Supplementary information for "Effects of electricity sector climate policies in a second-best world of missing risk markets"

Emil Dimanchev[1,2,*], Stein-Erik Fleten[3], Steven A. Gabriel[3,4,5], and Magnus Korpås[1]

[1]Department of Electric Energy, NTNU - Norwegian University of Science and Technology, Trondheim, Norway
[2]Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA
[3]Department of Industrial Economics and Technology Management, NTNU - Norwegian University of Science and Technology, Trondheim, Norway
[4]Department of Mechanical Engineering, University of Maryland, College Park, MD, USA
[5]Department of Mathematics and Systems Analysis, Aalto University, Espoo, Finland
[*]Contact: emild@mit.edu

Nomenclature

Indices and Sets

$s \in S$ Demand scenarios

$t \in T$ Time steps (hours)

$r \in R$ Technology resources

$G \subset R$ Generation technologies (gas, wind, solar)

$O \subset R$ ($O \cap G = \emptyset$) Storage technologies (batteries)

Parameters

D_{ts} Demand (MWh)

C_r^{var} Variable cost ($/MWh)

Ω Weight for risk aversion (fraction)

Ψ Probability level used to parameterize risk aversion (fraction)

A_{rt} Availability of generation resource (fraction)

C_r^{inv} Investment cost ($/MW)

F^{ch} Charging efficiency (fraction)

F^{dch} Discharging efficiency (fraction)

N_r^s Power to energy ratio for storage technologies (fraction)

C^{cap} Price cap ($/MWh)

W_t Weight of representative time period (fraction)

P_s Probability of demand s (fraction)

E_r^{co2} Emissions intensity (tCO_2/MWh)

Variables

g_{rts} Generation (MWh)

x_r Capacity (MW)

y_{ts} Load shedding (MWh)

e_{rts} Energy stored, i.e., state of charge (MWh)

z_{rts}^{ch} Charging of storage technology (MWh)

z_{rts}^{dch} Discharging from storage technology (MWh)

$\tilde{\zeta}$ Value-at-Risk (VaR) for representative investor (\$)

$\tilde{u}_s$ Loss relative to VaR for representative investor (\$)

π_{rs} Revenues net of operating costs (\$/MW)

λ_{ts} Price of electricity (\$/MWh)

μ_{rts} Generation capacity rent (\$/MW)

$\phi_{rts}^{soc}, \phi_{rts}^{cap}, \phi_{rts}^{c}, \phi_{rts}^{d}, \phi_{rts}^{bal}, \xi_{rts}^{d}$ Dual variables corresponding to storage constraints

θ_s^Z Binary indicating whether scenario s is in the CVaR tail

S1 Model formulation

We use the equilibrium generation expansion model developed in Dimanchev et al. (2023), which we describe here briefly (this model is also publicly available[1]). The model represents generation expansion in a power system where investors and consumers do not share risk. To that end, our approach formulates the optimal decision making problems of different market participants and solves them simultaneously as a system of necessary and sufficient[2] optimality conditions. We model risk-averse investors using a representative price-taking investor agent choosing to deploy capacity x_r of any technology r (we consider gas, wind, solar, and Li-ion batteries). The model also includes a system operator agent dispatching the resources built by investors in a least-cost way (effectively acting on behalf of consumers), while meeting demand and respecting engineering constraints. Note that our equilibrium model is consistent with the canonical optimization-based method for generation expansion if investors are risk-neutral[3].

The model's mathematical formulation is included below. For the derivation, we refer the reader to Dimanchev et al. (2023). In this paper, we add the investment tax credit (ITC) parameter I_r^{inv} and the CO_2 tax parameter C^{tax}. The ITC parameter I_r^{inv} represents a fraction and acts as a reduction in the investment cost C_r^{inv}. The CO_2 tax represents an exogenous $\$/tCO_2$ cost.

Below, we first show the investor's necessary and sufficient conditions[4]. These expressions represent common economic relationships: for example, (1a) is a zero-profit condition; (1b) is a classical optimality condition, which relates cost of investment C_r^{inv} to future revenues π_{rs}, adjusted for risk (which relies on expressions (1c)-(1k)). Specifically, the risk-adjusted future revenues represent the combination of expected revenues π_{rs} and their CVaR, which is contained in variable ν_{rs}. The CVaR takes on the value of the Ψ-worst tail of the profit distribution via (1k). The amount of weight investors place on CVaR is exogenously set by Ω which in effect determines the degree of risk aversion. Risk aversion is parameterized using illustrative values of: $\Omega = 0.5$[5], and $\Psi = 0.25$[6], as we do not attempt to quantify real market outcomes (see sensitivity analysis below).

