ifo WORKING PAPERS

376
2022

August 2022

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ifo INSTITUTE
Leibniz Institute for Economic Research
at the University of Munich

Imprint:

ifo Working Papers
Publisher and distributor: ifo Institute – Leibniz Institute for Economic Research at the University of Munich
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An electronic version of the paper may be downloaded from the ifo website:
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ifo Working Paper No. 376

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Abstract

Policymakers misjudge results of technology-rich optimization models because those models specify investment cost differently and thus are not equally sensitive towards changing financing cost and discount rates. We apply an intertemporally optimizing power market model to analyze three different investment cost specifications. The three specifications lead to a substantially different pace and rate of adoption for specific generation technologies and diverging carbon prices. The first assumes that an investment is financed by equity only, the second one applies a mix of equity and debt, and the third one assumes complete debt financing. The equity specification is completely insensitive towards changing financing cost, fosters early wind power deployment, and finally yields lowest carbon prices. The mixed capital one is extremely sensitive towards changing financing cost and postpones wind power deployment towards later periods. The debt specification is also insensitive towards changing discount rates and in general yields lowest investments and highest carbon prices.

JEL code: C61, C68, Q40, Q41

Keywords: Investment cost, discounting, financing cost, optimization model, power market model

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Declaration of interests. The authors declare that they have no known competing conflict of interest or financial interests that could have appeared to influence the work reported in this paper.
Acknowledgements. We gratefully acknowledge the financial support by the German Federal Ministry for Economic Affairs and Energy (grant number ”020E100374092”).
CRediT author statement. Mathias Mier: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Visualization; Roles/Writing - Original Draft; Valeriya Azarova: Conceptualization; Investigation; Methodology; Roles/Writing – Original Draft.

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1. Introduction

Technology-rich optimization models are widely used as tools to provide robust policy recommendations. Such models run different scenarios to advise decision-makers by informing them about the role of climate change and assessing the impact of potential changes in environmental, climate, and energy policies (Cao et al., 2016). Modeling temporal and spatial resolution, technological details, and economic behavior are some of the major future challenges of detailed numerical energy system and power market models (Pfenninger et al., 2014). Some models are already capable of depicting complete hourly resolution of the year when optimizing myopically (e.g., Poncelet et al., 2016). Others have flexible spatial resolution below country-level scope which can be adjusted in line with the specific research question (e.g., Martínez-Gordón et al., 2021). Others have fundamental technology richness and depict, for example, additional technological characteristics of storages such as maximum cycles or power plants with ramping constraints (e.g., Ringkjøb et al., 2018). However, such improvements bring the models only moderately closer in depicting reality and simultaneously drive them even further apart from each other prohibiting sensible comparison of the models' results. At the same time, one crucial driver of models' outcomes—*investment behavior* of firms and investors—is not covered in these advancements. We address this gap in the existing research by elaborating on the role of investment heterogeneity in technology-rich optimization models with detailed temporal and spatial resolution. In this regard, we evaluate the impact of three diverging *investment cost specifications* and their sensitivity with respect to changing *financing cost* and *discount rates* by quantifying the resulting technology mix and carbon prices in the European power market until 2050.

Growing attention has been devoted to detailed modeling of technical aspects (Ventosa et al., 2005) including generation technologies and representation of the grid in parallel with a more sophisticated representation of hourly timeseries and storages (Lopion et al., 2018). However, investment cost specifications have not yet been the major focus in the modeling community due to relative complexity of the underlying theory and an absence of agreement for a dominant theory explaining investment behavior in energy markets. Some of the commonly applied strategies to model investment costs in energy system and power market models include total investment cost (e.g., EUREGEN), annuities (e.g., dynELMOD, REMix, TIMES), and weighted average cost of capital (e.g., EMMA, NEMS, GEM-E3-Power). EUREGEN (e.g., Weissbart and Blanford, 2019) considers total investment cost in the investment period and thus has the implicit assumption that investments are financed by equity only. We thus refer to this specification as *equity* specification in the following. For instance, dynELMOD (e.g., Gerbaulet and Lorenz, 2017) or REMix (e.g., Hess et al., 2018) are configured to include investments on an annuity basis. Such a specification does not account for the entire investment cost in the year of investment. Instead, annuities need to get paid over the investment's depreciation (or payback) time. Annuities calculate from an interest rate and the length of the depreciation period. Such an approach thus implicitly assumes that an investment is financed by debt capital only. We thus refer to it as *debt* specification in the remainder. EMMA (e.g., Hirth and Steckel, 2016), NEMS, or GEM-E3-Power (e.g., Polzin et al., 2021) apply investment cost in form of a weighted average cost of capital (WACC). Their approach is similar to the debt one but using a WACC instead of annuities reflects the fact that an investment is financed by equity and debt capital. We call this specification *capital*. Moreover, Hirth and Steckel (2016) and Polzin et al. (2021) show results of some first efforts to reflect the underlying investment cost heterogeneity. For instance, Hirth and Steckel (2016) show that increasing the capital cost encourages use of fossil fuels and can be harmful for renewables. Polzin et al. (2021) introduce a varying WACC on a country and technology-level for the European Union in GEM-E3-Power and demonstrate how differentiated WACC assumptions have large impacts on investment decisions and technology uptake both in the medium- and in the long-term. They detect particularly significant impacts for solar and wind technologies, which are seen as key technologies to decarbonize power markets and entire economies. However, none of these contributions discuss how the chosen investment cost specification impacts the outcomes of the model.

In this paper, we advance a more differentiated picture of power market investments by testing the impact of three diverging investment cost specifications (equity, debt, and capital). We use the EUREGEN model—a European power market partial equilibrium model that optimizes investments, decommissioning, and dispatch for generation, storage, and transmission technologies intertemporally until 2050—to quantify the impact of those investment cost specifications on capacity expansion, generation mix, and carbon prices.[1]

We start by highlighting the impact of the three investment cost specifications under the assumption of same discount rates and financing cost. The equity specifications tends to invest earlier and substantially increases wind power already in 2025, further on continuing on this trajectory in the long-run. The debt specifications invests the least and has a preference towards gas-CCS and nuclear technologies. The gap to the two other cost specifications is persistent even in the long-term. The capital specification is somewhat in-between these two extremes. The equity specification increasingly invests under lower discount rates, whereas changes in the discount rates have less impact on investments for capital and debt specifications. Changes in the financing cost, on the opposite, are not relevant for decisions under the equity specification, whereas substantially impacting investment decisions under the capital and also moderately under the debt specification.

We begin by describing theoretical foundations of the modeling strategy in Section 2. Section 3 provides illustrative examples for the different investment cost specifications. Section 4 gives on overview of the calibration. Section 5 presents main results, whereas Section 6 summarizes robustness of results with regard to changing discount rates and financing cost. Section 7 concludes and highlights policy implications.

2. Investment cost specifications

Notation. Consider technologies j (e.g., wind onshore), regions r (e.g., Germany), time periods t (e.g., 2030), and installation periods v (e.g., 2005). We use subscript j, r to denote variables and

[1]See Weissbart and Blanford (2019) for the underlying basics of the EUREGEN model and Weissbart (2020), Mier and Weissbart (2020), Mier et al. (2020), Azarova and Mier (2021), Mier et al. (2022), Mier and Adelowo (2022), Mier et al. (2022,?), Siala et al. (2022) for applications.

parameters and parentheses for periods v, t, i.e., $Q_{jr}(v)$ is the capacity installed in period v and $C_{jr}(v)$ the constant unit cost. The discount factor δ follows from the discount rate ν.

