the energy price, even in case they are assumed to be deterministic. Of course, the complexity of the investment problem increases when the exogenous parameters are assumed to be subject to uncertainty that also impact the investment decision, which is the scope of this paper.

Concerning policy risk, we expect the level of the FIT to undergo multiplicative geometric Brownian shocks. Since support schemes for RES are gradually withdrawn, the drift of the geometric Brownian motion is taken to be negative. At the time the investment in wind and solar technology is made, the current level of the FIT is locked in and used to price surplus power that is sold to the grid over the expected useful lifetime of the energy park. Therefore, the current level of the FIT has also an impact on the optimal generation mix, since the current level of the FIT enters as a parameter in the non-linear pricing relation affecting the optimal renewable energy portfolio. A detailed description of the stochastic process associated with the remuneration policy can be found in Appendix A.

Due to technology diffusion and technological learning, the prices of the investment goods for renewable energies are subject to random exogenous innovation shocks. Therefore, the prices of the investment goods are uncertain and are expected to decrease. Since renewable energy investments are characterized by high capital costs, uncertainty over the capital expenditures is a major driver of investment risk. Generally, the price of both technologies can be considered as subject to uncertainty. However, we assume that major technological process and product innovations occur only for solar technology. In contrast to that, only minor technological innovations are expected in wind technology and are considered as negligible.[5] Therefore, the exogenous price for wind technology is assumed to be fixed. A detailed description of the stochastic process associated with the stochastic innovations in solar technology can be found in Appendix A.

2.1. Timing of the investment

Let us illustrate the effects of investment timing in a simplified one step-model before turning to the fully dynamic model. In the one-step model only at two points in time (today t_0 and the future state t_1) an investment in RES can be made. Since the timing of the investment in wind and solar technology is not exogenously fixed, the energy manager has the option to postpone the investment decision today at t_0 to the future t_1 and to receive new information about the evolution of the uncertain parameters, in order to re-evaluate the investment opportunity. During this time period $[t_0, t_1]$ the energy manager has to secure the electricity supply of the firm and purchases power to cover the demand.

[5] This represents a model limitation which, however, can methodologically be treated in the same way as uncertainty associated with solar technology.

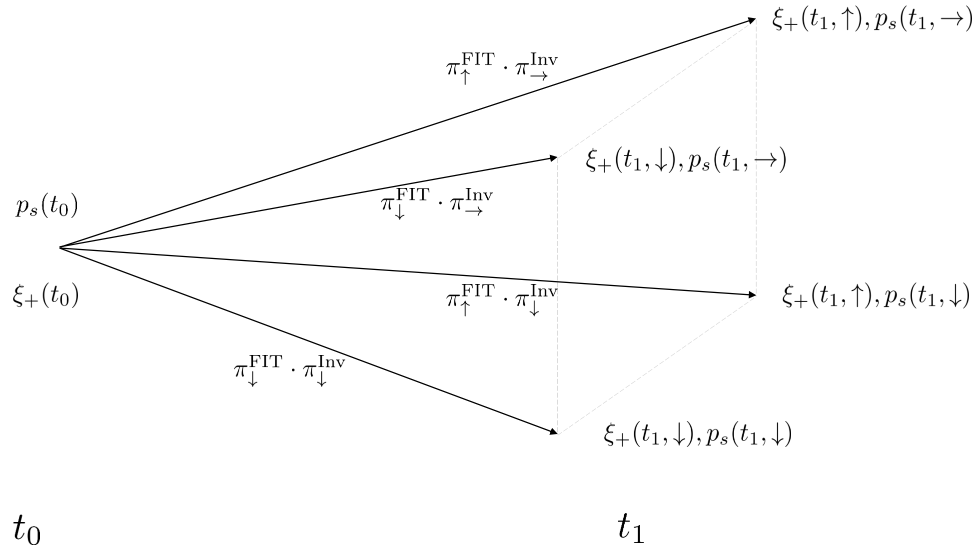

Figure 3: This figure represents the joint grid of the states of nature in the one-step problem with the 4 possible states arising in the future.

However, including the possibility of deferring the investment decision to the future state t_1 generally introduces managerial flexibility and therefore creates a value which has to be considered in the investment decision.

Since we consider the combined impact of the multiple sources of uncertainty, we solve for the optimal investment decision on the joint grid representing uncertainty of the states of nature, i.e., the level of the remuneration policy and the stochastic price per unit of solar technology installed, which is illustrated in Fig. 3. These two dynamic sources of uncertainty, i.e., policy uncertainty and uncertainty over the investment price of solar technology, drive the optimal timing of the investment towards different directions. Due to the expected decrease of the level of the FIT, the energy manager tends to invest in RES earlier, since the likelihood of the remuneration policy to offer a higher compensation for selling surplus power to the grid is also higher. In contrast to policy uncertainty, due to the expected decreasing price of solar technology the energy manager tends to invest later in order to reduce the expected capital expenditures of the energy investment. The optimal investment decision therefore has to balance the expected trade-off associated with investing in RES at t_0 or investing in RES at t_1.

The energy manager not only has the opportunity to adopt a lumpy investment strategy or to postpone the investment decision as such to the future state t_1 (which includes the opportunities to invest in wind technology/solar technology/a diversified energy portfolio at t_0 or t_1, or to not invest at all), but also to follow a staged investment strategy. In the staged investment strategy, the energy manager introduces additional flexibility in terms of including the possibility to invest partially (we assume – as a simplifying assumption – that in staged investment the investment budget is split in two equally sized portions) in wind technology at the first stage decision at t_0 and to keep the option to expand in solar/wind technology in the second stage decision at t_1 alive.[6] Therefore, following this strategy, the energy manager has the option to choose the timing of the partial investments in wind and / or solar technology independent of each other. For the energy manager who follows a staged investment strategy, the current level of the FIT is locked in at time t_0 the early investment in wind technology is made. However, if he or she decides to expand this energy portfolio in the future t_1, the new level of the FIT at t_1 is assigned from t_1 onwards to price surplus power and therefore overwrites the old level of the FIT at t_0.[7] Hence, the benefit associated with a staged investment strategy is that the energy manager can immediately alter cash-flows that arise from purchasing outside power to cover the demand. The trade-off is that the energy manager sacrifices a part of the flexibility options, since the single solar energy portfolio – which is valuable in case of a low price of solar technology – is not attainable due to the early investment in wind technology. For completeness we remark that also the investment strategy to partially

[6] This also includes to reject in expanding the energy park at t_1.

[7] This assumption is done for reasons of tractability. If the level of the FIT for the early investment and the level of the FIT for later investment is fixed independently, the FIT fixed for the early invested capacity serves as a state variable for the second stage investment decision, increasing the dimensionality of the investment problem. Since the insight from our analysis is not driven by these subtleties, we avoid the overly complex model structure. It would also be possible to fix the level of the FIT with the early investment in wind technology for all times. In this case, however, we do not allow for small first stage investments.

invest in solar technology at t_0 and to keep the option to invest in wind/solar technology at t_1 alive, exists. However, technological innovations are expected only in solar technology and due to the characteristic features of the wind distribution, an investment in wind technology is more valuable in this case. Therefore, an an early partial investment in solar technology and keeping the option to expand the energy park is not considered as optimal and is not in the scope of the model.