[1] https://zenodo.org/records/10709502

[2] They are necessary and sufficient as the underlying optimization problem is linear (Dimanchev et al., 2023).

[3] The equilibrium model with risk-neutral investors produces the same result as an optimization model with risk-neutral investors as discussed in Dimanchev et al. (2023) where both model formulations can be found.

[4] From a mathematical perspective, these conditions represent the strong duality condition (1a) of the investor's profit maximization problem; (1k)-(1n) are the associated primal feasibility constraints; finally, expressions (1b)-(1j) ensure dual feasibility.

[5] This may be interpreted as 50% of capital being supplied by risk-averse investors.

[6] In our case this means that a risk-averse agent makes their decisions based on the single scenario that represents the worst outcome for that agent (recall that we have four demand scenarios each with a probability of 25%).

$$
\begin{aligned}
&\Omega\left[\sum_s P_s \sum_r \pi_{rs} x_r - \sum_r (1 - I_r^{inv}) C_r^{inv} x_r\right] + \\
&(1-\Omega)\left[\tilde{\zeta} - \frac{1}{\Psi}\sum_s P_s \tilde{u}_s\right] = 0 && \text{(1a)}\\
&(1 - I_r^{inv}) C_r^{inv} - \Omega \sum_s P_s \pi_{rs} - (1-\Omega)\sum_s \nu_{rs} \geq 0 \quad \forall\, r \in R && \text{(1b)}\\
&\theta_s^Z \in \{0, 1\} \quad \forall\, s \in S && \text{(1c)}\\
&\frac{1}{\Psi} P_s - \frac{1}{N^{cvar}} \theta_s^Z \geq 0 \quad \forall\, s \in S && \text{(1d)}\\
&\sum_s \frac{1}{N^{cvar}} \theta_s^Z = 1 && \text{(1e)}\\
&\nu_{rs} \geq 0 \quad \forall\, r \in R, s \in S && \text{(1f)}\\
&h_{rs} \geq 0 \quad \forall\, r \in R, s \in S && \text{(1g)}\\
&\nu_{rs} \leq \bar{M} \theta_s^Z \quad \forall\, r \in R, s \in S && \text{(1h)}\\
&h_{rs} \leq \bar{M}(1 - \theta_s^Z) \quad \forall\, r \in R, s \in S && \text{(1i)}\\
&\nu_{rs} + h_{rs} = \frac{1}{N^{cvar}} \pi_{rs} \quad \forall\, r \in R, s \in S && \text{(1j)}\\
&\tilde{u}_s \geq \tilde{\zeta} - \sum_r \pi_{rs} x_r + \sum_r (1 - I_r^{inv}) C_r^{inv} x_r \quad \forall\, s \in S && \text{(1k)}\\
&x_r \geq 0 \quad \forall\, r \in R && \text{(1l)}\\
&\tilde{u}_s \geq 0 \quad \forall\, s \in S && \text{(1m)}\\
&\tilde{\zeta} \in \mathbb{R} && \text{(1n)}
\end{aligned}
$$

The system operator's necessary and sufficient conditions are shown next[7]. These expressions contain the common economic and engineering relationships included in generation expansion models. Expressions (2b)-(2n) represent engineering constraints on power system operation. For example, (2e) ensures the power market's supply-demand balance between, one the one hand, generation g_{rts}, battery operation $z_{rts}^{dch}, z_{rts}^{cch}$ and load shedding y_{ts}, and on the other, demand D_{ts} in each time period t and scenario s. Physical constraints on power generation and energy storage are represented respectively by (2f) and (2g)-(2n). Expressions (2o)-(2x) are the optimality conditions related to optimal dispatch of generation and storage resources. For instance, (2s) relates the marginal costs of power generation to its marginal value. Finally, (2a) states that the total cost of operating the power system must equal its value.