Equity. The *equity* specification considers the entirety of the investment cost in the period of installation v. The objective is thus given by

$$\min_{\mathbf{Q},...} \quad \sum_t \delta(t) \sum_r \quad \left[\sum_j \sum_{v=t} Q_{jr}(v)\, C_{jr}(v) \times \Gamma_{jr}(v,t) + ... \right], \tag{1}$$

where $\mathbf{Q}$ is the vector of investment decisions.[2] $Q_{jr}(v)\, C_{jr}(v)$ are direct cost of investing into a technology and Γ is the *endeffect*. This endeffect reflects that the depreciation (or payback) time of an investment might expand beyond the model horizon, i.e.,

$$\Gamma_{jr}(v,t) \quad = \quad \frac{\sum_t \delta(t)\, \mathit{\Lambda}_{ir}(v,t)}{\sum_{t_{long}} \delta(t_{long})\, \mathit{\Lambda}_{ir}(v, t_{long})}. \tag{2}$$

t_{long} reflects an unconstrained time horizon to allow for full depreciation of every investment. Λ is a binary parameter that takes the value 1 when the investment still depreciates and 0 otherwise, i.e.,

$$\Lambda_{jr}(v,t) \quad = \quad \begin{cases} 1 & \text{if } t \leq v + t_{jr,depr}(v) \\ 0 & \text{if } t > v + t_{jr,depr}(v) \end{cases}, \tag{3}$$

where $t_{jr,depr}(v)$ is the depreciation time of an investment.[3] Observe that this specification is independent of any financing cost. Only discount rates determine the share of investment cost considered in the respective period and the discounting depicts the weight of the cost over time.

Capital. The *capital* specification assumes that a capital stock is subject to capital cost, best reflected by the weighted average cost of capital (WACC):

$$\min_{\mathbf{Q},...} \quad \sum_t \delta(t) \sum_r \quad \left[\sum_j \sum_{v \leq t} Q_{jr}(v)\, C_{jr}(v) \times \mathit{\Lambda}_{jr}(v,t)\, wacc + ... \right]. \tag{4}$$

[2]The optimization problem is subject to multiple constraints from which the demand-equals-supply, the resource adequacy, and the carbon constraints are the ones that drive investments mostly. We refrain from depicting them here in detail to focus on the differences between investment cost specifications.

[3]The installation period v reflects potential technological progress with respect to lifetime and also depreciation time.

Observe that this specification induces a stream of investment cost over the entire deprecation time of the respective investment ($\sum_{v\leq t}$), whereas the equity one considers investment cost only in the period of installation ($\sum_{v=t}$).

Debt. The *debt* specification assumes that an investment is financed by debt capital only. The annuity a reflects interests and repayment, i.e.,

$$a_{jr}(v) = \frac{i(1+i)^{t_{jr,depr}(v)}}{(1+i)} - 1. \quad (5)$$

This annuity is generally higher than the underlying interest rate i but decreases with increasing deprecation times. The underlying objective becomes:

$$\min_{\mathbf{Q},...} \sum_t \delta(t) \sum_r \left[\sum_j \sum_{v\leq t} Q_{jr}(v)\, C_{jr}(v) \times \Lambda_{jr}(v,t)\, a_{jr}(v) + ... \right]. \quad (6)$$

The only difference between capital and debt specifications is that the depreciation time of an investment affects the annual cost in the former.

3. Illustrative Examples

We now provide some intuition for the three different investment cost specifications by considering 2020, 2030, 2040, and 2050 investments into technologies with different depreciation times. Hereby, 2020 is the first period of investments and 2050 the last one (end of the planning horizon). We consider wind investments that depreciate 25 years and nuclear investments with 40 years of depreciation. This allows us to derive some insights into the relative competitiveness of investments in the three investment cost specifications depending on the investment timing (2020, 2030, 2040, or 2050) and depreciation time (25 or 40 years). Table 1 presents wind turbine investment and Table 2 shows the example of a nuclear technology investment. The upper parts of both Tables show current investment cost and the lower ones the net present value of investment cost after discounting. We assume that each investment period covers five years (2020 reflects 2016 to 2020, ..., 2030 reflects 2026 to 2030, ...). The applied discount rate is thus an average over the respective five years. For parsimony, we assume that WACC, interest rate, and discount rate are all the same at 7% level. For illustrative purposes, we assume that both technologies cost 100 €.

We begin with wind turbine investments. The equity specification considers the entire investment cost in the moment of installation and (as described in Section 2) applies endeffects below 1 when the depreciation times spans beyond the end of the planning horizon. This is not the case for 2020 and 2030 investment but for 2040 investments (only 15 years within planning horizon yields an endeffect of 0.7816) and 2050 investments (only 5 years with endeffect of 0.3518). The debt specification, in turn, includes the annuity of 8.52% (from 25 years depreciation time) in each year

Table 1: Comparison of 2020, 2030, 2040, and 2050 investment into wind turbines for the three different investment cost specifications

		2020	2025	2030	2035	2040	2045	2050	Total	Diff*	Diff**
Current investment cost (cost = 100, in €)											
	Equity	100.00							100.00		
2020	Debt	42.91	42.91	42.91	42.91	42.91			214.53	114.53%	
	Capital	35.00	35.00	35.00	35.00	35.00			175.00	75.00%	-18.42%
	Equity			100.00					100.00		
2030	Debt			42.91	42.91	42.91	42.91	42.91	214.53	114.53%	
	Capital			35.00	35.00	35.00	35.00	35.00	175.00	75.00%	-18.42%
	Equity					78.16			78.16		
2040	Debt					42.91	42.91	42.91	128.72	64.69%	
	Capital					35.00	35.00	35.00	105.00	34.35%	-18.42%
	Equity							35.18	35.18		
2050	Debt							42.91	42.91	21.95%	
	Capital							35.00	35.00	-0.52%	-18.42%
Net present value of investment cost (cost = 100, in €)											
	Equity	82.00							82.00		
2020	Debt	35.18	25.09	17.89	12.75	9.09			100.00	21.95%	
	Capital	28.70	20.46	14.59	10.40	7.42			81.58	-0.52%	-18.42%
	Equity			41.69					41.69		
2030	Debt			17.89	12.75	9.09	6.48	4.62	50.83	21.95%	
	Capital			14.59	10.40	7.42	5.29	3.77	41.47	-0.52%	-18.42%
	Equity					16.56			16.56		
2040	Debt					9.09	6.48	4.62	20.20	21.95%	
	Capital					7.42	5.29	3.77	16.48	-0.52%	-18.42%
	Equity							3.79	3.79		
2050	Debt							4.62	4.62	21.95%	
	Capital							3.77	3.77	-0.52%	-18.42%

Periods from 2020 onward reflect five years, i.e., 2020 reflects 2016 to 2020, ..., and 2050 reflects 2046 to 2050. The endeffects of wind (onshore and offshore) investment are 1 in 2020 (35 years until 2050 and depreciation time of 25 years), 1 in 2030 (25 years until 2050), 0.7816 in 2040 (15 years until 2050), and 0.3518 (5 years until the end of the planning horizon). The annuity for an investment that depreciates 25 years is 8.58% (per year). The WACC is 7% (per year). Introducing discounting transforms current investment cost (upper part) into net present values of the investment cost (lower part). Diff* shows the difference of debt or capital specification, respectively, to the equity one. Diff** shows the difference of the capital to the debt specification.

of the planning horizon until the end of the depreciation time. Thus, a 2020 investment depreciates until 2040 so that the quinquennial costs are 42.91 €. Total (current) cost accumulates to 214.53 €, which is more than double the amount of the equity specification (100 €). Similarly for the capital specification, each year cost 7% until the end of the depreciation time. If the investment spans beyond the planning horizon, the debt and capital specifications apply the respective five-annual cost. The capital specification here is cheaper than the debt one (–18.42%).

