energies

Supplementary material to Modelling the transition towards a carbon-neutral electricity system - investment decisions and heterogeneity

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S1. Power plants parameters

In Table S.1 we present fuel cost, investment cost, lifetime and CO_2 emission intensity for each power plant. Data is adapted from Jonson et al. [1]. For NGCC (natural gas with combined cycle) and NGCC with CCS (carbon capture and storage) we based our estimate on Rubin and Zhai [2] and Cloete and Hirth [3]. The transport and storage cost for CO_2 is assumed to be 10 €/ton of CO_2, which gives a transport and storage cost of 4.6 €/MWh (given a storage of 460 gCO_2 per kWh).

Table S1. Assumed power plants parameters – costs and efficiencies.

Plant type	Capacity[1] (MW)	Fuel cost (cent/kWh el)	Investment cost (euro/kW)	Lifetime (years)	Emission intensity (gCO_2/kWh electricity)
Coal	500	2.0	1500	40	1000
NGCC	500	4.6 (natural gas)	800	30	432
		8.0 (biogas)			0
NGCC with CCS	500	5.9	1400	30	51
Nuclear	500	1.0	6000	40	0
Solar PV	500	0	800	25	0
Wind	500	0	1500	25	0

S2. Time slices

Table S2. Number of hours in each of the time slice (adapted from Jonson et al. 2020).

		Low wind	Medium-low wind	Medium-high wind	High wind
Low solar	Low q0	28	146	65	25
	Medium-low q0	256	1027	751	283
	Medium-high q0	153	645	434	255
	High q0	16	63	70	73
Medium-low solar	Low q0	34	128	53	21
	Medium-low q0	104	398	213	72
	Medium-high q0	59	268	235	119
	High q0	10	34	33	46
	Low q0	24	35	19	7

[1] We also test a case with 50 MW nameplate capacity. See the results in section S5.5.

Medium-high solar	Medium-low q0	124	227	163	81
	Medium-high q0	264	703	419	138
	High q0	17	52	89	53
High solar	Low q0	0	0	0	0
	Medium-low q0	23	15	15	1
	Medium-high q0	48	102	10	8
	High q0	1	3	2	0

Table S3. Values of the demand reference, solar availability and wind availability.

	Low level	Medium-low level	Medium-high level	High level
Demand reference *q0* (GW)	37.3060	47.6100	63.2400	71.5555
Solar availability	0	0.0311	0.3439	0.6731
Wind availability	0.0689	0.1912	0.4282	0.7470

S3. IRR and profitability calculation

In section 4.4 of the main article, we presented an *ex post* analysis of the internal rate of return (*IRR*) of investment and individual agents' *performances index* (*PI*). The *IRR* is derived from the net present value (*NPV)* expression:

$$NPV = \sum_{t=1}^{T} \frac{R_t - C_t}{(1 + IRR)^t} - I \qquad (1)$$

where t is the year, T is the lifespan of the plant and R_t is this plant's revenue in year t, C_t is its total operating cost of year t, and I is the investment cost of the plant.

The *IRR* is the discount rate that makes the NPV of a project equal to zero. We solve for IRR by setting $NPV = 0$.

The *performance index PI* is defined by

$$PI = \frac{TR_t - TC_t - A_t}{TI} \qquad (2)$$

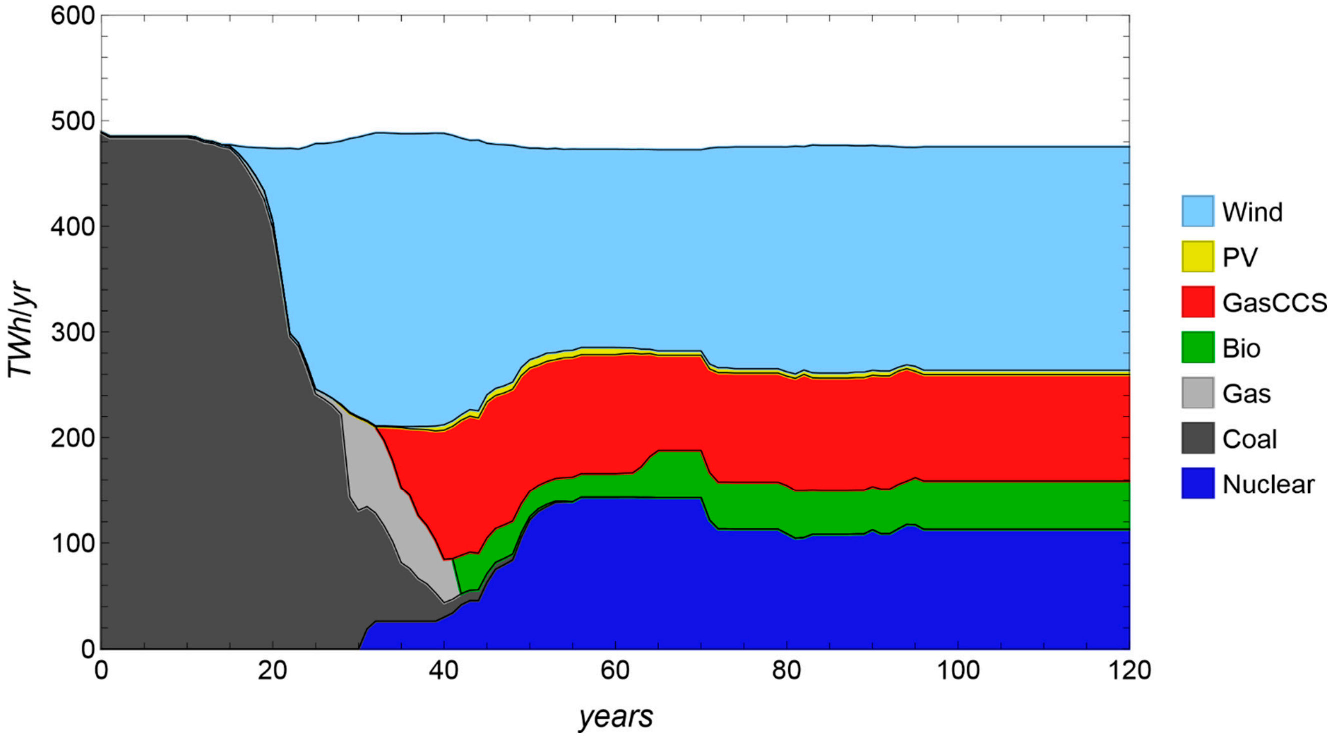
where t is the year, TR_t is the total revenue of an agent in year t, TC_t is its total operating cost in year t of this agent, A_t is the total annuitized investment cost this agent has to pay in year t, and TI is the total investment costs of all plants this agent currently has.

S4. Supplementary results

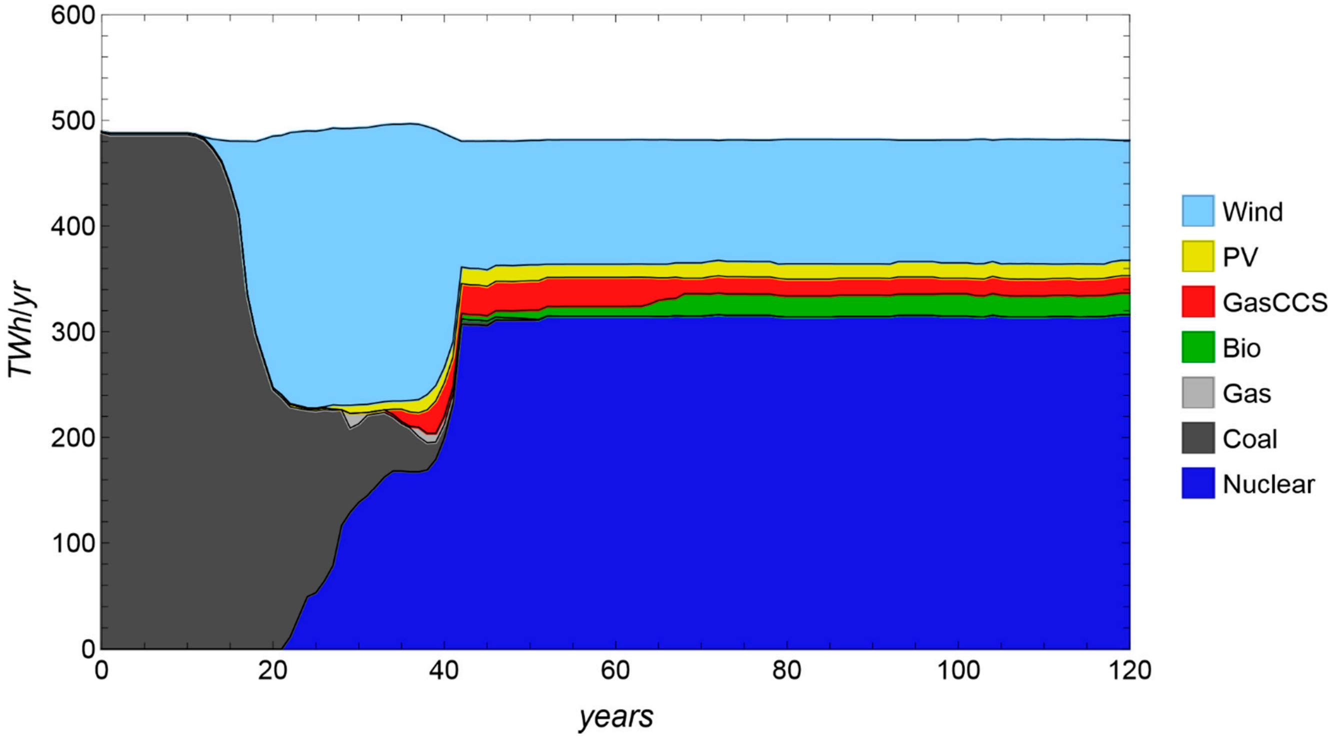
Here we report additional results for the three cases presented in the main article. The results include: (1) electricity production profile, (2) the capacity profile of individual agents and (3) economic performances of individual agents.