In order to simplify the problem, we assume an effective infinite lifetime of the energy park. This can be made plausible by assuming that the energy manager re-invests in the same energy portfolio after the expected useful lifetime of the energy park.[8] The underlying assumptions in the investment model are summarized in Tab. 1.

3. Valuing the renewable energy investment

In order to determine the value of the option (in terms of the total costs of the firm's power supply) of investing in a renewable energy park (with different renewable energy portfolio options), we have to determine expected costs of every energy portfolio in every possible state of the future (see Fig. 3). Generally, in this dynamic investment problem at two points in time a decision has to be made: The first stage decision at t_0 and the second stage decision at t_1. We assume, that the firm's power demand d is deterministic and that the budget that can be used for the energy investment is given by I_0. The costs of purchasing one unit of pre-contracted power in case of a power shortfall is exogenously fixed and denoted by ξ_-. Since the power output per unit of installed capacity in wind technology P_w and the power output per unit of installed capacity in solar technology P_s are stochastic, the energy manager takes into account the expected shortfall costs (where

[8] Formally, we introduce the re-investment in the energy assets by introducing an effective interest rate r', s.t. the present value associated with the finite investment opportunity at the interest rate r is the same as the present value of the infinite investment at the effective rate r'. Therefore, generally $r' \geq r$ holds true. This represents a model limitation since we don't consider the flexibility to re-balance the energy portfolio after the finite lifetime but continue to re-invest in the same energy portfolio.

Table 1: This table summarizes the model assumptions.

Variable	Assumptions
FIT ξ_+ [€$/MWh$]	(i) GBM with negative drift $\mu < 0$ (ii) At time of investment the current level of FIT is locked in
Price per unit of solar technology p_s [€$/MWh\, inst.$]	(i) Number of innovations per year Poisson distributed (ii) Fixed size of innovation α
Energy price ξ_- [€$/MWh$]	Fixed price per MWh of shortfall in the power supply
Demand d $[MW]$	Deterministic demand over efficient lifetime of the energy park
Budget I_0 [€]	Max. amount that can be invested in RES. We impose $I_0 \leq 2p_w d$, ensuring that with a staged investment no surplus power can be sold.
Timing of the investment	Only at two points in time t_0, t_1 an investment in RES can be made
Renewable energy portfolio $\mathbf{x} = (x_w, x_s)$ $[MW]$	We consider 3 different energy portfolios: (a) single energy investment wind $x_w = I_0/p_w$, $x_s = 0$ (b) single energy investment solar $x_s = I_0/p_s$, $x_w = 0$ (c) diversified energy portfolio $x_w = I_0/(2p_w)$, $x_w = I_0/(2p_w)$
Investment strategy	(i) *Lumpy investment*: invest in portfolios (a)-(c) either at t_0 or at t_1 (ii) *Staged investment:* invest in wind capacity $x_w = I_0/(2p_w)$ at t_0 and keep the option to expand $x_s = I_0/(2p_s)$ in solar technology at t_1 alive

balancing energy has to be purchased) and the expected remunerations for selling surplus power to the grid. For a given level of the FIT ξ_+, the current price of solar technology p_s (which is different in the future states since they are subject to uncertainty) and the price of wind technology p_w (which is fixed), the expected costs of power procurement are given by: (i) the investment costs I to build the energy park, minus (ii) expected remunerations from selling surplus power to the grid and plus (iii) purchasing pre-contracted power in case of a shortfall in the power supply. The investment costs (i) have to be paid instantaneously and are considered as sunk costs, whereas the cash flows associated with the expected remunerations and expected shortfall costs (ii) and (iii) arise continuously during the effective lifetime of the energy park and therefore have to be discounted.

We describe the evolution of the states of nature, i.e., the level of the FIT ξ_+ and the technological innovation α via a set of trees. Each tree characterizes the state of the investment, i.e., investment decisions which are already fixed. All possible energy portfolios considered in this investment model are shown in Fig. 4, i.e.: no investment in RES (A), staged investment in wind technology (B), the diversified energy portfolio (C), the single energy investment in wind technology (D) and the single energy investment in solar technology (E). In case of a RES investment that exhausts the budget (i.e., the trees C,D and E), the corresponding investment opportunities can be immediately valued since there are no further flexibility options left and nodes in these trees represent stopping at absorbing nodes. Since we assume irreversibility of the investment, we do not consider the opportunity of selling the power generation facilities. Therefore, undoing the investment and returning to the tree A representing no investment in RES is not in the scope of this model. In contrast to trees C, D, and E where the investment decision is already fixed, trees A and B represent states with investment flexibility.

Given that currently (at a given time t) no investment (tree A) or a staged investment (tree B) was made, the budget left (i.e., I_0 or $I_0/2$) can be used to expand the energy park in the future. Fig. 4 indicates these flexibility options associated with the investment strategy via arrows. Investing in a renewable energy technology and thereby expanding the current renewable energy portfolio corresponds to a jump between the trees A-E. Investment at $t+1$ can be done in the same way as at t, leading to a jump to the corresponding node in the tree that represents the investment decision (the state of nature is preserved). The costs associated with the jump between the trees corresponds to the investment $I \in \{I_0/2, I_0\}$ necessary to obtain the target renewable energy portfolio. In case the energy manager has not invested in RES (black arrows starting at tree A) he or she can decide to invest half the budget $I_0/2$ in wind technology (tree B) and keep the option to expand the energy park alive (stay in tree A) or invest the full budget I_0 in: a diversified portfolio (tree C), an undiversified portfolio in wind technology (tree D) or an undiversified portfolio in solar technology (tree E). The energy manager can always choose to postpone the investment decision, continue the current energy portfolio and therefore also to remain within the current tree, at least for the coming time step (thereby keeping the flexibility alive and reconsidering an investment after observing the shocks to the stochastic state variables p_s and ξ_+). In case of an early investment in wind technology (tree B), the energy manager has the option to expand in wind or solar technology (tree C or tree D). However, due to irreversibility of the investment the portfolio representing a single energy investment in solar technology cannot be obtained in this case.

3.1. Costs and cash flows of the investment

Let us now discuss the costs and expected cash flows associated with an investment in RES in more detail. The decision to invest in RES corresponds to a jump between the trees in Fig. 4 and generates sunk costs of either $I_0/2$ or I_0, depending on the type of the investment strategy.[9] However, the actual capacity installed in solar technology depends on the current level of the investment price of solar technology $x_s = I/p_s$ and therefore varies according to the possible states of nature in the future. In contrast to that, the price of wind technology is constant and therefore the installed capacity in wind technology is either $x_w = I_0/p_w$ or $x_w = I_0/(2p_w)$, for all possible states of nature that occur in the future. This is of special importance, since the value of the investment depends on the installed capacities in wind and solar technology, respectively. We assume that the hourly stochastic power output per capacity installed in wind P_w and solar technology P_s to be iid distributed. Therefore, if the capacity installed in wind technology is x_w, the capacity installed in solar technology is x_s and the level of the FIT at the time of the last

[9]Investing half of the budget available $I_0/2$ corresponds to a staged investment strategy (black arrows in Fig. 4) and investing the total budget available I_0 corresponds to a lumpy investment strategy (red arrows in Fig. 4).