Table 2: Comparison of 2020, 2030, 2040, and 2050 investment into nuclear for the three different investment cost specifications

		2020	2025	2030	2035	2040	2045	2050	Total	Diff*	Diff**
Current investment cost (cost = 100, in €)											
	Equity	97.12							97.12		
2020	Debt	37.50	37.50	37.50	37.50	37.50	37.50	37.50	262.53	170.32%	
	Capital	35.00	35.00	35.00	35.00	35.00	35.00	35.00	245.00	152.27%	-6.68%
	Equity			87.41					87.41		
2030	Debt			37.50	37.50	37.50	37.50	37.50	187.52	114.53%	
	Capital			35.00	35.00	35.00	35.00	35.00	175.00	100.20%	-6.68%
	Equity					68.32			68.32		
2040	Debt					37.50	37.50	37.50	112.51	64.69%	
	Capital					35.00	35.00	35.00	105.00	53.69%	-6.68%
	Equity							30.76	30.76		
2050	Debt							37.50	37.50	21.95%	
	Capital							35.00	35.00	13.80%	-6.68%
Net present value of investment cost (cost = 100, in €)											
	Equity	79.64							79.64		
2020	Debt	30.76	21.93	15.63	11.15	7.95	5.67	4.04	97.12	21.95%	
	Capital	28.70	20.46	14.59	10.40	7.42	5.29	3.77	90.63	13.80%	-6.68%
	Equity			36.44					36.44		
2030	Debt			15.63	11.15	7.95	5.67	4.04	44.44	21.95%	
	Capital			14.59	10.40	7.42	5.29	3.77	41.47	13.80%	-6.68%
	Equity					14.48			14.48		
2040	Debt					7.95	5.67	4.04	17.65	21.95%	
	Capital					7.42	5.29	3.77	16.48	13.80%	-6.68%
	Equity							3.31	3.31		
2050	Debt							4.04	4.04	21.95%	
	Capital							3.77	3.77	13.80%	-6.68%

Periods 2020 onwards reflect five year, i.e., 2020 reflects 2016 to 2020, ..., and 2050 reflects 2046 to 2050. The endeffects of nuclear investment are 0.9712 in 2020 (35 years until 2050 and depreciation time of 40 years), 0.3644 in 2030 (25 years until 2050), 0.1448 in 2040 (15 years until 2050), and 0.0331 (5 years until the end of the planning horizon). The annuity for an investment that depreciates 40 years is 7.5% (per year). The WACC indeed is 7% (per year). Accounting for discounting transforms current investment cost (upper part) into net present values of investment cost (lower part). Diff* shows the difference of debt or capital specification, respectively, to the equity one. Diff** shows the difference of the capital to the debt specification.

Observe that the relative differences of equity to debt and capital specification shrink with later investments. However, applying discounting (lower part of the Table) restores the relative competitiveness across investment cost specifications over time. Given our calibration, the debt specification inherits 21.95% higher total investment cost than the equity one, whereas the capital specification is even cheaper (–0.52%). The relative difference between debt and capital specification remains constant when applying discounting due to identical allocation of investment cost over time.[4]

Now turn to nuclear investments. These have a longer depreciation time and thus the annuity (7.5%) is closer to the WACC, so that both specifications are similar with regard to the investment cost (difference of 6.68% only). However, the longer depreciation time of nuclear does not impact the relative competitiveness of technologies in between equity and debt specifications but rather for the capital specification. Indeed, the capital specification is now substantially more expensive compared to the equity one (+13.8%). Such results hint that the equity and the capital specifications, in general, foster investments (because they are comparably cheaper), whereas there are distortions between the equity and the capital specification with regard to the relative competitiveness of technologies. In particular, the capital specification seems to foster technologies with shorter depreciation times (wind, solar, gas, gas-CCS, bio-CCS), whereas the equity specification has a clear advantage when depreciation times are longer (nuclear and transmission technologies).

4. Calibration

Investment cost and depreciation time. Table 3 summarizes investment cost and depreciation times for generation, storage, and transmission technologies. Observe that costs for conventional gas (gas-CCGT, gas-ST, gas-OCGT) technologies and lignite remain constant over time. Costs for all other generation technologies decrease over time, whereas the reduction is the most pronounced for solar and wind offshore. Furthermore, power-to-gas costs are assumed to be constant as well since the technology is not applied yet on a large-scale. In turn, costs of batteries fall considerably from 1,740 to 440 €/kW, assuming an energy-to-power ratio of 4. Finally, we consider transmission technologies. An AC-line is less expensive than a DC-line but overall line length is generally higher and only DC-lines can connect countries under water.

Carbon constraint and electricity demand. When modeling the European power market, one can either decide to establish a quantity target or carbon prices as outcome of a quantity regulation (EU ETS). We opt for the first option and reflect recent ambitions of the EU advanced in the *European Green Deal.* Table 4 shows the outcome. The CO_2 quantity is 843.5 Mt in 2020 and drops to zero in 2045. In 2050, the target is even negative (-84 Mt) to compensate for other sectors that might not be able to fully decarbonize (e.g., aviation). Electricity demand is the crucial determinant for the overall capacity expansion. We obtain electricity demand from a CGE calibration that accounts for certain quantity targets and electrification of industrial and transport sectors (Mier et al., 2020, 2022, Siala et al., 2022). Overall electricity demand doubles from 3,089 TWh to 6,204 TWh. Appendix A shows the respective country values.

[4]Note that market forces might restore that the relative competitiveness of each investment for all three investment cost specifications is same by changing specification-specific WACC, interest rates, and discount rates.

Table 3: Investment cost and depreciation time (in years) for generation (€/kW), storage (€/kW), and transmission (€/MW per km) technologies

	2020	2030	2040	2050	Depreciation
Gas-CCGT	850	850	850	850	25
Gas-CCS	1,495	1,495	1,495	1,495	25
Gas-OCGT	437	437	437	437	25
Gas-ST	850	850	850	850	25
Coal	1,500	1,410	1,380	1,365	40
Coal-CCS	3,415	3,210	3,142	3,108	40
Lignite	1,640	1,640	1,640	1,640	40
Oil	822	822	822	822	25
Bioenergy	4,236	4,149	4,063	4,020	25
Bio-CCS	4,361	4,272	4,183	4,139	25
Geothermal	11,993	11,498	11,127	11,004	30
Nuclear	6,006	5,082	4,488	4,356	40
Solar	1,027	858	780	715	25
Wind offshore	3,024	2,520	2,268	2,088	25
Wind onshore	1,397	1,339	1,310	1,296	25
Power-to-gas	1,520	1,520	1,520	1,520	20
Battery	1,740	1,120	780	440	16 to 22
AC-line	770	770	770	770	50
DC-cable	1,152	1,152	1,152	1,152	50

We restrict hydro and pump storage capacity to existing capacity and thus refrain from showing cost and depreciation time. We assume energy-to-power ratios (kWh/kW) of 720 for power-to-gas and 4 for batteries. Pump storage ratios are 4 in Slovenia (185 MW installed generation capacity) and 3,685 in Norway (1,344 MW installed generation capacity).

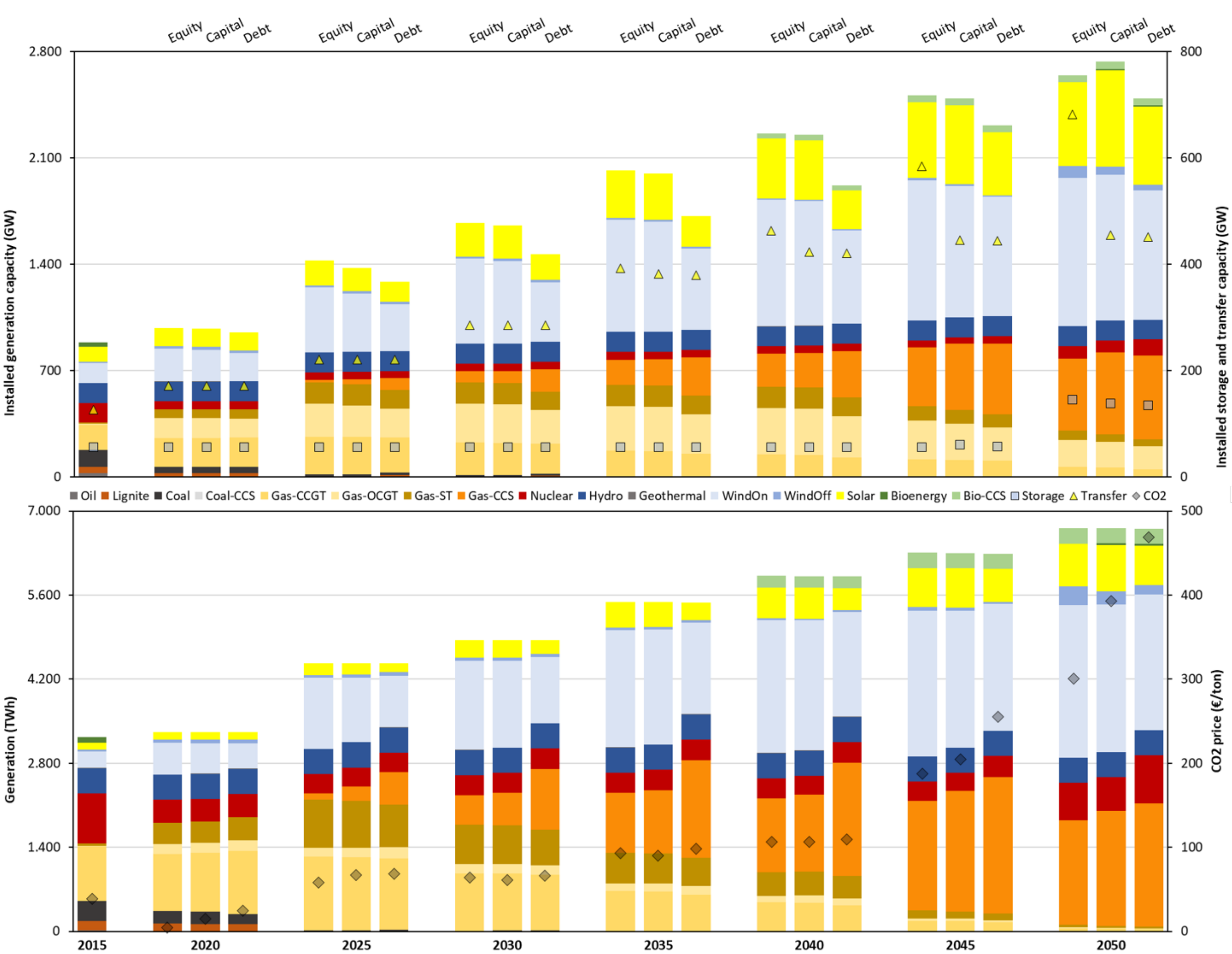
Table 4: CO_2 quantity target and electricity demand