S4.1 Electricity production profile

Figs. S1a-c depict the electricity production for the homogeneous case, heterogeneous hurdle rate (HHR) case and heterogeneous foresight (HF) case. We observe that the production level stays around 480 TWh/year in all three cases and that the fuel source for electricity production shifts from coal to a combination of different low carbon technologies over time. Comparing these three cases, we see that the HF case largely resemble the homogeneous case, but with an earlier abandon of coal. In the HHR case, there is more electricity that is produced from nuclear, while less from wind and gas-fired plants.


600
500
400
300
200
100
0
TWh/yr
0
20
40
60
80
100
120
years
Wind
PV
GasCCS
Bio
Gas
Coal
Nuclear

(a)


600
500
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100
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TWh/yr
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20
40
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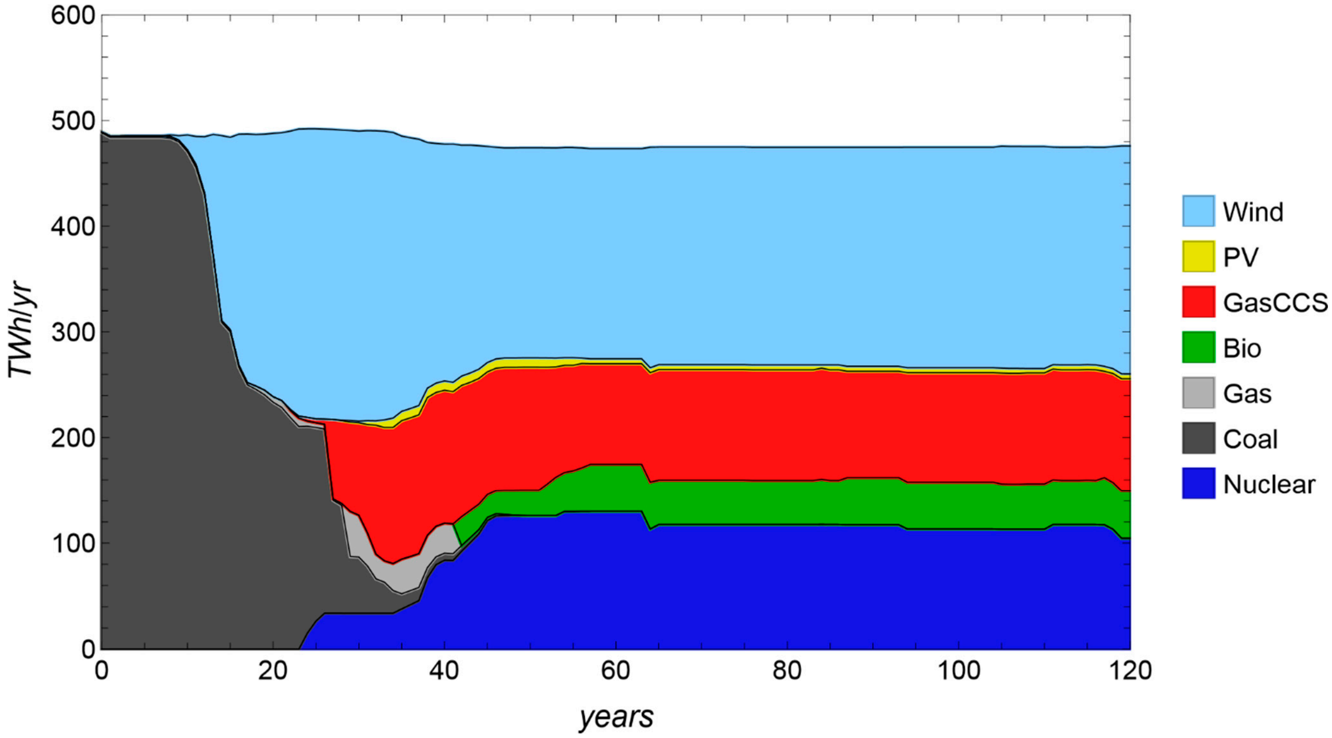
100
120
years
Wind
PV
GasCCS
Bio
Gas
Coal
Nuclear

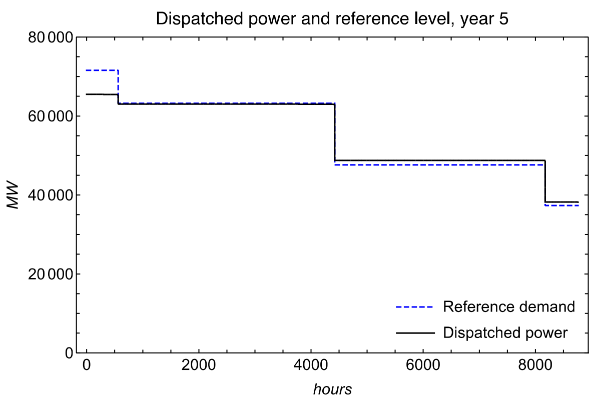
(b)

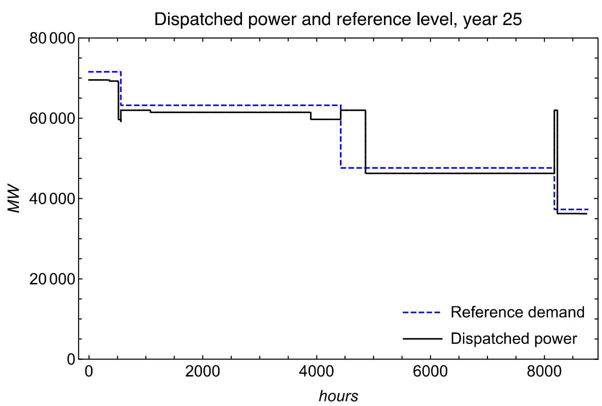


(c)

Figure S1. c Annual electricity production by technologies in the (a) homogeneous case, (b) HHR case, and (c) HF case.

Electricity production over the year is shown in Fig. S2 for four different years, illustrated by the dispatched power for the 64 time slices during the year, along with the corresponding reference demand level. Moving from a situation where production is typically close to the reference demand level to a system with a slightly lower production point due to an average increase in the electricity price. When carbon prices are introduced and lead to a slightly higher average cost of electricity production, this induces, through the price-elastic demand, a slight drop in the average output. But when wind generation is high, overall electricity production sometimes well exceeds the reference level. In the supplementary material we also present overall electricity output by technologies (see Fig. S1a-c).