[7]From a mathematical perspective, (2a) is the strong duality condition of the system operator's cost-minimization problem; (2b)-(2n) represent the primal feasibility constraints; and expressions (2o)-(2x) represent the dual feasibility constraints.

$$\sum_t W_t \sum_r C_r^{var} g_{rts} + \sum_t W_t \sum_r C^{tax} E_r^{co2} g_{rts} +$$
$$\sum_t W_t C^{cap} y_t = \sum_t \lambda_t D_{ts} - \sum_r \pi_{rs} x_r \quad \forall\, s \in S \tag{2a}$$
$$g_{rts} \geq 0 \quad \forall\, r \in G, t \in T, s \in S \tag{2b}$$
$$e_{rts}, z_{rts}^{ch}, z_{rts}^{dch} \geq 0 \quad \forall\, r \in O, t \in T, s \in S \tag{2c}$$
$$y_{ts} \geq 0 \quad \forall\, t \in T, s \in S \tag{2d}$$
$$\sum_r^{|G|} \left[g_{rts}\right] + \sum_r^{|O|} \left[z_{rts}^{dch} - z_{rts}^{ch}\right] + y_{ts} = D_{ts} \quad \forall\, t \in T, s \in S \tag{2e}$$
$$g_{rts} \leq x_r A_{rt} \quad \forall\, r \in G, t \in T, s \in S \tag{2f}$$
$$e_{r1s} = e_{r|T|s} - \frac{1}{F^{dch}} z_{r1s}^{dch} + F^{ch} z_{r1s}^{ch} \quad \forall\, r \in O, s \in S \tag{2g}$$
$$e_{rts} = e_{rt-1s} - \frac{1}{F^{dch}} z_{rts}^{dch} + F^{ch} z_{rts}^{ch} \;\; \forall\, r \in O, t \in \{2, 3, ..., |T|\}, s \in S \tag{2h}$$
$$e_{rts} \leq \frac{1}{N_r^s} x_r \quad \forall\, r \in O, t \in T, s \in S \tag{2i}$$
$$z_{rts}^{ch} \leq x_r \quad \forall\, r \in O, t \in T, s \in S \tag{2j}$$
$$z_{rts}^{dch} \leq x_r \quad \forall\, r \in O, t \in T, s \in S \tag{2k}$$
$$z_{r1s}^{dch} \leq e_{r|T|s} \quad \forall\, r \in O, s \in S \tag{2l}$$
$$z_{rts}^{dch} \leq e_{rt-1s} \quad \forall\, r \in O, t \in \{2, 3, ..., |T|\}, s \in S \tag{2m}$$
$$z_{rts}^{dch} + z_{rts}^{ch} \leq x_r \quad \forall\, r \in O, t \in T, s \in S \tag{2n}$$
$$\lambda_{ts} \in \mathbb{R} \quad \forall\, t \in T, s \in S \tag{2o}$$
$$\mu_{rts} \geq 0 \quad \forall\, r \in G, t \in T, s \in S \tag{2p}$$
$$\phi_{rts}^{soc} \in \mathbb{R} \quad \forall\, r \in O, t \in T, s \in S \tag{2q}$$
$$\phi_{rts}^{cap}, \phi_{rts}^{c}, \phi_{rts}^{d}, \phi_{rts}^{bal}, \xi_{rts}^{d} \geq 0 \quad \forall\, r \in O, t \in T, s \in S \tag{2r}$$
$$W_t C_r^{var} - \lambda_{ts} + W_t C^{tax} E_r^{co2} + \mu_{rts} \geq 0 \quad \forall\, r \in G, t \in T, s \in S \tag{2s}$$
$$W_t C^{cap} - \lambda_{ts} \geq 0 \quad \forall\, t \in T, s \in S \tag{2t}$$
$$\phi_{rts}^{soc} - \phi_{rt+1s}^{soc} + \phi_{rts}^{cap} - \xi_{rt+1s}^{d} \geq 0 \quad \forall\, r \in O, t \in \{1, 2, ..., |T| - 1\}, s \in S \tag{2u}$$
$$\phi_{r|T|s}^{soc} - \phi_{r1s}^{soc} + \phi_{r|T|s}^{cap} - \xi_{r1s}^{d} \geq 0 \quad \forall\, r \in O, s \in S \tag{2v}$$
$$- F^{ch} \phi_{rts}^{soc} + \phi_{rts}^{c} + \phi_{rts}^{bal} + \lambda_{ts} \geq 0 \quad \forall\, r \in O, t \in T, s \in S \tag{2w}$$
$$\frac{1}{F^{dch}} \phi_{rts}^{soc} + \phi_{rts}^{d} + \xi_{rts}^{d} + \phi_{rts}^{bal} - \lambda_{ts} \geq 0 \quad \forall\, r \in O, t \in T, s \in S \tag{2x}$$

where π_{rs} represent energy sales revenues defined as follows for generation and storage resources respectively:

$$\forall\, r \in G,\ \pi_{rs} := \sum_{t} \mu_{rts} A_{rt}$$

$$\forall\, r \in O,\ \pi_{rs} := \sum_{t} \left[\frac{1}{N_r^s} \phi_{rts}^{cap} + \phi_{rts}^{c} + \phi_{rts}^{d} + \phi_{rts}^{bal} \right]$$