	2020	2025	2030	2035	2040	2045	2050
CO_2 quantity target (Mt)	843.5	770.2	639.0	491.5	245.8	0	-84
Electricity demand (TWh/a)	3,089	4,153	4,500	5,081	5,480	5,830	6,204

5. Main results

We now present the differences in the technology mix and resulting carbon prices across the three investment cost specifications (equity, capital, debt). The upper panel of Figure 1 shows installed generation capacities by technology (bars with scale on the left axis, in GW), total storage (gray squares), and transfer (yellow triangles) capacities (both on the right axis, in GW). The lower panel depicts generation by technology (on the left axis, in TWh) with the resulting CO_2 price (on the right axis, in €/ton). We show period 2015 (calibration year) only once since it is the same for each specification due to missing (endogenous) investments and then all periods from 2020 onwards for each specification. Each period is clustered for the three investment cost specifications *equity* (the first column), *capital* (the second), and *debt* (the third).[5]

Figure 1: Impact of investment cost specifications on technology mix and CO_2 price



The 2015 technology mix comprises conventional gas capacity (gas-CCGT, gas-ST, gas-OCGT, total of 182 GW with generation share of 29.4%), nuclear (125 GW, 25.8%), coal (110 GW,

[5]We show 2020 only for the sake of completeness but refrain from describing 2020 outcomes because the results of this period are largely driven by the adjusted 2015 calibration that already pushes for pipeline investment. In addition to those 2020 pipeline effects, there are immediate adjustments processes (decommissioning of unnecessary old capacity), and intertemporal adjustments with regard to investments (adding capacity that is beneficial also later in response to decommissioning of old capacity) and decommissioning (intertemporally non-beneficial capacity). Those effects undermine the comparability of the three different specifications in 2020.

10.3%), wind (142 GW, 9.4%), solar (98 GW, 3.4%), and hydro (131 GW, 12.9%). The remaining technologies are oil, lignite, geothermal and bioenergy. Oil, lignite, coal, geothermal, and bioenergy do not play a substantial role in the future technology mix and we thus refrain from analyzing them in detail. We also do not discuss hydro since its expansion is restricted by existing capacity. Hydro generation thus is constant until 2050 (418 TWh) but the generation share drops from 12.9% to 6.2% due to rising electricity demand (see Table 4). Total 2015 storage capacity consists only of pump storage and is at 56 GW (turbine and pump capacity; this value remains unchanged until 2040). International transfer capacity is at 127 GW.

There are already substantial differences across investment cost specifications from 2025 onwards. The equity specification increases wind power from 142 GW in 2015 to 443 GW in 2025, whereas capital and, even more pronounced, the debt one face considerably lower wind power deployment rates (400 or 324 GW, respectively). This pattern persists until 2050, where equity (capital, debt) yields 1,053 GW (1,013 GW, 889 GW) of wind power. Generation differences are even more significant (2025 shares of 27.5%, 25.2%, and 20.4%; 2050 shares of 42.5%, 39.8%, and 36%). The debt specification, in turn, relies fundamentally more on gas-CCS (2025 share of 12.2% vs. 2.5%, 2050 share of 30.6% vs. 25.9%). Interestingly, also solar deployment is lower for the debt specification. In 2050, the debt specification also relies more on nuclear power (104 GW/12% for debt vs 84 GW/9.3% for equity and 77 GW/8.4% for capital). Moreover, bio-CCS becomes competitive for all the three specifications in 2040 and final deployment is the comparable across specifications. Storage generation capacity increases in 2045 (power-to-gas addings, not for equity) and 2050 (battery addings for all specifications but power-to-gas again not for equity) from 56 GW (2015 to 2040) to 134–145 GW (2050). However, the reservoir capacity increases from 14.6 TWh to 15.1 TWh (equity), 23.2 TWh (capital), and 18.6 TWh (debt) only. The missing storage investments for equity are substituted by higher investments into transfer capacity. In particular, from 2035 onwards the boundaries of transmission expansion are lifted and consequently the equity specification increases transfer capacity considerably more (from 285 GW in 2030 to 682 GW in 2050) than the other two specifications (452 or 454 GW, respectively). The transfer capacity differences are also reflected in the amount of transfers. Finally, CO_2 prices (derived from the quantity target constraint) are generally the lowest for equity (58 €/ton in 2025, 301 €/ton in 2050) and the highest for debt (69 €/ton in 2025, 469 €/ton in 2050). The capital specification is in-between the two. However, carbon prices in 2030 and 2035 are lower for capital (compared to equity) due to the massive transfer capacity expansion in the equity specification that starts in 2035. In 2030, thus, the equity specification holds back relevant investments (mainly good wind spots) and catches up in the later periods. This, finally, yields considerably lower carbon prices when applying the equity specification.

Remember from our illustrative examples that technologies with short depreciation times are similarly competitive for equity and capital (difference of 0.52%). Investments with longer depreciation times, in turn, are substantially more expensive for the capital than for the equity specification (difference of 13.8%). The debt specification is the most expensive of the three and retains the difference of 21.95% to the equity one irrespective of the duration of the depreciation. We thus expect that the equity specification invests more in nuclear power (40 years) and eventually in transfer capacity (50 years). We do observe higher transmission investments but nuclear expansion is only slightly higher than for the capital specification. In particular, wind power expansion is considerably higher, whereas solar deployment is by far higher for capital (550 GW vs. 636 GW in 2050). Indeed, the higher relative competitiveness of transfer capacity in the equity specification fosters wind power expansion because wind power is most suitable to balance differences across countries. The capital specification, in turn, uses power-to-gas for balancing temporal deviations between intermittent renewables supply and demand, which consequently fosters solar expansion. Surprisingly, the debt specification shows an intense gas-CCS expansion (same depreciation time of 25 years as for wind power) and an even higher nuclear expansion in the long run. The reasoning of this pattern is obvious, when considering that not only wind power expansion but also solar deployment is the lowest for debt. Those intermittent technologies are the two most capital intensive in relation to the respective generation output. The debt specification thus generally invests considerably less but uses technologies with higher running cost (such as gas-CCS) to meet decarbonization goals.

6. Robustness

We analyze the three investment cost specifications under the same discount rate assuming also the same financing cost (discount rate, interest rate, and WACC of 7%). Now, we test robustness of investment patterns when either changing underlying discount rates, financing cost, or both from 1% to 11% in two-percentage point steps. We conduct this analysis for each specification separately. Appendix B contains the visualized results.