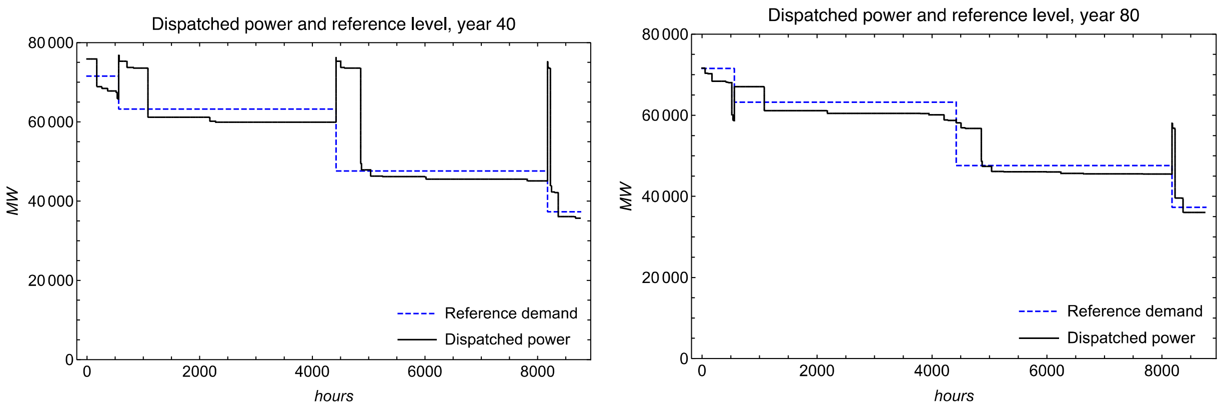
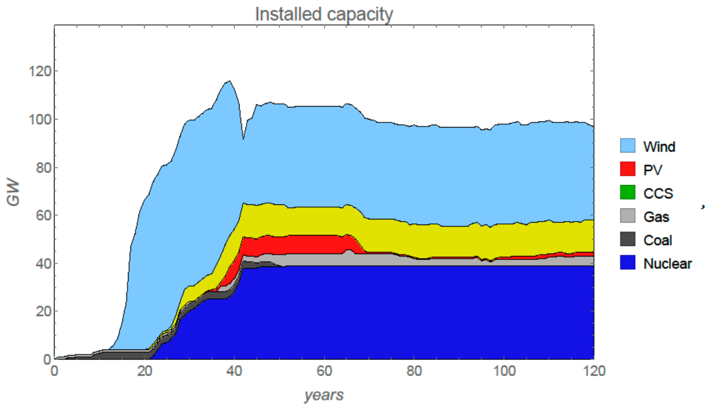
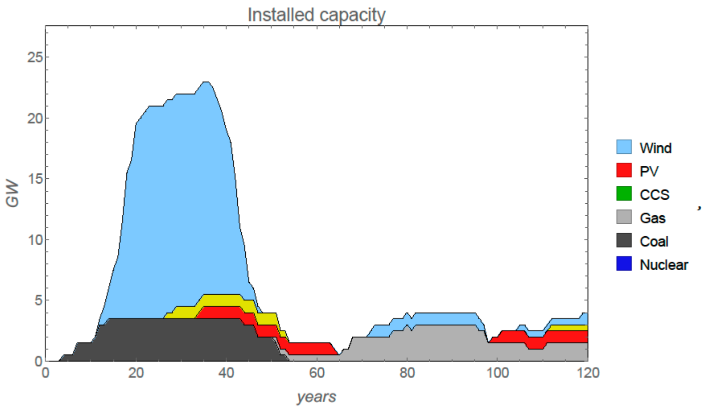


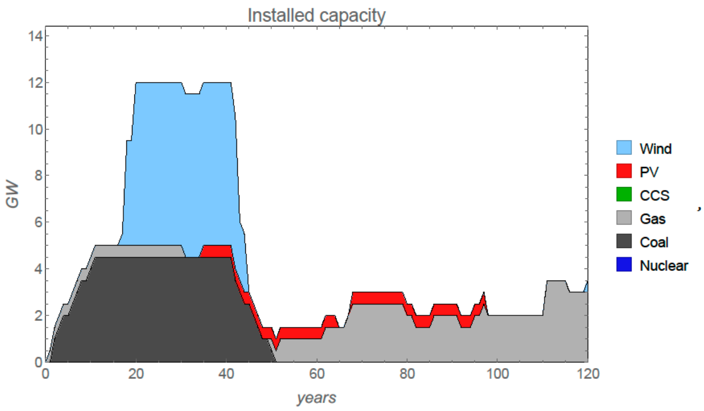
Figure S2. The reference demand level (dashed) and the dispatched power (solid) across the time slices of the year, for four different years (years 5, 25, 40, and 80) in the homogeneous case.

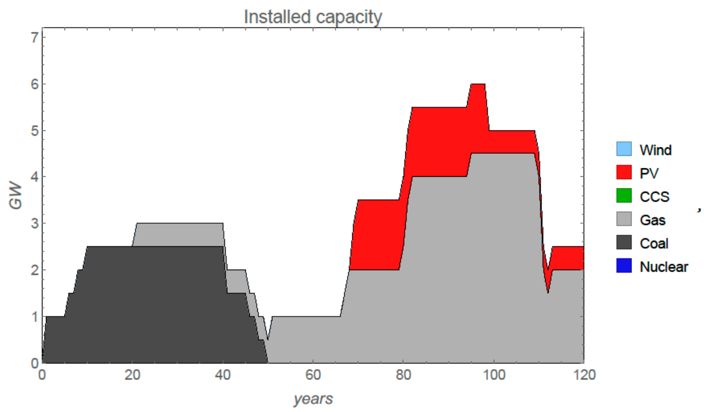
S4.2 Individual agents' capacity and financial performances of individual agents

In Fig. S3 we present the installed capacity for individual agents in the HHR case that made any investment. It is clearly seen that it is the agents with the lowest hurdle rate that dominate the electricity system. (Note that since the order of investment decisions are randomised the exact result may differ from one simulation to another, but the picture for the dominating agents are essentially unchanged). Fig. S4 illustrate the performance index of these agents.


Installed capacity
GW
years
Wind
PV
CCS
Gas
Coal
Nuclear


Installed capacity
GW
years
Wind
PV
CCS
Gas
Coal
Nuclear


Installed capacity
GW
years
Wind
PV
CCS
Gas
Coal
Nuclear


Installed capacity
GW
years
Wind
PV
CCS
Gas
Coal
Nuclear

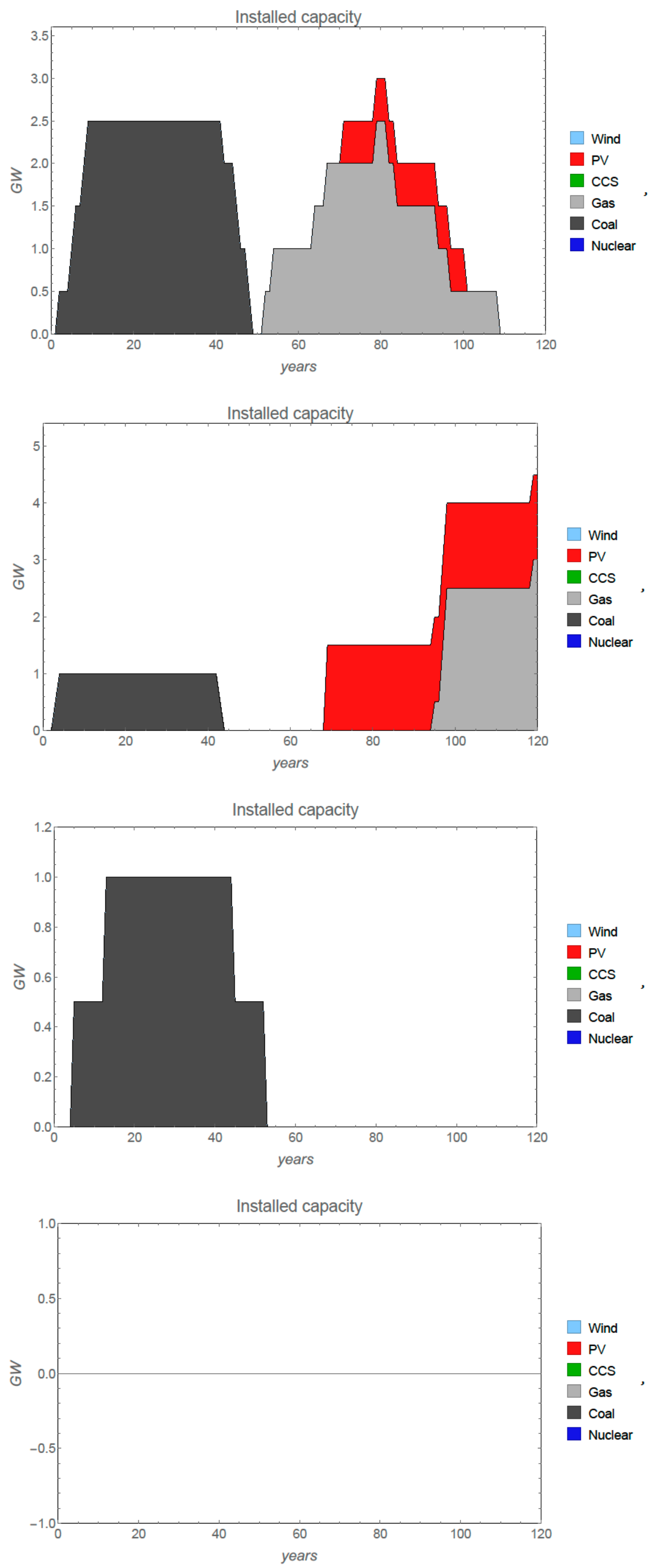


Figure S3. Illustration from one simulation showing the installed capacity of agents with hurdle rates from 5%/year (top figure) to 6.75%/year (bottom figure) in the HHR case. (Agents with hurdle rate equals to and larger than 6.75%/year did not make any investment.).