The entire generation expansion model (1)-(2) is solved as a Mixed Integer Quadratically Constrained Program[8] using the Gurobi non-convex solver (Gurobi, 2020). To facilitate numerical solutions, we upper-bound renewable and storage capacity investments. For this, we define maximum capacity values three times larger than peak demand, which are not expected to be restrictive for the levels of decarbonization we model (Sepulveda et al., 2018). Additional numerical details are provided in Dimanchev et al. (2023). The instance of our equilibrium model[9] that we solve in this paper contains approximately 180,000 continuous variables, 4 binary variables[10] and 16 bilinear constraints[11]. We observed a maximum solution time across policy cases of 4,600s using Gurobi version 10.0.2 with cluster computing including 48-core Intel(R) Xeon(R) 2.10GHz CPUs and 32GB RAM.

S2 Quantifying system costs

System costs are defined from the perspective of a government making decisions "here and now" (i.e., before the realization of uncertainty). Two ways can be used to quantify system cost: from a risk-neutral perspective, or from a risk-averse perspective (i.e., risk-adjusted system cost).

S2.1 System cost from a risk-neutral perspective

Risk-neutral system costs, denoted Y^{RN}, are defined below. The first term represents investment costs and the second term represents uncertain operating costs. Operating costs are comprised of the cost of generation g_{rts} and load shedding y_{ts}. The value of operating costs is calculated in expectation (which reflects risk-neutrality) of the operating costs across scenarios s with probabilities P_s. This definition of system cost can be interpreted as the overall cost perceived by a risk-neutral central planner.

[8]This is due to the integer variables θ_s^Z, and the bilinear terms $\pi_{rs} x_r$, representing the product of revenues and capacity investment.

[9]Used to solve the main case of interest, i.e., a power system with risk aversion and missing markets.

[10]One for each scenario.

[11]This is equal to the product of the number of scenarios and technologies.

$$Y^{RN} := \sum_r C_r^{inv} x_r + \sum_s P_s \sum_t W_t \Big[\sum_r C_r^{var} g_{rts} + C^{cap} y_{ts} \Big] \tag{3}$$

S2.2 Risk-adjusted system cost

Risk-adjusted (i.e., risk-averse) system costs, denoted Y^{RA}, are defined in the expression below. The first term represents investment costs while the second and third terms represent risk-adjusted operating costs (cost of generation g_{rts} and load shedding y_{ts}). The risk adjustment is modeled by using Ω to weight the expected operating costs (second term) and the CVaR (third term). The CVaR is the cost of the Ψ-worst tail of the distribution of operating costs. As we have chosen $\Psi = 0.25$, the CVaR represents the operating costs (i.e., cost of generation and load shedding) in the most expensive scenario (which is the scenario with highest demand). This definition of system cost can be interpreted as the overall cost perceived by a risk-averse central planner, and is equivalent to the formulation used in prior research (Munoz et al., 2017).

$$\begin{aligned} Y^{RA} := \sum_r C_r^{inv} x_r + \Omega \Big[\sum_s P_s \sum_t W_t \Big[\sum_r C_r^{var} g_{rts} + C^{cap} y_{ts} \Big] \Big] \\ + (1 - \Omega) \Big[CVaR \Big] \end{aligned} \tag{4}$$

S2.3 Implications of policy for system cost

Note that the policy parameters related to ITCs, I_r^{inv}, and carbon pricing, C^{tax}, are not included in the system cost definitions above. This is because system costs are defined from a societal perspective. The tax credits paid to producers constitute a cost to taxpayers. In other words, from a societal perspective, all technologies incur their full investment cost C_r^{inv}. Similarly, the CO_2 tax cost incurred by producers matches the revenues accrued to the government.

S3 Sensitivity analysis: comparison to risk-neutral and deterministic modeling approaches

Here we place our findings in the context of more traditional methods for policy analysis: first, assuming risk-neutral investors, and second, using a deterministic model that omits uncertainty entirely. Table S1 describes how the methodologies compare. As in our main manuscript, we show that risk-neutral and deterministic models bias policy cost and effectiveness estimates relative to capturing the incompleteness of risk markets (as our in missing markets case). Most notably, our analysis shows that these methods also exaggerate policy cost relative to the missing markets case. This can be seen by comparing the results in Figures S1-d and S2-d for a given case relative to the "missing markets" case. Regarding policy effectiveness, Figures S1-b and S2-b show that emission reduction estimates also vary across methods, but the direction is less consistent.