Equity. Intuitively, lower discount rates price up later investments, but also later generation. However, generation costs are less relevant for wind and solar power as well as for nuclear power. We thus expect that lower discount rates lead to generally lower investments but, in turn, foster early expansion of wind, solar, and nuclear power to reduce generation cost in the long-run. We find that the early expansion effect dominates. Overall investments are higher for lower discount rates because later generation costs play substantial roles. 2025 wind and solar power deployment is the highest for the lowest discount rates (wind: 563 GW for 1% and 371 GW for 11%, solar: 187 GW for 1% and 149 GW for 11%). The relative differences shrink over time but are prevalent until 2050 (wind: 1,146–979 GW for 1–11%; solar: 554–520 GW for 1–11%). The early deployment effect dominates only partly because indeed nuclear deployment in 2020 and 2025 is substantially lower for discount rates of 1–3%. From 2030 onwards lower discount rates yield also the highest nuclear capacity (132–73 GW for 1–11% in 2050). Remember that all specifications encounter the very same quantity target. As a consequence, higher discount rates substitute wind, solar, and nuclear power by CCS technologies. Final bio-CCS deployment is the same, although higher discount rates deploy slightly earlier. However, gas-CCS capacity is substantially higher for 11% (347–536 GW for 1–11%). We thus observe a substantial shift between generation cost-intensive and low generation cost technologies when applying varying discount rates.[6]

Capital. The capital specification allocates investment cost over time by paying the WACC over the depreciation time of the investment. This allocation should reduce the sensitivity of the capital specification with regard to discount rate changes. However, we still expect that lower discount rates foster early investments into technologies with lower generation cost (wind, solar, nuclear). This intuition, however, does not hold. Indeed, lower discount rates foster early gas-CCS deployment (145–10 GW for 1–11% in 2025), whereas wind (214–448 GW for 1–11%) and solar deployment (118–163 GW for 1–11%) are the highest with a discount rate of 11%. The higher gas-CCS shares in 2025 to 2040 for low discount rates substitute for conventional gas technologies and wind power. Nuclear differences are negligible. Differences across specifications dissipate completely in the long-run, leaving the 2050 system with negligible differences. Such a convergence is a result of the end of the planning horizon that does not consider that investment costs in the future periods are discounted differently. Yet the equity specification accounts for such an effect via endeffects and thus is more suitable for depicting the technology mix in the very last period. Changing the WACC should induce substantial changes because investments in general become substantially cheaper for lower WACC. In particular, we expect that lower WACC yields major investments into wind, solar, and transfer capacity, whereas higher WACC relies more on gas-CCS. This intuition is indeed confirmed but also storage investments increase tremendously. Interestingly, substantial shares of coal remain active for 1% WACC until 2030 because the remaining technology mix is clean enough to cover for it. 2025 wind power capacity differs from 874–241 GW for 1–11% already. 2050 wind capacity spreads are still enormous (1,868–856. The higher wind share yields lower nuclear, gas-CCS, and also bio-CCS usage for a WACC of 1%. However, the sensitivity of falling WACC seems to be higher than the one for rising ones. The systems for WACC of 7% or 11%, respectively, differ not as much as for 3% and 7%. However, carbon prices indeed do (almost 800 €/ton for 11% in 2050). The CO_2 quantity target pushes for a similar technology mix (for high WACC) and the resulting carbon price fully covers those higher investment cost. Remember that lower discount rates foster early gas-CCS deployment (and hamper wind power investments) and lower WACC, in turn, fosters early wind power investments (and hampers gas-CCS deployment). Merging both effects leaves a technology mix and carbon prices completely dominated by changing financing cost. Indeed, gas-CCS shares for high WACC and high discount rates are slightly lower than for high WACC only, but differences are negligible.

Debt. The discounting effect is even less pronounced than for the capital specification. For lower discount rates, there is slightly higher gas-CCS usage—gas-CCS substitutes for wind power and conventional gas—in early periods but 2050 generation technology mix is the same. However, storage and transfer capacities are indeed higher for lower discount rates. Here, the higher emphasis

[6]Remember that the equity specification uses endeffects that are below 1 when the depreciation time of an investment spans above the planning horizon. This endeffect is calculated by using discount rates. Consequently, financing cost does not matter for the equity specification and we thus test robustness of changing discount rates only.

on later (generation) cost lead to a small increase of wind and solar generation by means of transfers and storage operations, whereas nuclear generation drops. The financing cost sensitivity (we change the interest rate from 1 to 11%) results in annuities that are substantially less sensitive than the WACC. For example, the annuity for wind power investments is 4.54% when assuming an interest of 1% and 11.87% for 11% (8.52% for 7%). Thus, the debt specification already balances extreme investment patterns for very low financing cost. However, lower financing cost still increase investment into wind and solar power, whereas higher financing cost increase gas-CCS deployment. Lower cost also fosters nuclear expansion, which could not be observed for the capital specification because financing costs were so low that wind and solar power expansion is sufficient to meet decarbonization targets. Jointly reducing discount rates and financing cost is again dominated by financing cost as it is the case for changing WACC.

7. Conclusions and policy implications

We analyze three different investment cost specifications that are commonly used in technology-rich optimization models with detailed temporal and spatial resolution. We implement those specifications in the EUREGEN model, which optimizes investments, decommissioning, and dispatch decisions of multiple generation, storage, and transmission technologies for the European power market (28 countries) until 2050. The equity specification considers all investment cost in the period of installation, the capital specification pays the weighted-average cost of capital (WACC) as long as an investment still depreciates, and the debt specification uses annuities that reflect interest and repayment instead of using a WACC. We find substantial differences in the technology mix and resulting carbon prices across those specifications.

The equity specification fosters early wind power deployment and expands international transmission capacity tremendously. The debt specification invests considerably less in total and instead relies more on generation cost-intensive technologies such as gas-CCS. The capital specification lies in between the other two but comes with substantially higher solar deployment than the equity specification in the long-run. In particular, the capital specification closes the gap from the early wind power deployment in the equity specification over time. The three investment cost specification are unequally sensitive to changing discount rates and financing cost (i.e., changing WACC or interest rates, respectively). We observe non-linear patterns for changing discount rates and financing cost across investment cost specifications. Lower discount rates foster wind power deployment (and hamper gas-CCS usage) for the equity specification but yield substantially higher gas-CCS capacities in early periods for the capital and the debt specification. In the long-run, varying discount rates does not change much for the capital and the debt specifications. For the equity one, the magnitude of differences for varying discount rates reduces over time but is still substantial in the last period. Financing cost does not impact the equity specification at all. For the capital and the debt specification, higher financing costs have similar effects as do higher discount rates for the equity one.

To our knowledge, all publications applying technology-rich and detailed optimization models fail to discuss the impact of the used investment cost specification. In particular, a model with a equity specification is unsuitable to analyze the effect of changing financing cost and best reflects a social planner perspective. Models with capital or debt specification, in turn, are not adequate when analyzing changing discount rates but are good at reflecting a firm or investor perspective. Lacking discussion of the investment cost specification and its implications on the outcomes of the model leads to potential misinterpretation of the respective results by policymakers. Hence, when modeling energy systems and power markets with a large degree of technological detail one needs to account for the underlying investment cost specification. Improving models further with regard to temporal, spatial, and technological resolution has a minor impact compared to the way of specifying investment cost. The results of our comparative analysis of the investment cost specification suggest that policymakers should interpret the outcomes carefully and eventually consult different models with a varying specification of investment cost. Modelers and policymakers need to pay more attention to the role of investment cost specifications, technology-specific financing cost, and overall discount rates. They need to take into account the fact that some specifications are quite resistant to changes in the interest and discount rates, whereas others are extremely sensitive. Moreover, we suggest to base the modeling analysis on available empirical studies evaluating underlying market-specifics and then deciding for country-specific investment cost specifications. Also mixing the different specifications with varying financing cost and discount rates can improve the predictability quality of those models.

Our analysis is subject to some limitations. We focus on the general impact of different investment cost specifications and test robustness of our results with regard to changing financing cost and discount rates. We thus do not seek to resolve differences across specifications that would lead to different discount rates and financing across specifications and also across countries. Instead, the goal of our analysis is to provide some guidance on interpreting results under varying investment cost specification and is thus only a first step in improving the depiction of investment behavior in such models. Moreover, investment cost specifications are, to a certain degree, the channel to reflect the diversity of investors and respectively the specifics of their investment decisions and behaviors due to diverging preferences with respect to specific generation technologies, uncertainty, payback times, or access to different sources of capital. In particular, the three investment cost specifications considered by the literature kind of reflect different investor types with varying investment budget, financing cost, and discount rates. Estimating shares of those investor types in different countries and markets and then applying those outcomes in detailed optimization models would be a useful topic for further research.