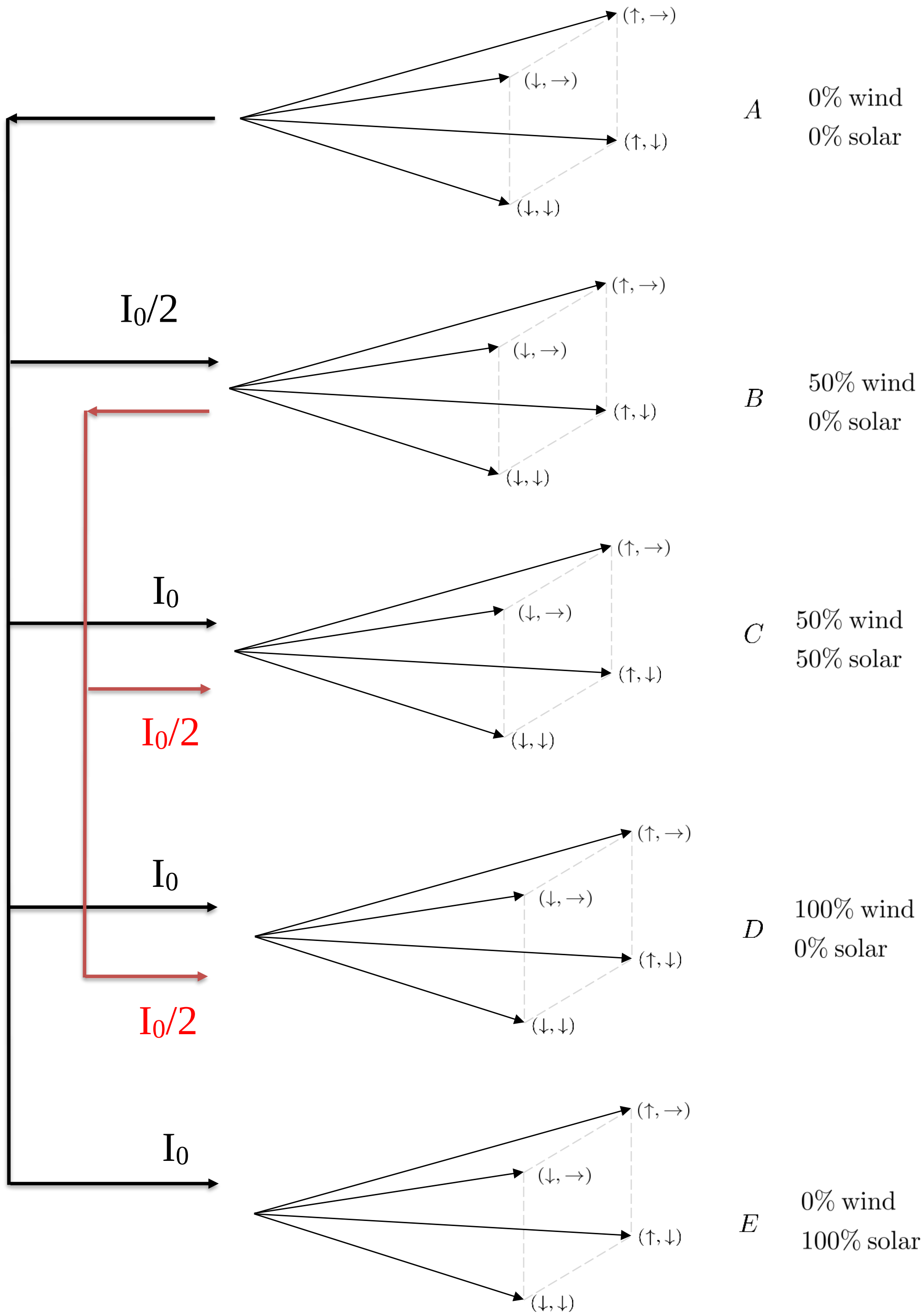

Figure 4: This figure illustrates all possible energy portfolios of wind and solar technology considered. The arrows illustrate the flexibility options (black: flexibility options when no investment has occured, red: flexibility options when a partial investment in wind technology has occured).

investment in RES is ξ_+,[10] the value of the investment is given by

$$V_I(x_w, x_s, \xi_+) = \delta(\underbrace{-\xi_+ \mathbb{E}[\max\{x_w P_w + x_s P_s - d; 0\}]}_{\substack{\text{expected remunerations from selling} \\ \text{surplus power to the grid}}} + \underbrace{\xi_- \mathbb{E}[\max\{d - x_w P_w - x_s P_s; 0\}]}_{\text{expected shortfall costs}}), \tag{1}$$

where δ denotes the present value factor. Therefore, the value associated to the definite decision of rejecting an investment in RES once and for all and, thus, purchasing total power to cover demand in the future is given by $V_I(0, 0, \xi_+) = \xi_- d\delta$ and is independent of the level of the FIT. However, if the energy manager decides to postpone the investment by Δt and previously an early investment in RES with x_w capacity installed in wind technology (tree B) occurred, where the level of the FIT at the time of the investment in wind technology was ξ_+, the cash flow arising during the period Δt due to deferring the investment is simply given by

$$c(x_w, \xi_+) = \Delta t(\underbrace{-\xi_+ \mathbb{E}[\max\{x_w P_w - d; 0\}]}_{\substack{\text{expected remunerations from selling} \\ \text{surplus power to the grid}}} + \underbrace{\xi_- \mathbb{E}[\max\{d - x_w P_w; 0\}]}_{\text{expected shortfall costs}}). \tag{2}$$

If no investment was made in RES the cash flow arising due to deferring the investment is given by $c(0, \xi_+) = \Delta t \xi_- d$ and corresponds to purchasing total power to cover the firm's electricity demand during the time span Δt via pre-contracted energy.

Note that in (2) the cash-flow depends also on the current level of the FIT that is locked-in. However, we impose the constraint $I_0 \leq 2p_w d$ on the investment budget. This guarantees that in case of a staged investment the first stage investment in wind technology (with investment costs $I_0/2$) installs a capacity which is sufficiently low such that no surplus power can be generated, i.e., $\Pr\{x_w P_w - d \leq 0\} = 1$ holds true. In this case the cash-flow is independent of the level of the FIT but depends only on installed

[10] The level of the FIT at the time a consecutive investment in RES overwrites the previously locked-in FIT.

capacities in wind technology x_w. This is due to the fact that in this case $\mathbb{E}[\max\{x_w P_w - d; 0\}] = 0$ and (2) becomes

$$c(x_w) = \Delta t \xi_- \mathbb{E}[\max\{d - x_w P_w; 0\}]. \tag{3}$$

We impose this constraint to avoid the level of the FIT of the first stage investment as a state variable in the investment problem of the second stage. Since the power output per installed capacity of wind technology is bounded from above $P_w \leq 1$ and the capacity in case of a partial investment in wind technology is $x_w = I_0/(2p_w)$, we have that $x_w P_w \leq d$ holds true with certainty, given the budget is constrained by $I_0 \leq 2p_w d$.