We note that the risk-neutral case features negative policy costs. This is by construction: it is driven by the fact that the decisions of risk-neutral investors are mis-aligned with optimal risk-averse planning. Recall that policy cost is from the perspective of a risk-averse government. Risk-neutral investors build less capacity than a risk-averse central planner would. As climate policies encourage more overall investment, they help align the decisions of risk-neutral investors with the objective of a risk-averse central planner, leading to a negative policy cost. If we instead estimate policy costs from the perspective of a risk-neutral government (Figure S3), this effect disappears as expected.

Case name	Uncertainty	Risk preference	Long-term markets
Complete markets	4 demand scenarios	Risk-averse market participants	Complete trading of long-term contracts
Missing markets	4 demand scenarios	Risk-averse market participants	No trading of long-term contracts
Risk-neutral	4 demand scenarios	Risk-neutral market participants	N/A
Deterministic	1 demand scenario (average)	Effectively risk-neutral	N/A

Table S1: Alternative approaches to modeling risk in power systems

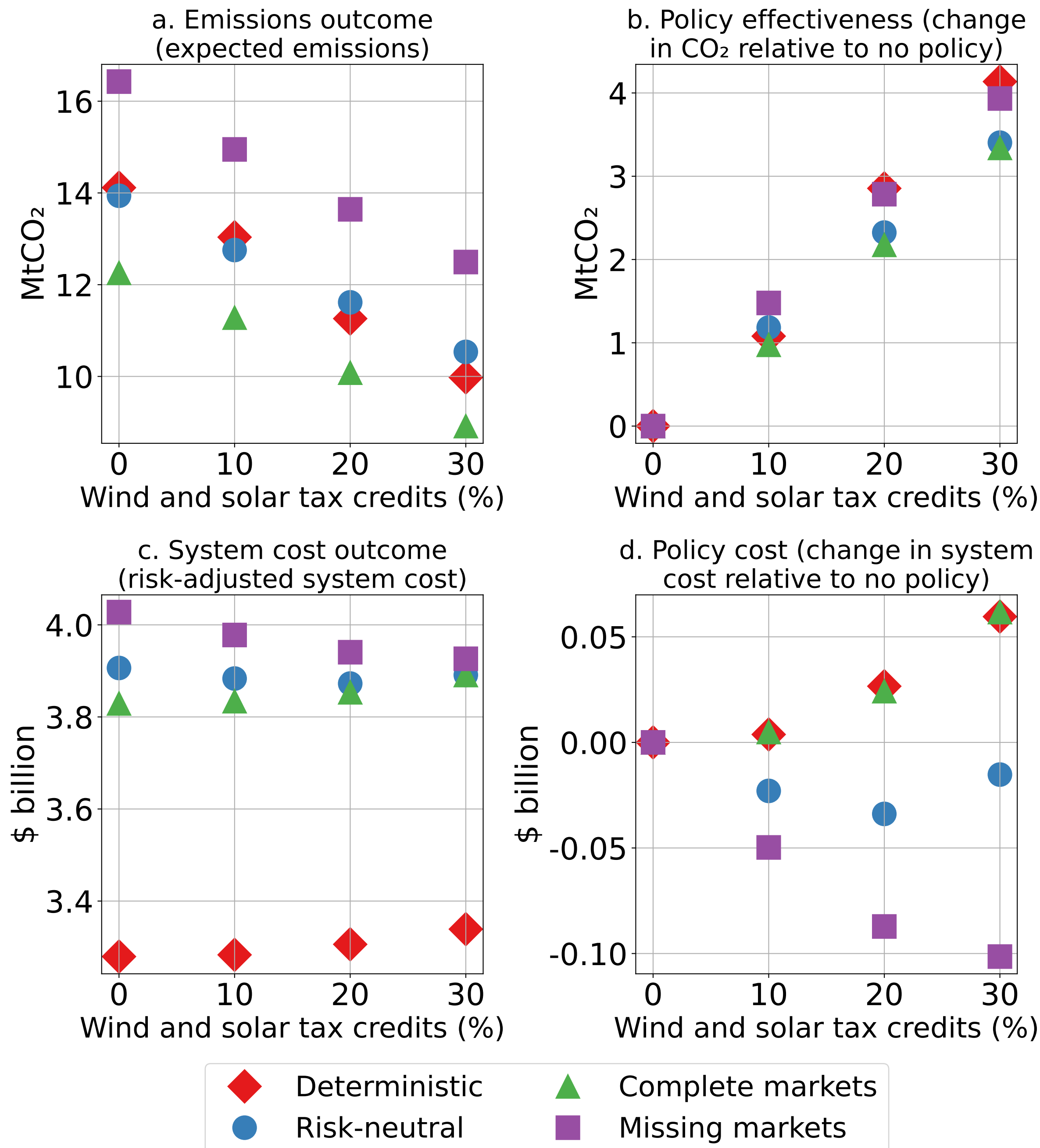

Figure S1: Comparisons of alternative modeling approaches (Investment Tax Credits) Right panels show changes in outcomes relative to no policy (i.e., the differences in the corresponding left panel between a given result and the result for 0% tax credits)