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Appendix A. Electricity demand (TWh/a) for each country from 2020 to 2050

	2020	2030	2040	2050
Austria	64	91	147	163
Belgium	82	107	157	196
Bulgaria	30	36	39	43
Croatia	16	18	20	25
Czech Republic	63	121	133	149
Denmark	32	35	47	56
Estonia	8	11	12	14
Finland	73	79	82	91
France	450	768	868	986
Germany	534	843	874	950
Greece	53	54	63	71
Hungary	37	53	71	81
Ireland	26	32	42	49
Italy	319	562	644	735
Latvia	7	9	12	13
Lithuania	12	18	18	20
Luxembourg	6	8	14	17
Netherlands	113	186	199	226
Norway	124	126	168	190
Poland	143	179	267	293
Portugal	52	62	70	76
Romania	47	58	67	80
Slovak Republic	27	39	56	60
Slovenia	13	17	22	24
Spain	247	367	523	568
Sweden	133	161	248	282
Switzerland	61	71	128	151
United Kingdom	317	389	489	595
Sum	3,089	4,500	5,480	6,204

Appendix B. Supplementary visualization

Figure B.1: Discount rate sensitivity for equity investment cost specification

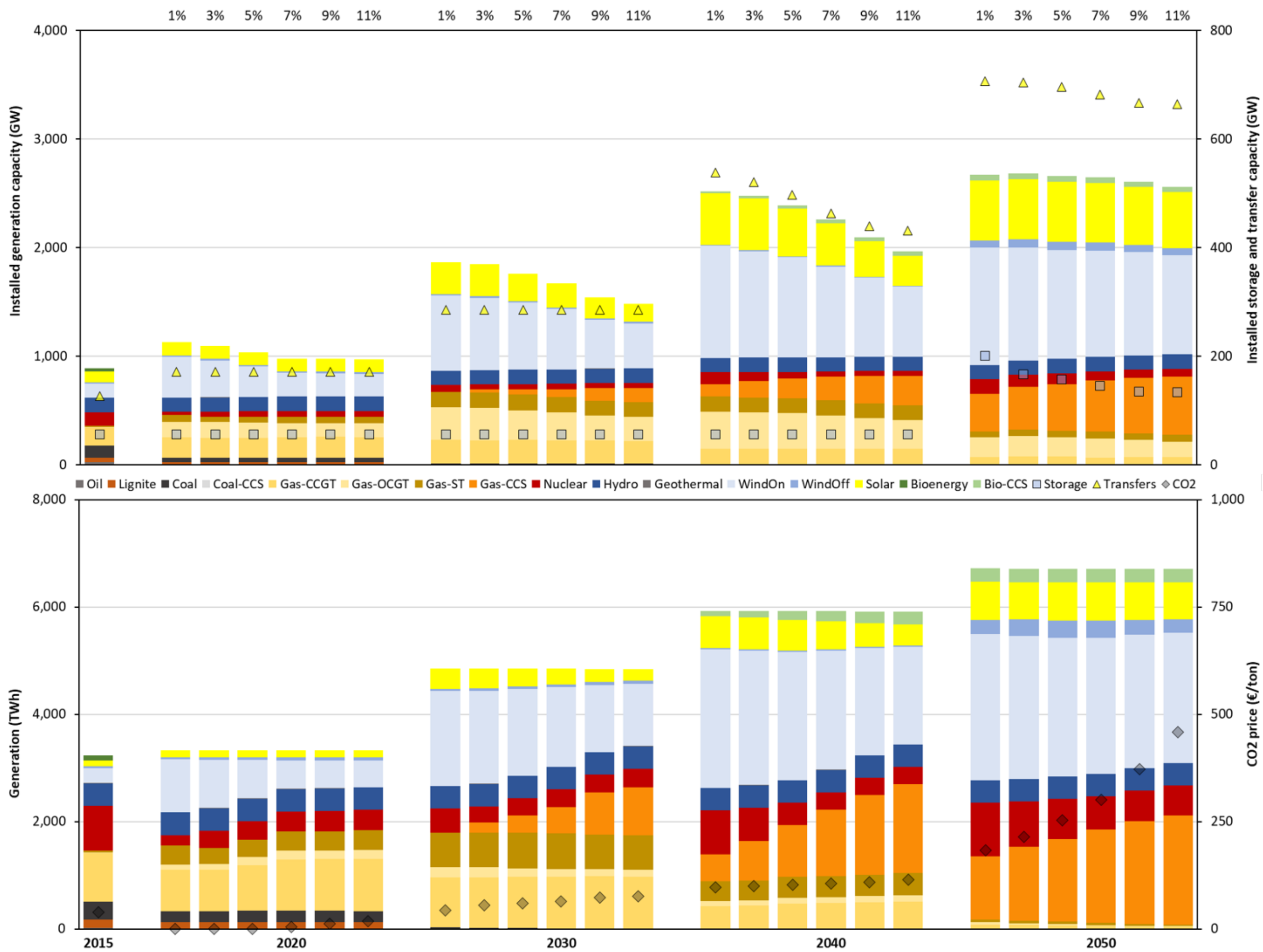

Figure B.2: Discount rate sensitivity for capital investment cost specification

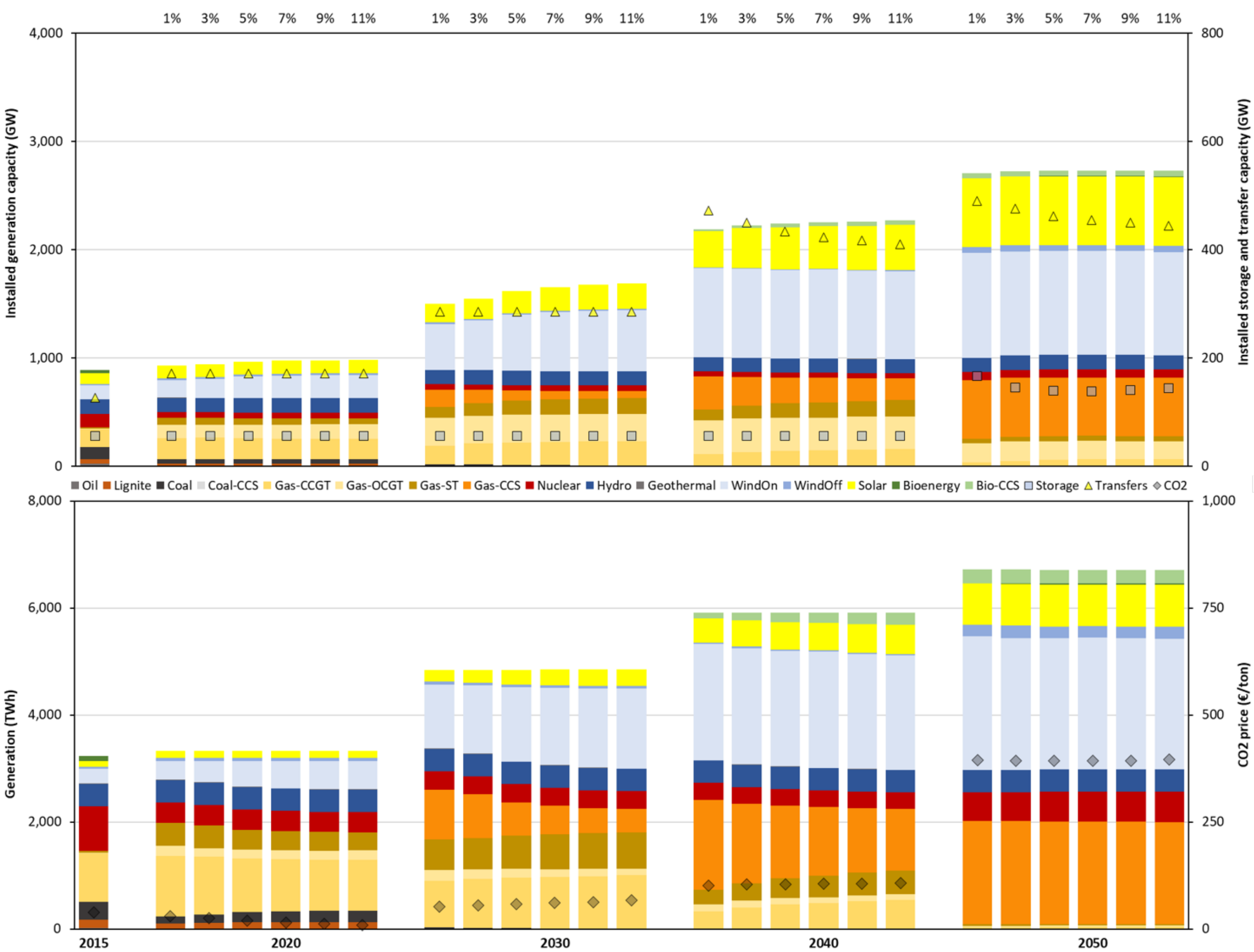

Figure B.3: Financing cost sensitivity for capital investment cost specification

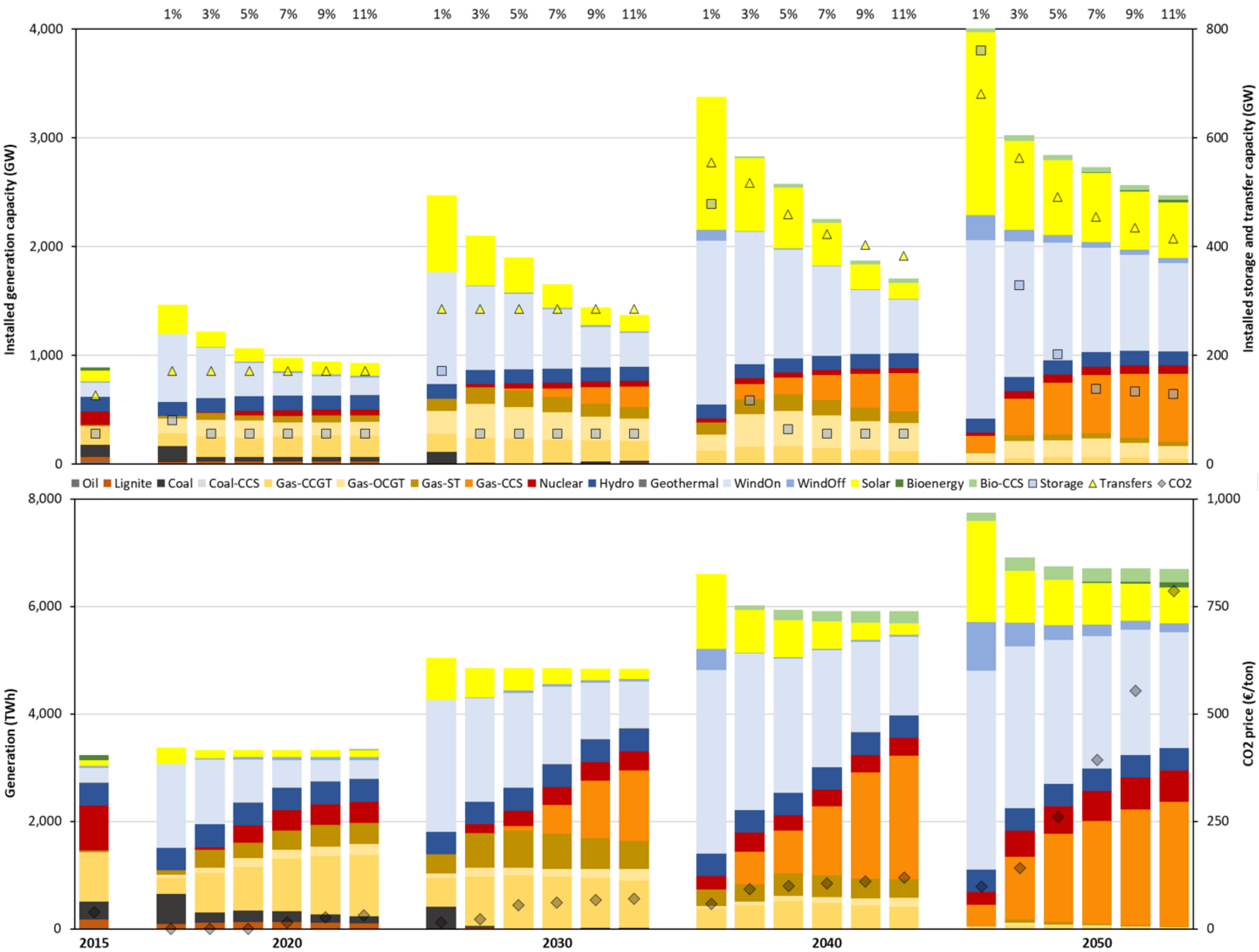

Figure B.4: Discount rate and financing cost sensitivity for capital investment cost specification