4. Value of the option to invest

We determine the value of the investment opportunity in RES by using dynamic programming methods based on Bellman's Principle of Optimality. $V_t(\xi_+, p_s)$ denotes the value of the investment opportunity in terms of the minimum attainable present value of the power procurement costs at time t, given that the current state of nature is (ξ_+, p_s). The terminal value at the end of the decision horizon T is determined by investing in the energy portfolio that refers to the minimum expected power procurement costs under given flexibility, or refrain from investment at all. Due to different flexibility options, the value of the terminal nodes of the trees A and B are different. Let us denote the value of the investment at the final decision nodes of: (i) the diversified portfolio (tree C), (ii) the single wind technology portfolio (tree D) and (iii) the single solar technology portfolio (tree E) by:

$$
\begin{aligned}
V^C(p_s,\xi_+) &= V_I\left(\frac{I_0}{2p_w},\frac{I_0}{2p_s},\xi_+\right)\\
V^D(p_s,\xi_+) &= V_I\left(\frac{I_0}{p_w},0,\xi_+\right)\\
V^E(p_s,\xi_+) &= V_I\left(0,\frac{I_0}{p_s},\xi_+\right).
\end{aligned}
\tag{4}
$$

Furthermore, the value of rejecting to invest in RES and purchasing total power to cover the demand is given by $V^{Ni}(p_s,\xi_+) = V_I\,(0,0,\xi_+)$ and the value to abandon the option to expand, given that an early investment in wind technology has occurred is given by $V^{Ne}(p_s,\xi_+) = V_I\,(I_0/(2p_w),0,\xi_+)$.

In case of a staged investment strategy, represented by tree B, the only investment opportunities at the final nodes are to: (i) invest $I_0/2$ to obtain the single wind technology portfolio (tree D) (ii) invest $I_0/2$ in solar technology to obtain the diversified technology portfolio (tree C) or (iii) abandon the option to expand the energy park (stay within tree B). Therefore, at the final nodes we have

$$
V_T^B(p_s,\xi_+) = \min\left\{\frac{I_0}{2}+V^D(p_s,\xi_+);\,\frac{I_0}{2}+V^C(p_s,\xi_+);\,V^{Ne}(p_s,\xi_+)\right\}.
\tag{5}
$$

In case of no previous investment in renewable energy technologies, represented by tree A, the investment opportunities are to: (i) invest I_0 in the single wind technology portfolio (tree D) (ii) invest I_0 in the diversified technology portfolio (tree C), (iii) invest I_0 in the single solar technology portfolio (tree E), (iv) to abandon the option to invest in RES or (v) invest $I_0/2$ in wind technology (tree B). Therefore, at the final nodes we have

$$
\begin{aligned}
V_T^A(p_s,\xi_+) = \min\Big\{& I_0+V^D(p_s,\xi_+);\,I_0+V^C(p_s,\xi_+);\,I_0+V^E(p_s,\xi_+);\\
& V^{Ni}(p_s,\xi_+);\,\frac{I_0}{2}+V_T^B(p_s,\xi_+)\Big\}.
\end{aligned}
\tag{6}
$$

Having determined the value of the investment opportunity at the final nodes, we iterate backwards in time to determine the value of the investment opportunity at each preceding node. Therefore, assume that we have determined the value of the trees in each possible state of nature at time t. Since the value of the investment in RES depends on the value of expanding the energy park, given that an early investment in wind technology has already occurred (i.e., it is possible to jump from tree A to tree B), we first have to solve for the value of tree B.

Concerning the tree B, at each point in time $t-1$ the energy manager has the opportunity to: (i) invest $I_0/2$ to obtain the single wind technology portfolio (tree D) (ii) invest $I_0/2$ in solar technology to obtain the diversified technology portfolio (tree C) or (iii) defer the investment decision, obtain the cash flow and stay within tree B. Therefore, the value of the option to expand the energy park, given by the Bellman equation is

$$V_{t-1}^{B}(p_s,\xi_+) = \min\left\{\frac{I_0}{2} + V^D(p_s,\xi_+); \frac{I_0}{2} + V^C(p_s,\xi_+); c\left(\frac{I_0}{2p_w}\right) + e^{-r\Delta t}\mathbb{E}_{t-1}[V_t^B(p_s,\xi_+)]\right\}, \tag{7}$$

where

$$\mathbb{E}_{t-1}[V_t^B(p_s,\xi_+)] = \sum_{p_s',\xi_+'} p(p_s',\xi_+'|p_s,\xi_+)V_t^B(p_s',\xi_+') \tag{8}$$

and $p(p_s',\xi_+'|p_s,\xi_+)$ denotes the conditional probability to obtain the state of nature (p_s',ξ_+') in the next time step, given the current state of nature is (p_s,ξ_+).

Concerning the tree A representing the full flexibility, in every preceding node at time $t-1$ the energy manager has the opportunity to: (i) invest I_0 in the single wind technology portfolio (tree D) (ii) invest I_0 in the diversified technology portfolio (tree C), (iii) invest I_0 in the single solar technology portfolio (tree E), (iv) invest $I_0/2$ in wind technology and keep the option to expand the energy park alive (tree B) or (v) defer the investment decision (stay in tree A). Therefore, the Bellman equation derives to

$$V_{t-1}^A(p_s, \xi_+) = \min\Big\{ I_0 + V^D(p_s, \xi_+); I_0 + V^C(p_s, \xi_+); I_0 + V^E(p_s, \xi_+); \\ \frac{I_0}{2} + V_{t-1}^B(p_s, \xi_+); c(0) + e^{-r\Delta t}\mathbb{E}_{t-1}[V_t^A(p_s, \xi_+)] \Big\}, \tag{9}$$

where the expected value of the investment in the next period is

$$\mathbb{E}_{t-1}[V_t^A(p_s, \xi_+)] = \sum_{p_s', \xi_+'} p(p_s', \xi_+' | p_s, \xi_+) V_t^A(p_s', \xi_+'). \tag{10}$$

This procedure can be followed iteratively to determine the current value of the investment opportunity in RES at $t = 0$, which is denoted by $V = V_0^A$.

5. Numerical results

We demonstrate the model in a use case, where we sample from real-world wind speed and solar irradiance data for a typical location in Central Europe where hourly data of the solar irradiance and the wind speed are available in the daytime.[11] The prices of the investment goods are given by $p_w = 1.4M€/MW$ for wind technology and at the starting time $t = 0$ $p_s = 1M€/MW$ for solar technology. The market rate is assumed to be $r = 1\%$[12]. All the results presented in this section are obtained for the one-step problem.