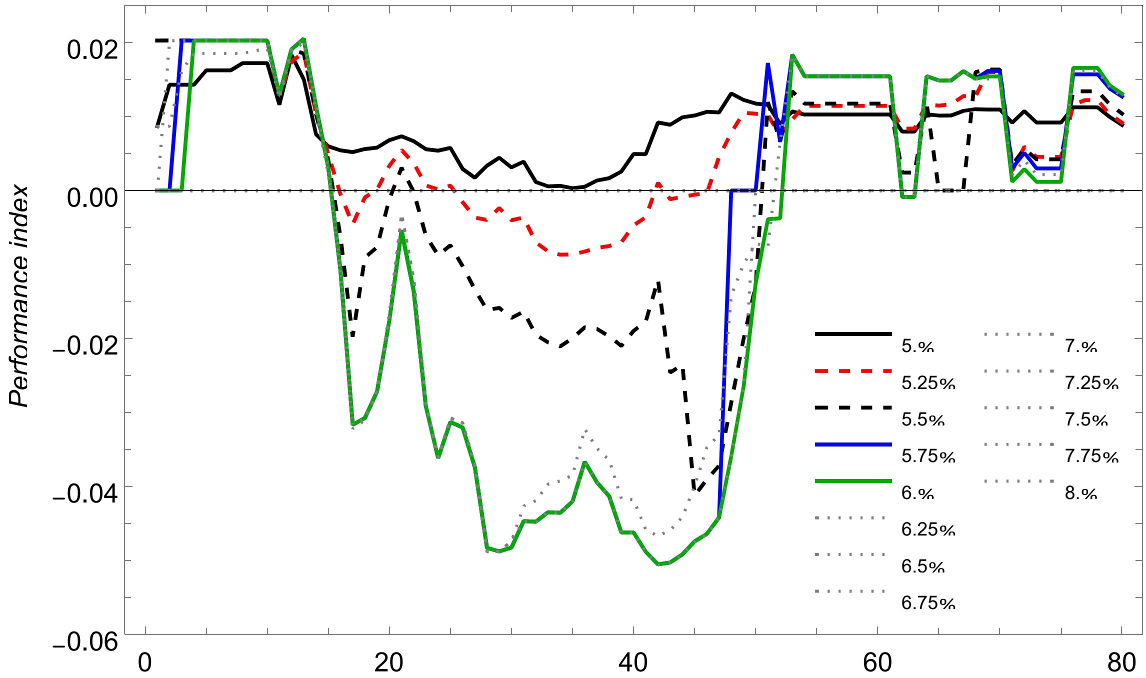


Figure S4. Individual agent's financial performance (measured by Performance Index) in the HHR case.

Fig. S5 shows all agents' installed capacity over time in the HF case. Initially, we can see that the agents who underestimate the increase in the carbon tax invest in coal, thereafter (around the year 10-30) it is the agents that expect the highest carbon tax that start to invest in low carbon technologies (primarily wind and then nuclear). After the stabilisation of the carbon tax (year 50), all agents have similar capacity profile. Fig. S6 shows the financial performances of all agents in the HF case.

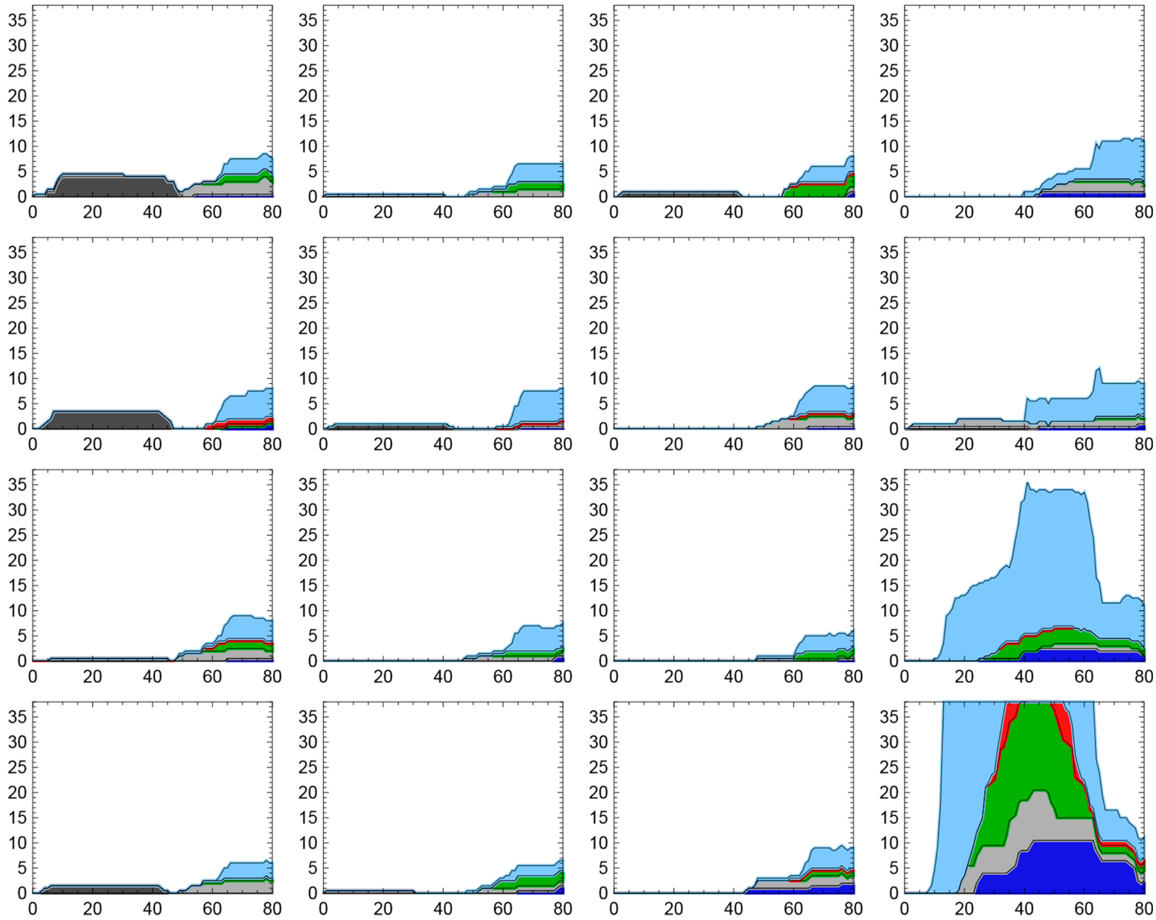


Figure S5. Individual agents´ installed capacity (GW) over the time period of 80 years in the HF case. First column (top to bottom) from β= 0 to β=0.3, with step of 0.1. Second column: from β= 0.4 to β=0.7; Third column: from β= 0.8 to β=1.1; Forth column: from β= 1.2 to β=1.5. (For installed capacity of the agent with β=1.5, see the main article).