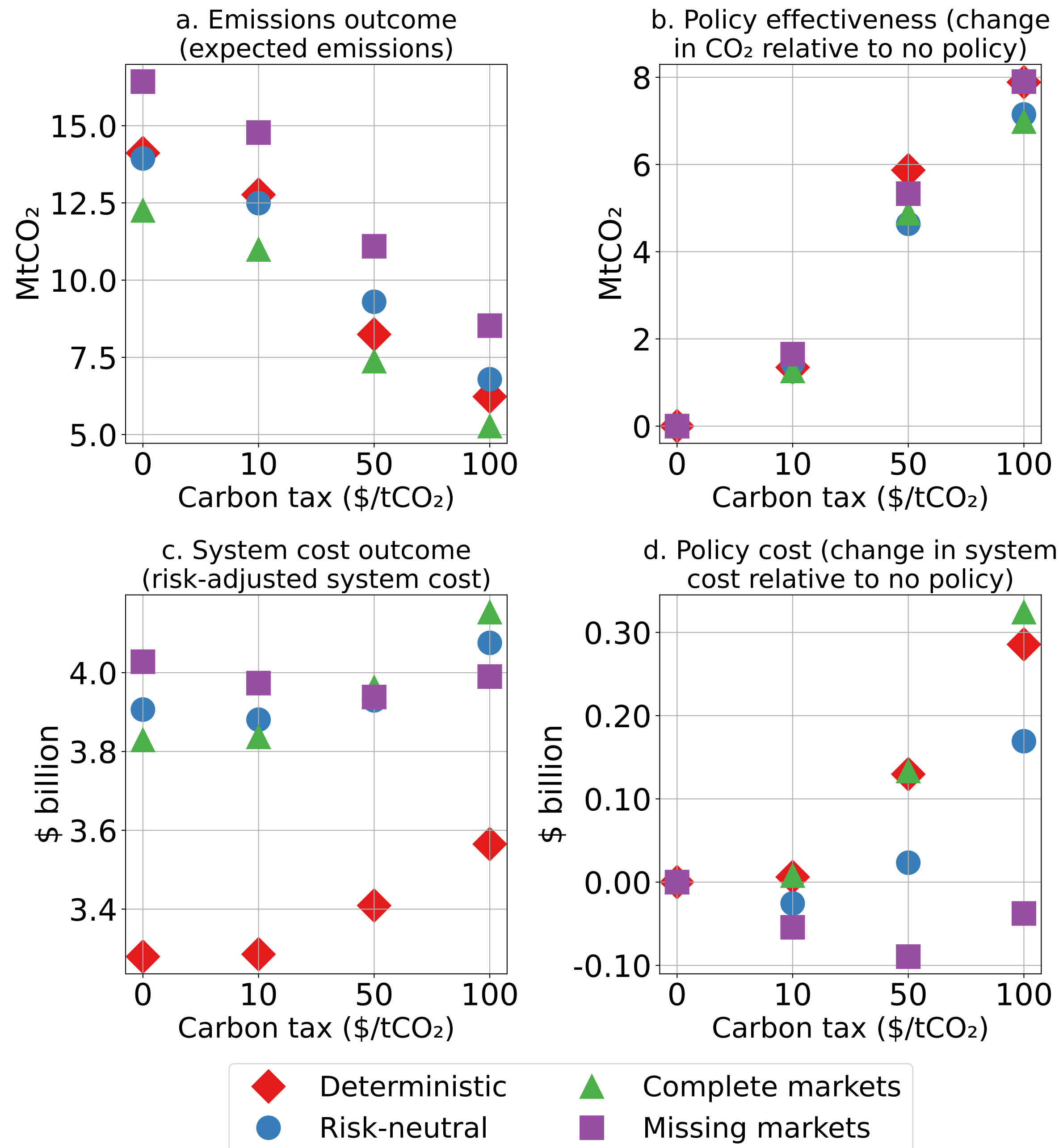

Figure S2: Comparisons of alternative modeling approaches (Carbon tax)
Right panels show changes in outcomes relative to no policy (i.e., the differences in the corresponding left panel between a given result and the result for a \$0/tCO_2 carbon tax)

S4 Sensitivity analysis: evaluating system costs from a risk-neutral perspective

The experiments in the main manuscript use risk-averse system costs. Here we test the implications of this choice by instead using risk-neutral system costs. This is illustrated in Figure S3, which is analogous to Figure 1 (bottom row) in the main text. We find that our paper's main finding holds, i.e., policy cost[12] is lower when considering missing markets (square markers). As expected, the distortion caused by the missing market problem is less costly to a risk-neutral society (relative to a risk-averse society). This diminishes the impact of missing markets. However, we still observe negative ITC costs (as shown by the square markers in the right panel). Applying the same test to our CO_2 tax results (not illustrated here) shows qualitatively similar results. However, policy costs are no longer negative for tax levels of \$50/tCO_2 and \$100/tCO_2.