In order to analyze the sensitivity of the value of the option to invest in RES with respect to a change in the policy of the FIT and the innovations in solar technology, we perform "what-if" analysis by simulating different parameters of the underlying stochastic processes, which is illustrated in Fig. 5. Fig. 5(a) shows the value of the RES investment as a function of the parameters μ and σ of the stochastic process associated with the

[11] From 10:00-18:00.
[12] Which gives an effective interest rate which considers re-investment of $r \approx 5\%$.

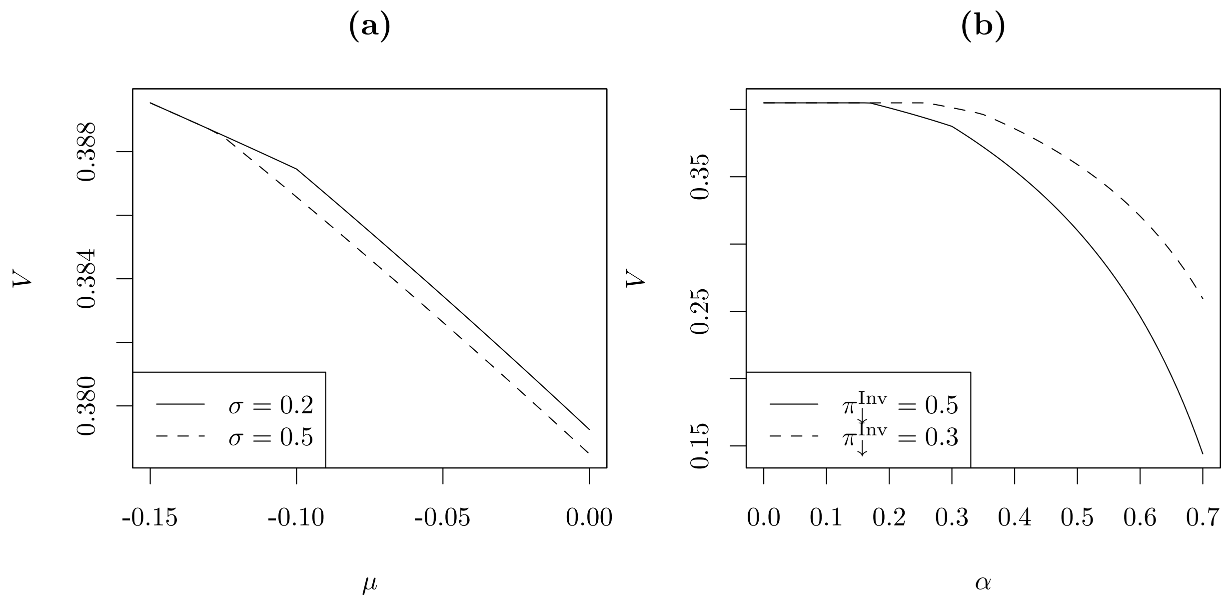

Figure 5: Figure (a) shows the value of the option to invest in RES as a function of the drift rate μ for two levels of σ ($\alpha = 0.3$, $\pi_{\downarrow}^{\mathrm{Inv}} = 0.5$). Figure (b) shows the value of the option as a function of the level of the innovation in solar technology for two levels of the probability to obtain an innovation in the next period ($\mu = -0.1$, $\sigma = 0.2$).

remuneration policy, for fixed values of the parameters describing stochastic innovations in solar technology. Since the drift is assumed to be negative $\mu < 0$, the absolute value $|\mu|$ indicates the long-term subsidy retraction rate.[13] We observe expected power purchasing costs to be decreasing with lower values of the subsidy retraction rates. To highlight the effect of the uncertainty associated with the withdrawal of the remuneration policy, Fig. 5(a) shows the value of the investment opportunity in RES for two scenarios of the uncertainty σ associated with the remuneration policy. In this context, a higher uncertainty leads to lower expected power procurement costs as increasing uncertainty in the retraction of the FIT refers to a higher probability that the FIT will increase in the future.

[13]Due to the fact that the energy manager expects an exponential decrease of the level of the FIT $\mathbb{E}[\xi_{+t}] = \xi_{+0}e^{-|\mu|t}$, higher values of $|\mu|$ refer to a scenario where the remuneration is withdrawn more quickly.

Fig. 5(b) illustrates the value of the investment option in RES as a function of the parameters of the stochastic process associated with the stochastic innovations in solar technology α and $\pi_{\downarrow}^{\mathrm{Inv}}$, for fixed values of the parameters describing the stochastic level of the FIT. Obviously, the expected total power procurement costs are decreasing with increasing size of the expected innovation in solar technology α. Whenever the expected technological innovations in the future are below a threshold value, the optimal investment strategy is to invest immediately and obtain the benefits that arise from a potentially higher remuneration of excess power (therefore, for small values of α, the value of the option is constant, i.e., independent of α). Furthermore, we observe that the value of the option is more sensitive to an increase in the level of exogenous innovations in solar technology α compared to a decrease in the subsidy retraction rate. This highlights the impact of technological learning on the optimal investment strategy. To analyze the impact of uncertainty associated with the technological jumps, Fig. 5(b) shows the value of the investment opportunity in RES for two scenarios of the probability $\pi_{\downarrow}^{\mathrm{Inv}}$ to obtain a technological innovation in the future. When the probability to obtain a technological innovation is higher, the expected power procurement costs are decreasing.

5.1. Strategic investment choice

We now discuss the optimal investment strategy in more detail. To do so, we illustrate the optimal investment strategy at $t = 0$ as a function of the current level of the FIT ξ_+ and the current price of solar technology p_s, for different scenarios of the exogenous energy price $\xi_- \in \{50€/MWh, 100€/MWh, 200€/MWh\}$ and the parameters of the stochastic processes $\pi_{\downarrow}^{\mathrm{Inv}} = 0.5$, $\alpha \in \{0.1, 0.3\}$ (minor or major technological innovations in solar technology), $\mu = -0.1$ and $\sigma = 0.2$.

Fig. 6 illustrates the optimal investment strategy for the case of low technological innovations in solar technology $\alpha = 0.1$ and for different scenarios of the price of pre-contracted power: the low-range (Fig. 6(a)), mid-range (Fig. 6(b)) and high-range (Fig.