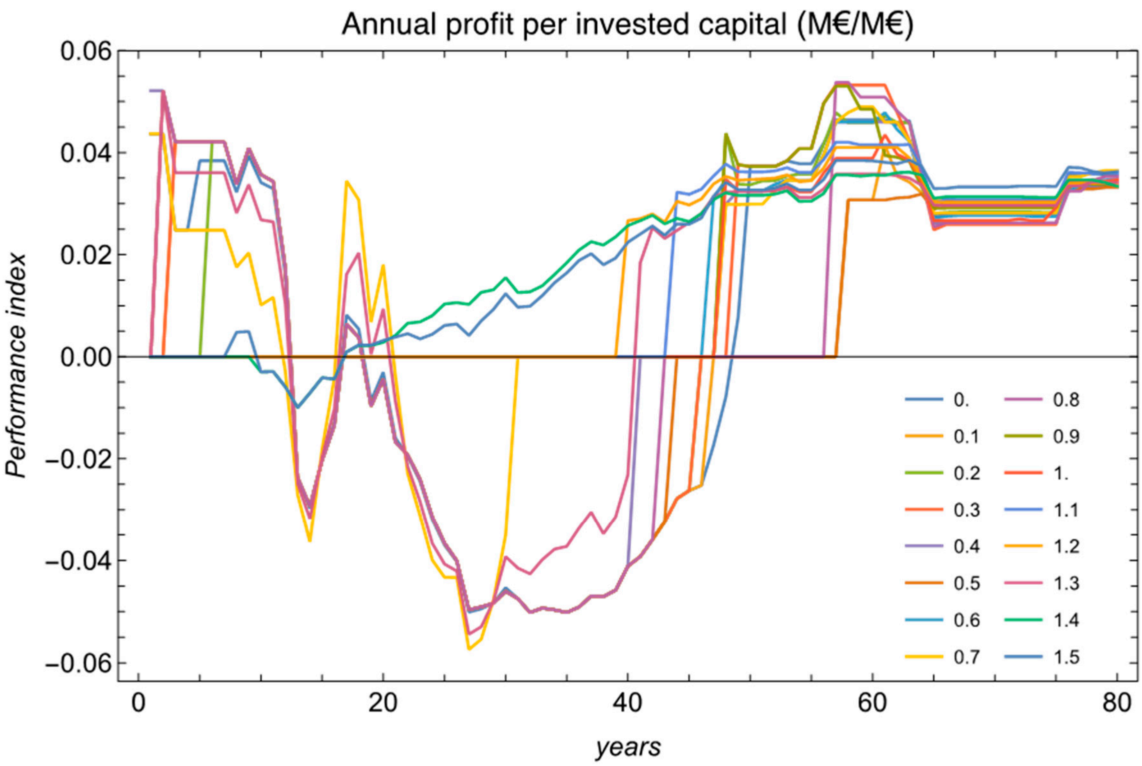
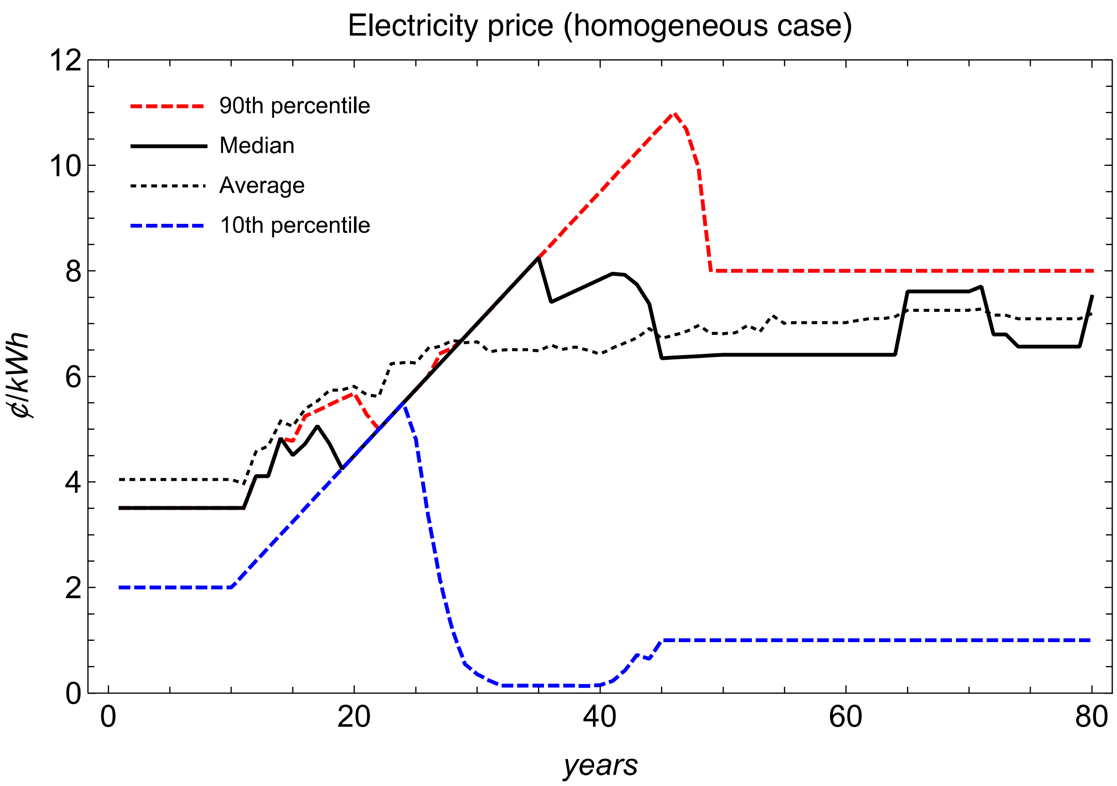


Figure S6. Individual agent's financial performance (measured by Performance Index) in the HF case.

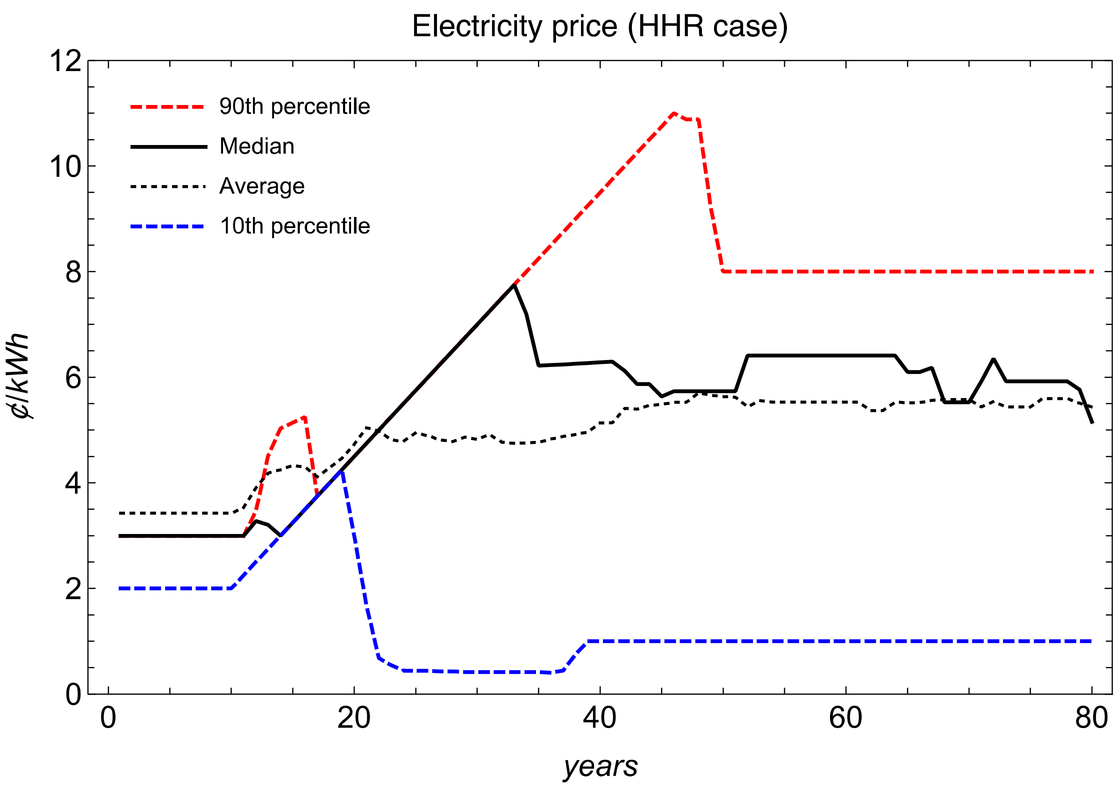
S4.3 Variations of electricity price – percentiles and standard deviation

The variation in price is also seen in Fig. S7, showing percentiles (10th and 90th) over the 80 years, along with median and average prices. In the homogeneous case (Fig. S6a), the price span decreases slightly in the initial phase of the transition. In year 25, we see that the 10th and 90th percentiles overlap, which means 80% of the prices are at the median level, despite the fact that we at this point have >65GW wind power, exceeding the combined capacities of coal and gas power. Figs. S7b-c show the price span for the HHR and HF cases. For the HHR case, the price span is smaller than in the homogeneous case, cf. Fig. S8. For the HF case, the main difference from the homogeneous case is the shift in time resulting from the 10-year foresight.