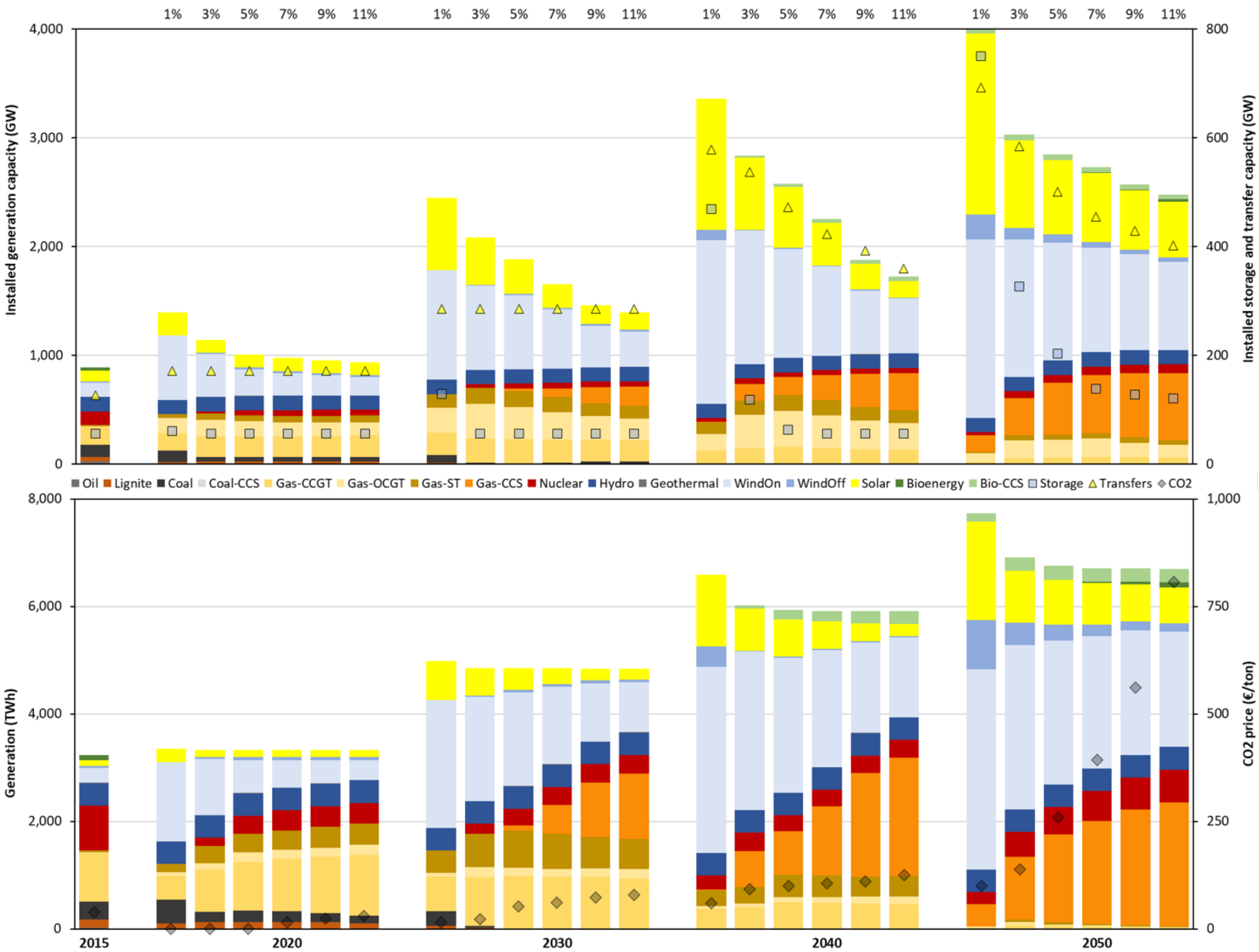

Figure B.5: Discount rate sensitivity for debt investment cost specification

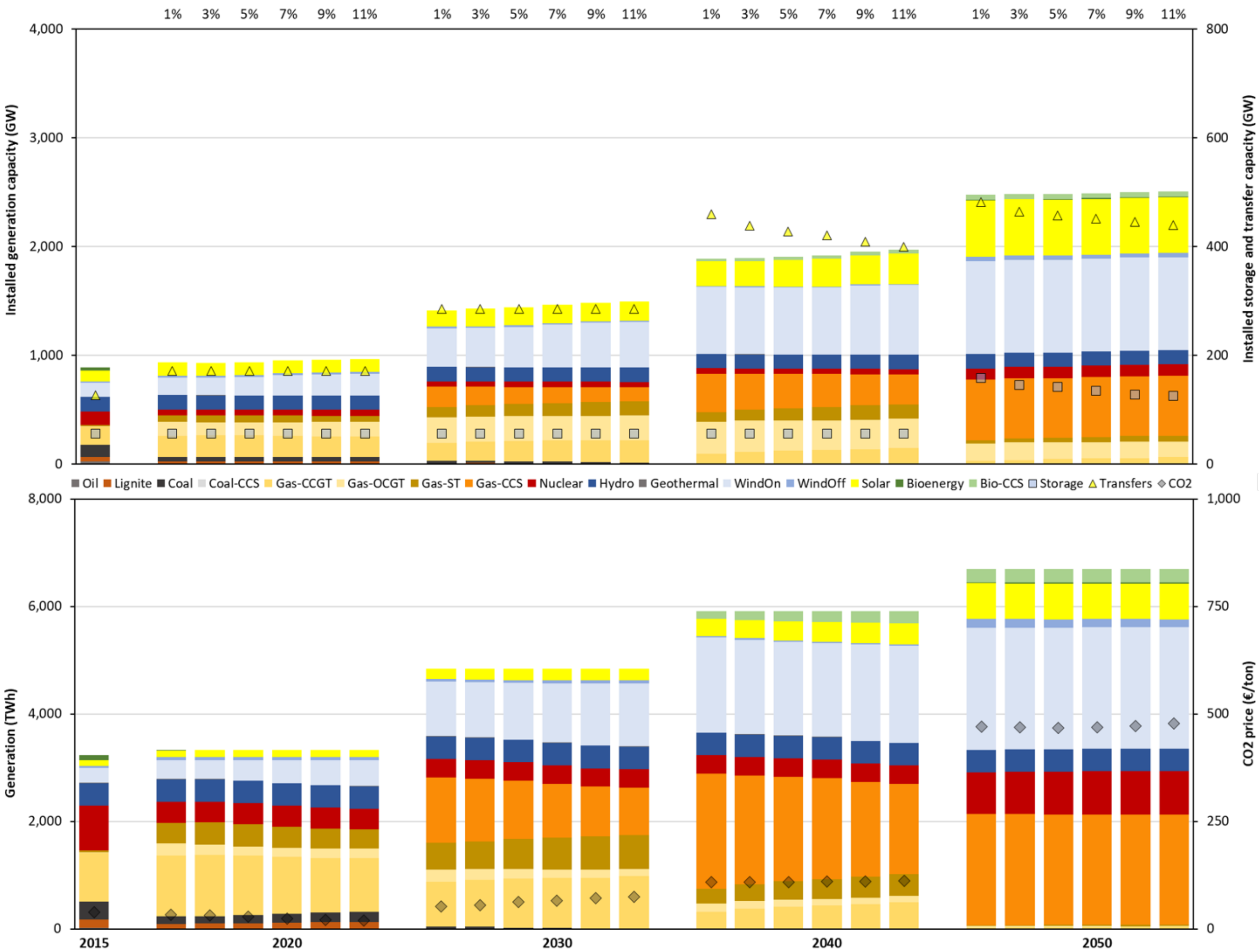

Figure B.6: Financing cost sensitivity for debt investment cost specification

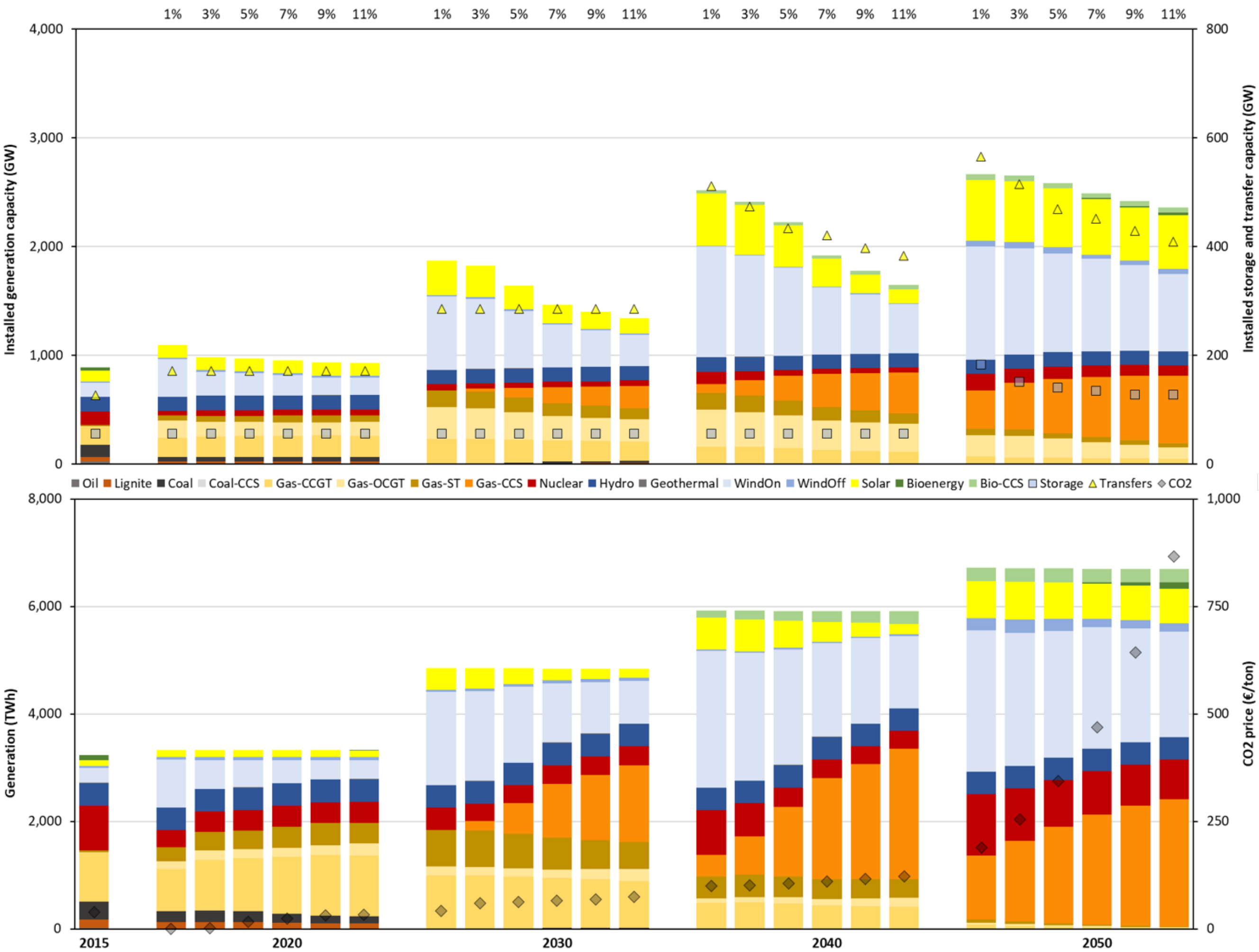

Figure B.7: Discount rate and financing cost sensitivity for debt investment cost specification