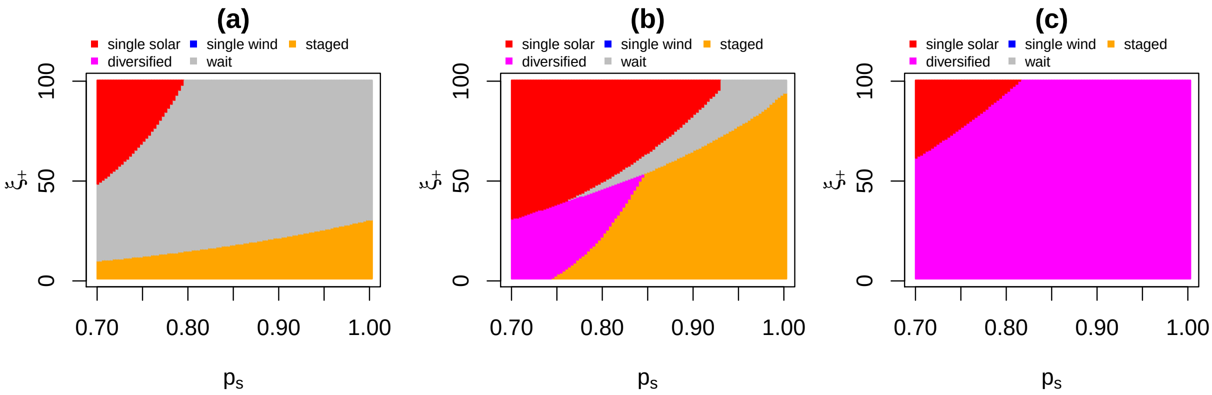

Figure 6: This plot shows the optimal investment strategy in RES for the scenario where minor innovations in solar technology are expected $\alpha = 0.1$ and: the (a) low $\xi_- = 50€/MWh$, (b) mid $\xi_- = 100€/MWh$ and (c) high energy price regime $\xi_- = 200€/MWh$.

6(c)) energy price regime. In the case of a low energy price (Fig. 6(a)), we observe that both a lumpy and a staged investment strategy can be the optimal investment choice, depending on the current level of the FIT and the current price for solar technology. Generally we observe for the low energy price regime, that whenever the level of the FIT is sufficiently high the optimal strategy is to invest in RES immediately and obtain the benefits from selling surplus power to the grid due to the high level of the remuneration policy. However, for the majority of scenarios considered, deferring the investment decision is the dominant strategy. Therefore, low energy prices trigger early investment only on rare occasions and cause the energy manager to adopt a "wait-and-see" attitude. With increasing price of pre-contracted energy (Fig. 6(b) and (c)), the energy manager tries to avoid purchasing expensive power to cover the demand and speeds up investment in self-generation facilities. More specifically, higher energy prices emphasize the importance of avoiding power shortfall and thus, the optimal decision is investing early in a solar dominated production.

This situation is quite different, when there are major innovations in solar technology expected $\alpha = 0.3$ (Fig. 7). In this scenario, keeping the flexibility to invest in shares of

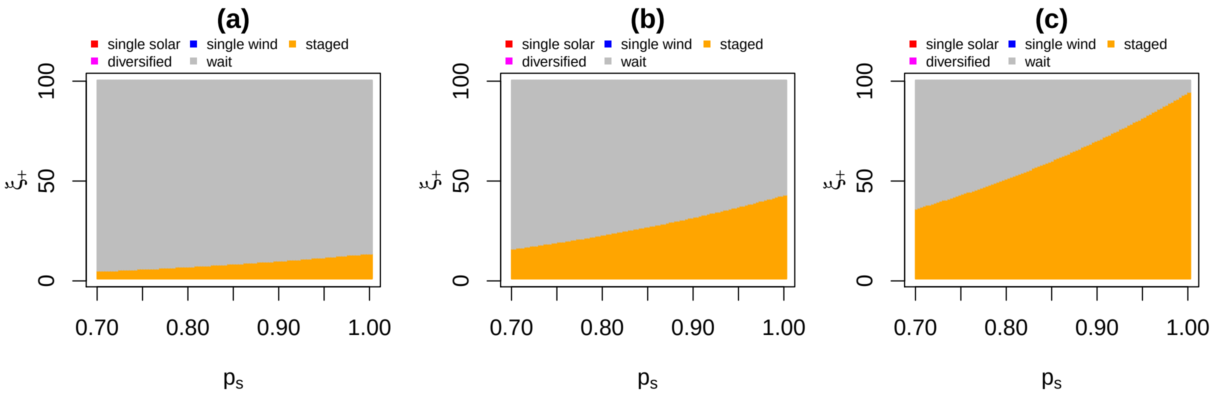

Figure 7: This plot shows the optimal investment strategy in RES for the scenario where major innovations in solar technology are expected $\alpha = 0.3$ and: the (a) low $\xi_- = 50€/MWh$, (b) mid $\xi_- = 100€/MWh$ and (c) high energy price regime $\xi_- = 200€/MWh$.

solar power in the future when the price for solar technology is low becomes a valuable strategy. Fig. 7(a)-(c) illustrates the optimal investment choice in the low-, mid-, and high-energy price regime. With increasing energy price we observe, that adopting a staged investment strategy becomes increasingly important. With the early investment in wind technology, the energy manager sacrifices a part of the flexibility to invest in solar technology. However, in this scenario the staged investment strategy optimally balances the benefits of an expected decrease in the investment price of solar technology and the cash-flow due to purchasing power and deferring a part of the investment.

5.2. Policy implications

Based on the energy manager's optimal decision as a price taker, we now discuss policy implications associated with the optimal design of the remuneration policy. To do so, consider the regulator's point of view who is in charge of determining the level of the FIT that is used for pricing surplus power that is sold to the grid by power generation facilities. We assume, that the policy maker regulates the long term trend of the remuneration policy by setting the subsidy retraction rate. Given the exogenous level of the innovations in

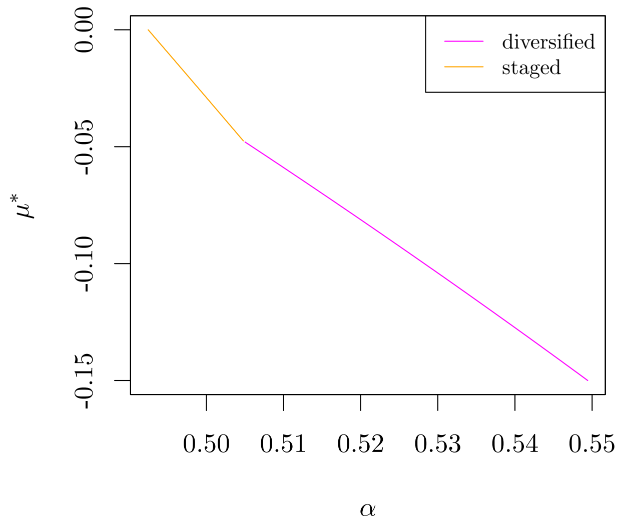

Figure 8: This figure shows the relationship between the level of innovation in solar technology and the endogenized drift rate μ^* s.t. the energy manager is indifferent in investing now or to defer the investment decision. The impact of the probability to obtain an innovation in solar technology is also demonstrated. In this numerical example $\sigma = 0.2$, $\pi_{\downarrow}^{\text{Inv}} = 0.1$ and $\xi_{-} = 100€/MWh$ are chosen.

solar technology α and the probability $\pi_{\downarrow}^{\text{Inv}}$ with which this innovation occurs in the next period, the regulator is interested in finding the critical subsidy retraction rate (i.e., the subsidy retraction rate $\mu^*(\alpha, \pi_{\downarrow}^{\text{Inv}})$), where the energy manager is indifferent in investing immediately in RES or to postpone the investment decision to the future. In this setting, the parameter μ^* is therefore an endogenous parameter that depends on the innovations of solar technology of the market. This boundary region is of particular importance, since choosing slightly higher values of the subsidy retraction rate facilitates early investment in RES. In contrast to that, slightly lower values of the subsidy retraction rate incentives the energy manager to defer investment in renewable energy technologies.