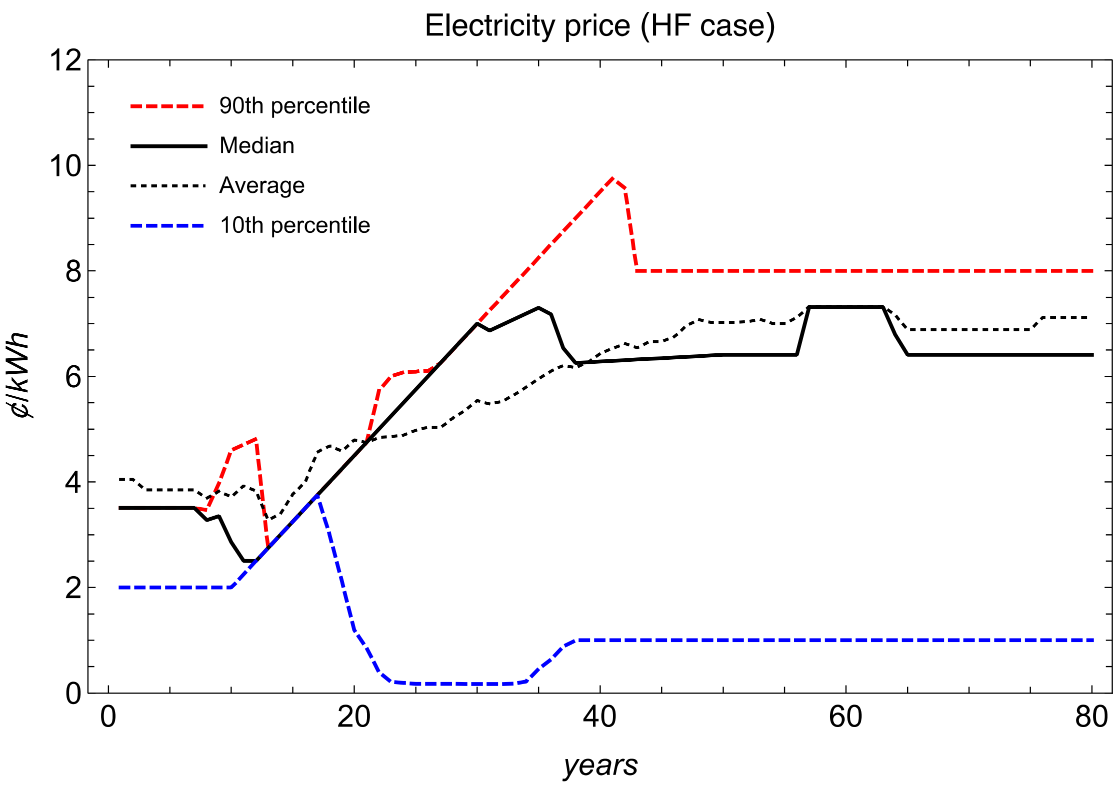
Electricity price (homogeneous case)
90th percentile
Median
Average
10th percentile
¢/kWh
years
0
2
4
6
8
10
12
0
20
40
60
80

(a)



Electricity price (HHR case)
90th percentile
Median
Average
10th percentile
¢/kWh
years
0
2
4
6
8
10
12
0
20
40
60
80

(b)



(c)

Figure S7. c Electricity-price spread over time illustrated by 10th and 90th percentiles, as well as the average and median prices for the (a) homogeneous case, (b) HHR case, and (c) HF case.

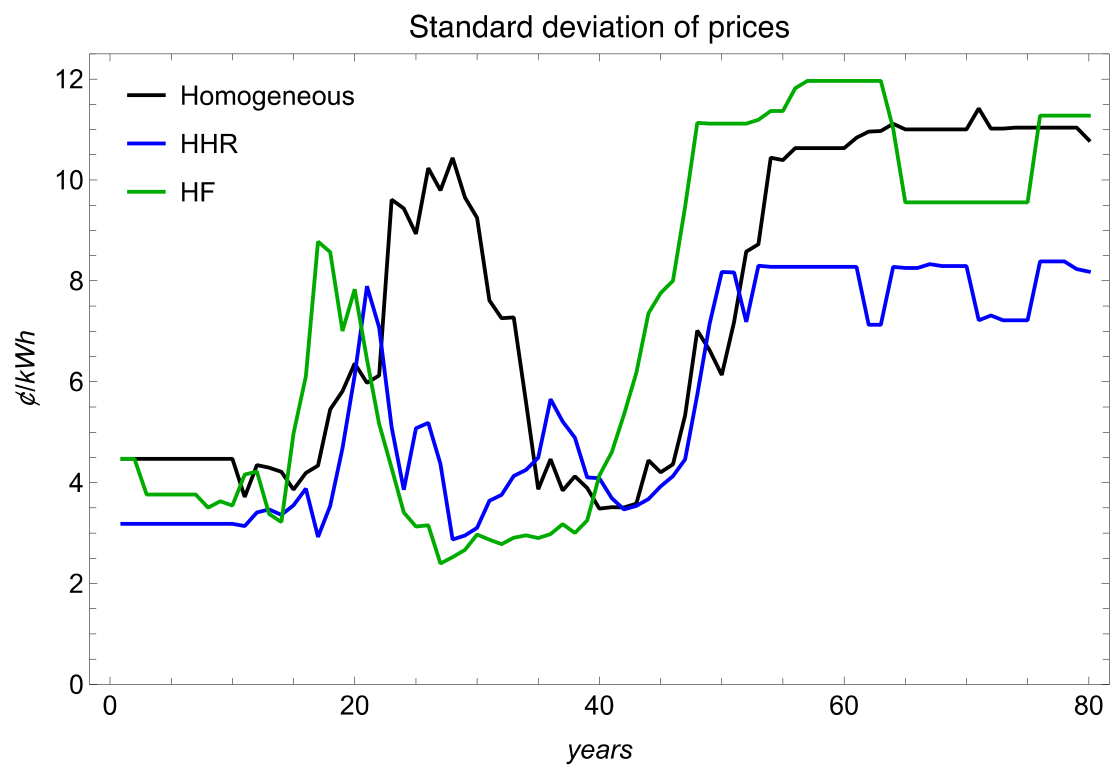


Figure S8. Standard deviation of electricity price for the homogeneous case, HHR case, and HF case.

S5. Sensitivity analysis

S5.1. Homogeneous 10-year foresight case

To exam how the agents´ foresight impact their investment decisions, we design a new case of homogeneous agents with a 10-year foresight (refer as *homogenous 10-year foresight case*). In this case, agents have the same characteristics as agents in *the homogeneous case* (described in section 3 in the main article), except that the agents in this case know the correct carbon price 10 years into the future instead of 1 year.

Fig. S9 shows that comparing with the base homogeneous case, agents with a 10-year foresight shift their investments earlier to low carbon technologies resulting in a faster CO_2 reduction. This is because longer foresight gives agents better information about the development of the future carbon price, the agents adjust their investment timely.

However, the CO_2 reduction in the homogeneous 10-year foresight case is slower when comparing to the heterogeneous foresight (HF) case, where agents also use 10-year information about the carbon price but are heterogeneous in their expectation of future carbon price. This result implies that the uncertainty about future carbon price in the HF case accelerate the transition process. This may seem counterintuitive, but here is our explanation. In the homogenous 10-year foresight case, all agents foresee the same correct information of the carbon price and all the agents make investments accordingly. However, in the HF case, the growth rate of future carbon price is uncertain, some agents underestimate the growth of the carbon price and continue to invest in coal for a longer period, while some agents overestimate price and shift their investment even earlier than the agents in the former case. As also explained in section 4.1 in the main article, the agents who overestimate the carbon price expect a higher electricity price, they invest more heavily in low carbon technologies, and the net outcome from under- and overestimated carbon price result in more investment in low carbon technologies.