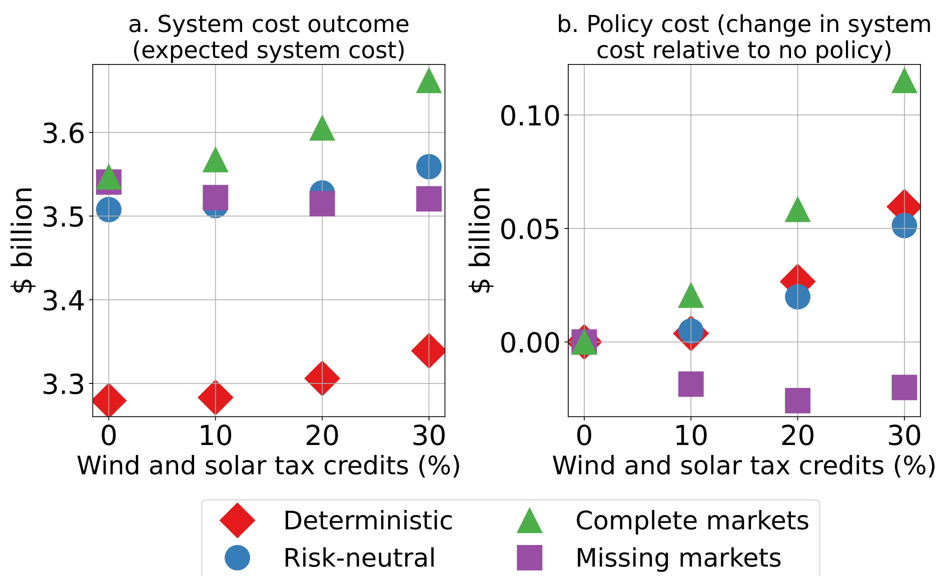

Figure S3: Investment Tax Credit costs using risk-neutral system costs

S5 Sensitivity analysis: alternative risk parameters

To test our result's sensitivity to the level of uncertainty, we consider an alternative case in which demand is less uncertain (maximum deviation of +/- 5%) than assumed in the main text (+/- 25%). Specifically, here we use four demand scenarios that shift demand in each hour by -5%, -2.5%, +2.5% and +5% respectively relative to projected demand. The result is

[12]Defined in the main manuscript as the increase in power system costs associated with a given policy

displayed in Figure S4, which is analogous to Figure 1 (bottom-row) in the main text. Note that we quantify system costs from a risk-averse perspective as in the main text. We find that policy costs are no longer negative for ITCs of 20% and 30% (as shown by the square markers in the right panel), but are nevertheless substantially lower than in the other cases. Applying the same test to our CO_2 tax cases (not illustrated here), we find that policy costs are once again lower in the missing markets case than all other cases, but that they are no longer negative for tax levels equal to \$50, \$100 per to CO_2.