The condition of how to obtain the endogenized subsidy retraction rate is indifference in the investment decision. The energy manager is indifferent in investing in RES at t_0 or deferring the investment decision to t_1, whenever the continuation value of the option to invest in RES is equal to the minimum power procurement costs associated with an investment at t_0. The subsidy retraction rate μ^* that fulfills this condition implicitly defines the boundary region denoting indifference of investing now or to postpone the investment decision, which is illustrated in Fig. 8.[14] Obviously, remunerations for surplus power must be withdrawn more quickly, whenever expected technological innovations in solar technology are higher. Fig. 8 also illustrates that the optimal portfolio choice is changing along the boundary region.

6. Conclusion

This paper extends the real options literature in the field of renewable energy investment. We analyze the optimal investment decision in renewable energy technologies (primarily wind and solar technology),[15] which is characterized by uncertain production volumes under policy uncertainty and stochastically decreasing prices for solar technology. The expected total power procurement costs to cover the firm's demand consists of the investment costs, minus expected remunerations for selling surplus power to the grid plus expected costs of a shortfall in the power supply. This nonlinear pricing relation introduces diversification benefits even for the risk neutral decision maker. Generally, the optimal investment decision in renewable energy technologies is not the investment in the energy technology with the highest expected power output per amount of invested capital, but to opt for a properly diversified energy portfolio that balances shortfall risks and benefits obtained from selling surplus power to the grid. Following the real options approach, we not only determine the optimal portfolio decision in renewable energy technologies but also the optimal timing of the investment. More specifically, the dynamic investment model also allows a staged investment strategy, i.e., an early partial invest-

[14] This boundary region can be determined by applying a bi-sectioning algorithm to iteratively find the value of the drift s.t. equality of the continuation value and the optimal portfolio choice associated with the static problem holds true.

[15] I.e., we do not take conventional (fossil fuel based) power plants into account.

ment in wind technology and keeping the option to expand in solar technology alive. An early investment in wind technology might be beneficial since it allows to immediately alter the cash-flow. In the use case we find that this staged investment strategy is of special importance, whenever the price of the energy that has to be purchased in case of a shortfall in the power supply is high, but major innovations in solar technology are expected. In this scenario, the optimal investment decision is to sacrifice a part of the flexibility for an early investment in wind technology. This demonstrates, that the option of a staged investment strategy in RES facilitates early investment in wind technology. Furthermore, with increasing price of pre-contracted energy (i.e., shifting more weight to the shortfall-tail of the cost distribution), the likelihood of the energy manager to adopt a staged investment strategy increases. Our investment model also provides valuable insights from the regulator's point of view, who sets the optimal subsidy retraction rate (i.e., creating a stimulus for early investment that counterbalances the incentive to delay investment which is usually present in investment decisions under uncertainty). Based on the partial equilibrium model referring to the energy manger's optimal portfolio choice, we infer the optimal subsidy retraction to be set by the regulator.

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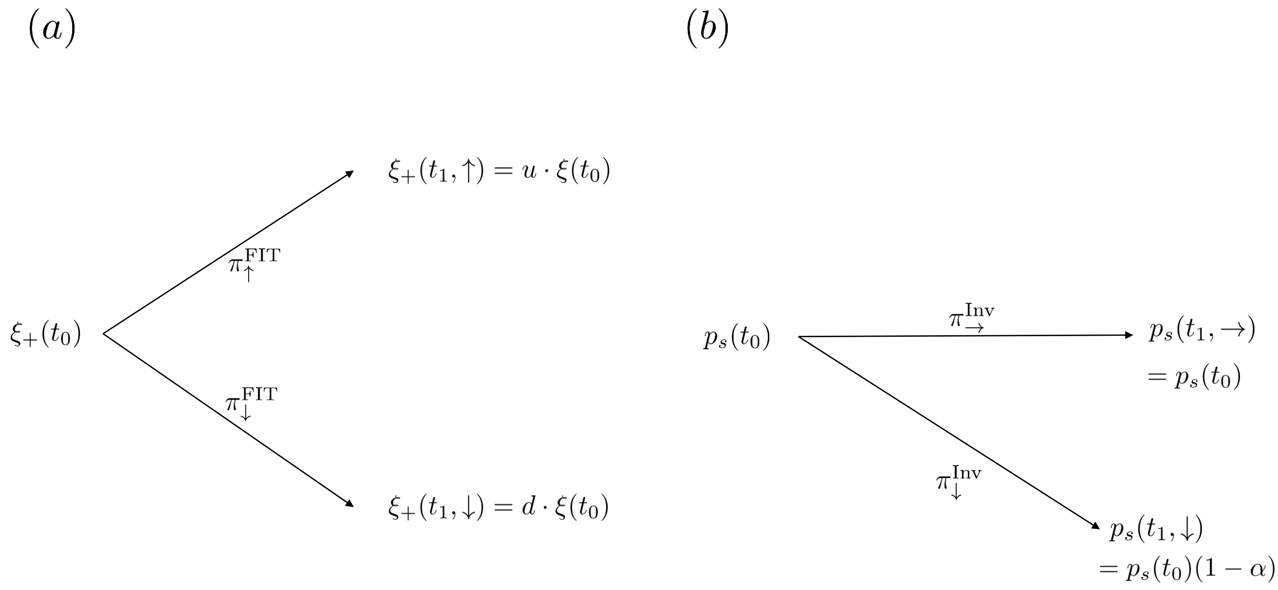

Figure 9: (a) shows the grid associated with the GBM of the level of the FIT and (b) shows the grid for the evolution of the investment price for solar technology.