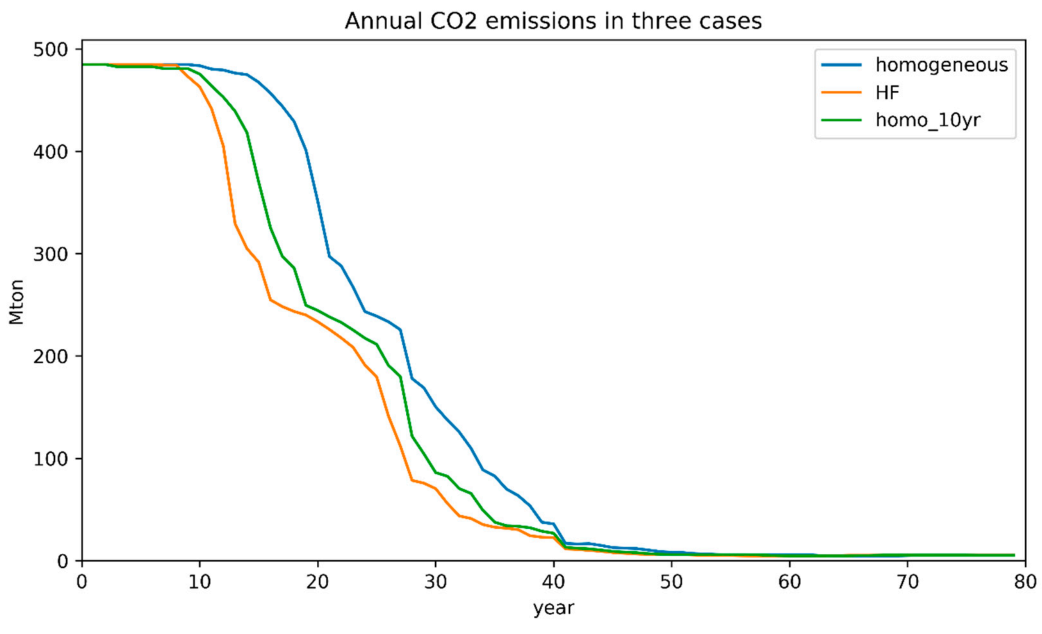


Figure S9. Annual emissions in the homogeneous case, HF case and homogeneous 10-year foresight case.

S5.2 The impact of the hurdle rate on the installed capacity of wind and how it is related to the availability of gas

We analyse how the installed capacity of wind changes as a function of the hurdle rate. Interestingly, we find that lower hurdle rate leads to *significantly* lower amounts of wind (almost half) despite the fact that a lower hurdle rate could be expected to favour a capital-intensive technology such as wind (Table S4). This is essentially the same finding as we show in the main manuscript when running the model in the HHR case.

However, here we also want to illustrate what happens when dispatchable (near) carbon neutral technologies - biogas, and gas with CCS are not available. In this case we find that (i) there is much less wind used overall, and (ii) the amount of wind is hardly affected by the change in the hurdle rate.

These results demonstrate the complementary nature of gas-fired and wind power plants in the electricity system. If gas is available, the market solution (as modelled in our agent-based model) leads to much more wind being installed than in the absence of gas. If the hurdle rate drops, with gas available, it means that both wind and nuclear gain competitiveness in relation to gas, but since nuclear takes a larger share of the market, it leads to less gas being installed and in turn that leads to a lower competitiveness for wind.

Table S4. Installed capacity of wind in year 80 in different set-ups in terms of hurdle rates and gas plants availability.

Hurdle rate	Gas fired power plants (biogas, and gas with CCS) are available	No gas fired power plants (biogas, and gas with CCS) are available
5%/year	42 GW	15 GW
8%/year	75 GW	15 GW

S5.3 System impacts from exogenous PV investments

We have tested a case where there are substantial PV investments. Starting from year 10, we add 3 GW of solar PV every year into the capacity mix, to represent investments from households and other investments made in response to subsides. Solar PV expands at this rate for about 20 years and eventually reaches a total of 75 GW. This is modelled as an exogenous assumption in the model.

The purpose with this analysis is to investigate how a more rapid and larger (exogenously driven) expansion of solar PV affects the development of the overall electricity system. The analysis is carried out in the case where agents exhibit heterogenous hurdle rates.

Fig. S10 shows that when exogenous PV is installed, agents invest less in nuclear capacity but more in wind and gas, compared to the case where there is no exogenous PV investments. This leads to less electricity generation from nuclear plants but more from solar, wind and gas power plants (Fig.S11).

We have also tested a case with a slower (exogenous) expansion of PV, where the Solar PV expands at a rate of 1 GW per year for about 20 years and reaches and stays at 25 GW. Results show that the impact from this exogenously driven 25 GW PV scenario on investments in other technologies is rather small.

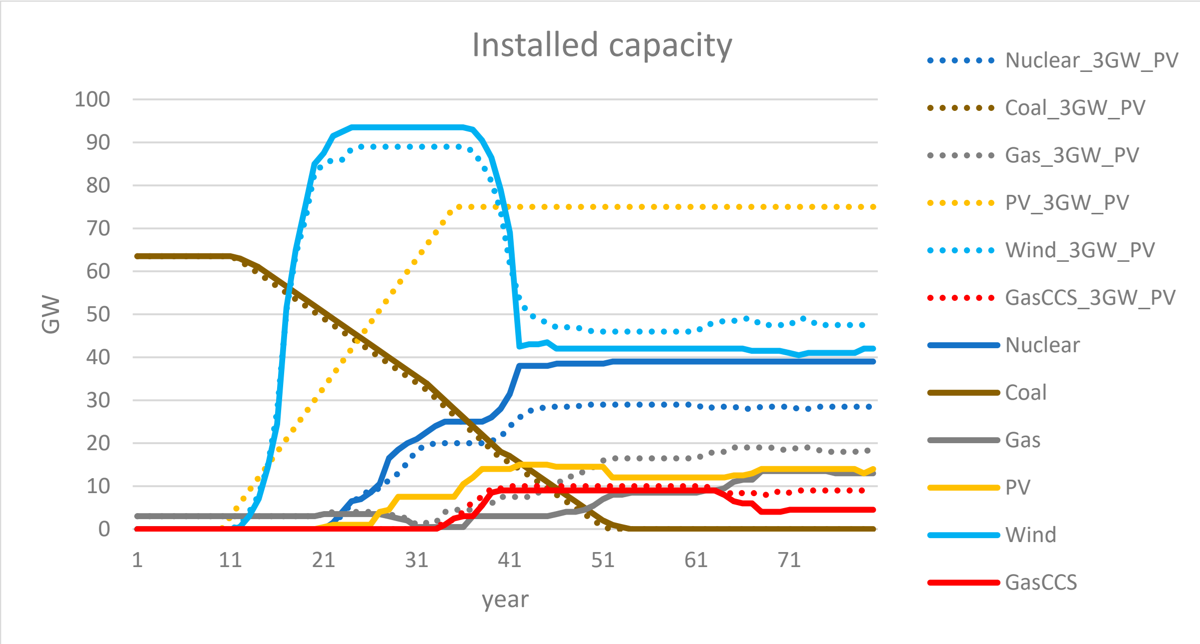


Figure S10. The system installed capacity in the HHR case. The dashed lines represent the case with exogenous PV investment from households, while the solid lines represent the HHR case in the main article where there is no PV investment from households (the level of PV investments is determined by endogenous decisions by the agents based on pure economic reasons).

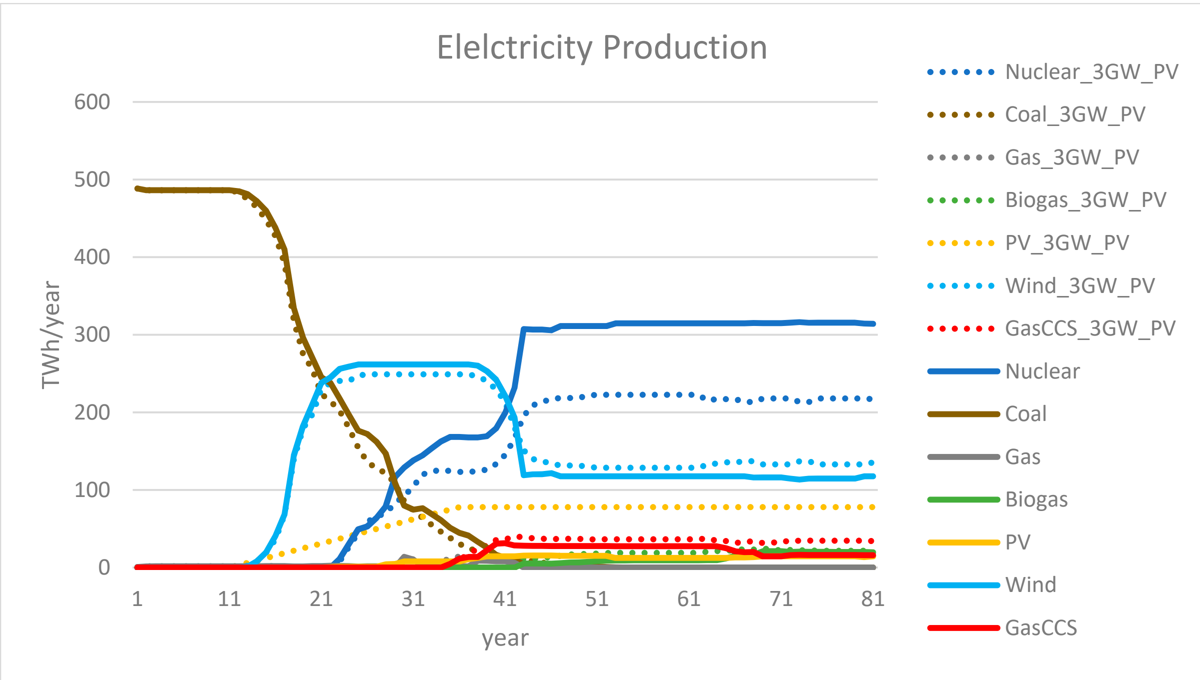


Figure S11. Annual electricity production by technology in the HHR case. The dashed lines represent the case with PV investment from the households, while the solid lines represent the HHR case in the main article where there is no PV investment from households.

S5.4 Growing electricity demand

We have tested a case where the electricity demand is growing over time. Between year 10 to year 50, the electricity demand grows at a rate of 1% per year, and then stays at that level thereafter. Fig. S12 shows that with a growing electricity demand, the installed capacity of each type of technology increases compared to our base case scenario where there is no growth in the electricity demand.

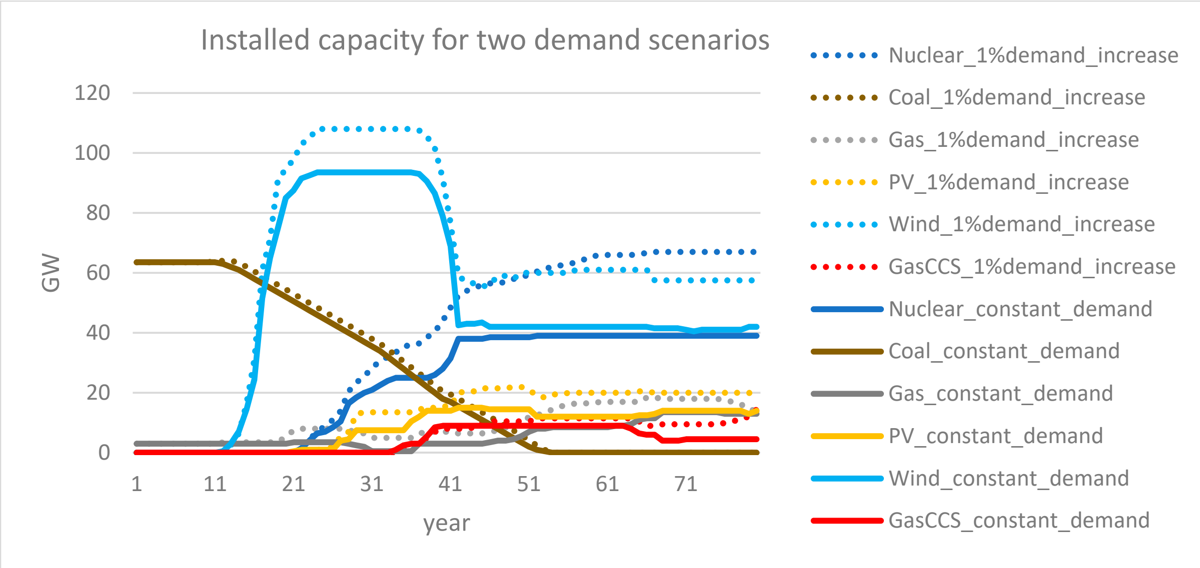


Figure S12. Installed capacity in the HHR case in the two demand scenarios. The solid line is the HHR case with a constant electricity demand as shown in the main article, whereas the dashed line is the scenario with a 1% growth in electricity demand.

S5.5 Size of the plant

In the main article, we use a uniform plant size of 500 MW. Here we test a case with a uniform plant size of 50 MW to test how the size of plants would impact the model results. Fig. S13 shows that there are slightly more nuclear and less wind and gas capacities in the case with plant size 50 MW, but the overall result is similar to the case with 500 MW plant. This indicates that using 500 MW plants does not have a strong impact on our model results. The reason why there is more nuclear in this case is because a smaller plant size makes it possible to invest in incremental steps.

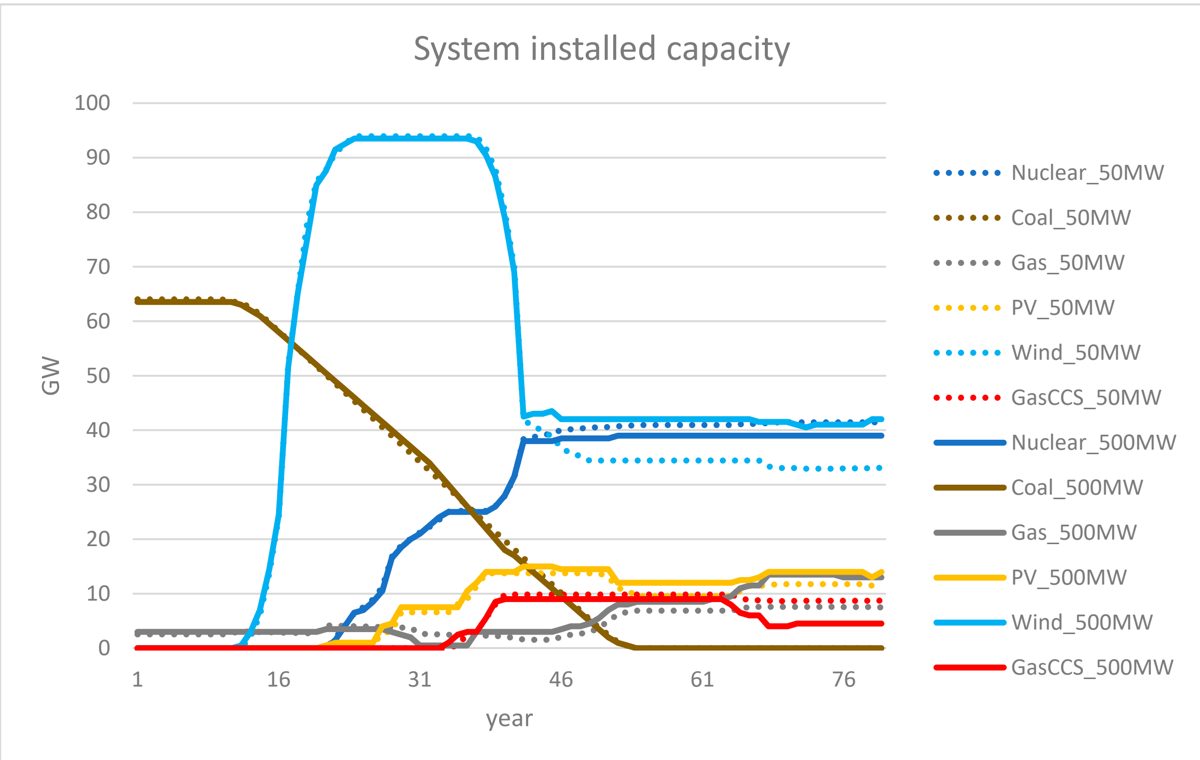


Figure S13. Installed capacity of individual technologies in the HHR case. The dashed lines represent the case with 50 MW plant size, and the solid lines represent the case with 500 MW plant size. This shows that results are similar in these two cases. In the HF case, the result is also similar between using 50 MW and 500 MW plant size.

References

1. Jonson, E., et al., *Exploring the competition between variable renewable electricity and a carbon-neutral baseload technology.* Energy Systems, 2020. **11**(1): p. 21-44.
2. Rubin, E.S. and H. Zhai, *The Cost of Carbon Capture and Storage for Natural Gas Combined Cycle Power Plants.* Environmental Science & Technology, 2012. **46**(6): p. 3076-3084.
3. Cloete, S. and L. Hirth, *Flexible power and hydrogen production: Finding synergy between CCS and variable renewables.* Energy, 2020. **192**: p. 116671.