A. Stochastic processes

Remuneration policy

We assume the level of the FIT follows a geometrical Brownian motion (GBM) $\mathrm{d}\xi_{+t} = \mu\xi_{+t}\mathrm{d}t + \sigma\xi_{+t}\mathrm{d}z_t$, with drift μ and volatility σ^2, where $\mathrm{d}z_t$ is increment to a Wiener process. Therefore, future values of the level of the FIT are log-normally distributed with mean $\mathbb{E}[\xi_{+t}] = \xi_{+0}\exp(\mu t)$ and variance $\mathbb{V}[\xi_{+t}] = \xi_{+0}^2\exp(2\mu t)(\exp(\sigma^2 t) - 1)$. Following Cox et al. (1979), we approximate the GBM via a binomial lattice, where the decision horizon is subdivided in elementary time intervals of length Δt. The up and down factors specifying the level of the FIT in the proceeding time step are given by

$$\begin{aligned} u &= e^{\sigma\sqrt{\Delta t}}, \\ d &= e^{-\sigma\sqrt{\Delta t}}. \end{aligned} \tag{A1}$$

The probability $\pi_\uparrow^{\text{FIT}}$ to obtain an up movement of the level of the FIT in the proceeding time step is given by

$$\pi_\uparrow^{\text{FIT}} = \frac{e^{\mu\Delta t} - e^{-\sigma\sqrt{\Delta t}}}{e^{\sigma\sqrt{\Delta t}} - e^{-\sigma\sqrt{\Delta t}}}. \tag{A2}$$

To obtain a valid probability $\pi_{\uparrow}^{\mathrm{FIT}} \in [0,1]$ has to hold true. Since the level of the remuneration policy is expected to decrease over time, the drift is negative $\mu \leq 0$. The requirement to obtain a probability measure therefore imposes a condition on the size of the time step, which has to be sufficiently small $\sqrt{\Delta t} \leq \sigma/|\mu|$. For $\Delta t \to 0$ this time-discrete process converges to a GMB. The process associated with the one step problem is illustrated in Fig. 9(a).

Prices of the investment goods

Due to technological learning and diffusion, the price per one unit of installed solar capacity p_s can decrease over time. We consider a stochastic model of technological learning and diffusion and assume that stochastic exogenous technological innovations occur over time. Whenever an innovation shock occurs, the price of solar technology decreases instantaneously by a fraction of $\alpha\%$ and when no innovation shock occurs, the price remains the same. We assume, that the number of innovations associated with solar technology ν follows a Poisson process with a rate of λ innovations per year. Therefore, the expected number of innovations in y years is given by $\mathbb{E}[\nu] = \lambda y$ and the probability to obtain k innovations over a time period of y years is given by

$$\Pr\{\nu = k\} = \frac{(\lambda y)^k}{k!} e^{-\lambda y}. \tag{A1}$$

Therefore, the price of solar technology in the future is

$$p_s(t_1) = \begin{cases} p_s(t_1, \downarrow) = p_s(t_0)(1-\alpha), & \text{if an innovation occurs} \\ p_s(t_1, \rightarrow) = p_s(t_0), & \text{if no innovation occurs.} \end{cases} \tag{A2}$$

Similar to the construction of the GBM, we divide the time horizon into time intervals of length Δt. Hence, the probability of obtaining a technological innovation in solar technology is approximated (linearly) with $\pi_{\downarrow}^{\mathrm{Inv}} = \lambda \Delta t$. The probability of multiple innovations within one time step Δt is of order $(\Delta t)^2$ and can safely be ignored for small Δt. Consequently, the probability that no innovation occurs is given by $\pi_{\rightarrow}^{\mathrm{Inv}} = 1 - \pi_{\downarrow}^{\mathrm{Inv}}$. To obtain a probability $\pi_{\downarrow}^{\mathrm{Inv}} \in [0,1]$, the condition $\Delta t \leq 1/\lambda$ has to hold true. The number of inventions in the decision period is Binomially distributed $\nu \sim \mathcal{B}(n, \pi_{\downarrow}^{\mathrm{Inv}})$, where for the number of intervals within the decision horizon $n \to \infty$, the probability mass function of the Binomial distribution converges to the probability mass function of a Poisson distribution with rate λ. The process associated with the one step problem is illustrated in Fig. 9(b).

B. Dynamic N-period Problem

Up to this point we have illustrated the investment model in the one-step problem. Let us now discuss the fully dynamic model and analyze the solution which is obtained for

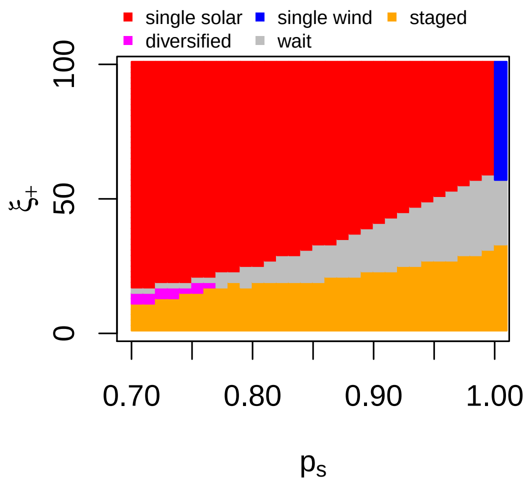

Figure 10: This figure illustrates the optimal investment strategy in the fully dynamic model as a function of the current price for solar technology and the current level of the FIT at $t = 0$.

an arbitrary but finite time horizon T.[16] Therefore, we split the time horizon into N equally spaced sub-intervals of length Δt.[17] In the fully dynamic model the same logic as in the one-step problem applies. At each point in time the energy manager faces the flexibility options to invest in RES, invest partially in wind technology or defer the investment decision, see Fig. 4. We solve the Bellman equations (7) and (9) backwards in time, starting at the terminal nodes at time T. We follow this procedure recursively and determine the value function iteratively up to time $t = 0$. In the one-step problem we have applied this iteration one time, whereas in the fully dynamic model we have to apply this step N times.

In the use case we assume that the decision to invest in RES can be made on a semi-annual basis, i.e., $\Delta t = 0.5$ with a time horizon $T = 10y$. Furthermore, we impose for the underlying process of the FIT $\mu = -0.1$, $\sigma = 0.2$ and for the underlying process of technological innovations in solar technology $\alpha = 0.025$ and $\pi_{\downarrow}^{\text{Inv}} = 0.25$ (per time

[16] The existence of a stationary solution requires some restrictions on the discount rate and on the expected rate of price reduction for solar production technology. The discount rate must be sufficiently large to outweigh the growth effect coming from expected price reduction. If expected price reduction is high, the area of solar panels that can be installed with fixed investment costs I_0 (or $I_0/2$) exhibits a large positive growth rate which must be more than offset by the discount factor in order to obtain stationarity. In real-life, however, also limited area available for solar panels and further limiting effects impose an upper bound to the installed capacity even when prices decline steeply. Hence, simple and realistic adaptations of the model will provide a stationary solution even with low interest rates and large expected price reductions. Therefore, for T sufficiently large, the solution approximates the stationary solution.

[17] With $N \to \infty$, i.e., $\Delta t \to 0$ the price process of the level of the FIT converges to a Geometric brownian motions.

step Δt, i.e., $\lambda = 0.5$). The energy price is $\xi_{-} = 50€/MWh$, the budget available is $I_0 = 0.25M€$ and the effective interest rate $r \approx 5\%$.

The fully dynamic model (Fig. 10) basically recovers the model effects obtained one-step problem. With increasing level of the remuneration policy, the optimal decision is to invest immediately in RES and with decreasing price of solar technology, the investment decision is in favor of solar technology. When the current level of the FIT is not sufficiently high, the optimal decision is either to postpone the investment decision or to follow a staged investment strategy and invest a fraction of the budget available in wind technology.