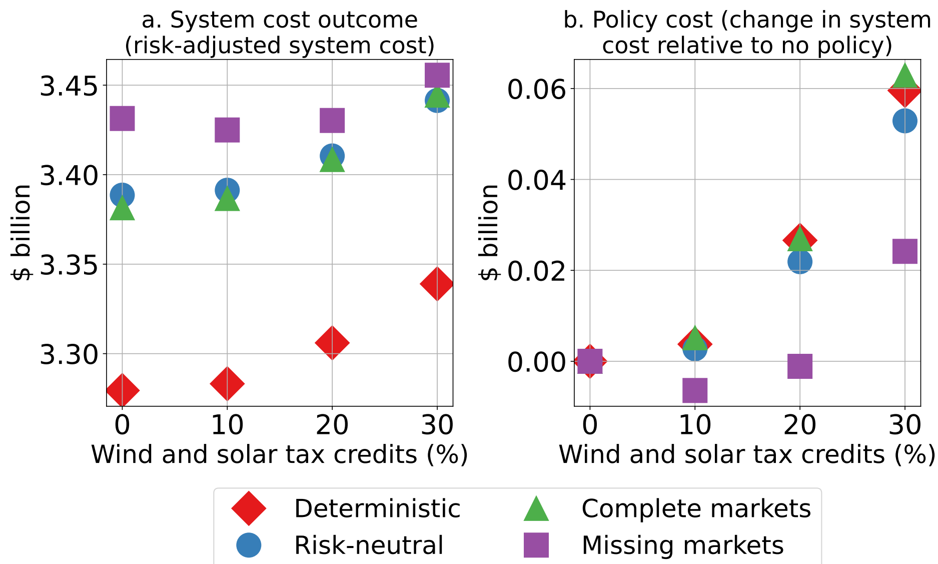

Figure S4: Investment Tax Credit costs for reduced demand uncertainty

Next, we consider a sensitivity case in which we change the risk aversion parameter Ω to represent a case in which market participants are less risk-averse (Figure S5). Note that parameter Ω weights risk aversion such that a value of 1 represents no risk aversion (i.e., risk neutrality) and value of 0 represents strong risk aversion, which in the construction of our model means that market participants make decisions only based on their future CVaR. For this sensitivity test, we use a value of 0.9, as opposed to the value of 0.5 used in the main text. We keep all other assumptions unchanged from the main analysis (system costs are also quantified from a risk-averse perspective).

In Figure S5, we observe that costs are once again overestimated when the missing market problem is neglected (i.e., the square markets in the left panel are lower than the rest). This test also shows that costs are no longer negative for 20% and 30% ITCs. Similarly, applying the same test to the CO_2 tax (not illustrated here), we find costs are no longer negative for the \$50 and \$100 per ton CO_2 taxes.

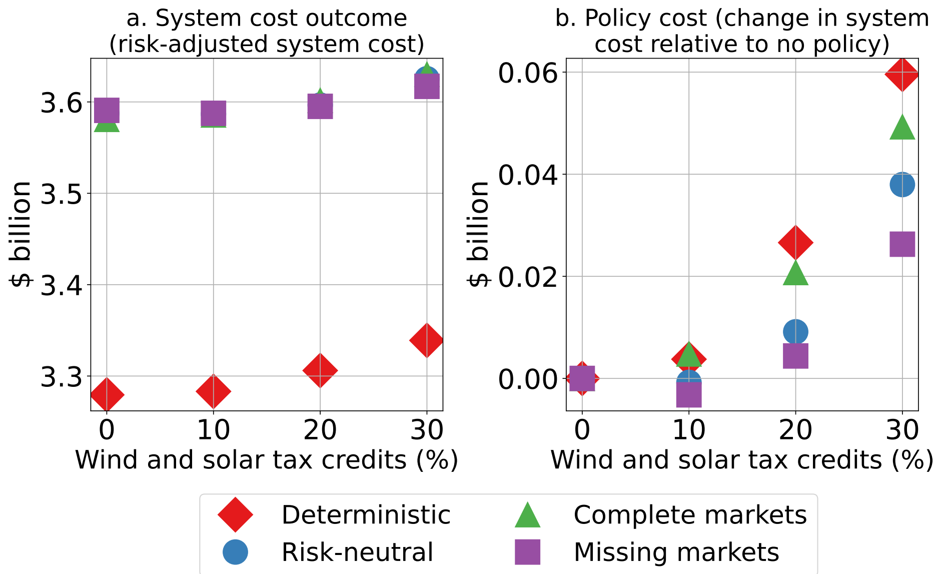

Figure S5: Investment Tax Credit costs for a reduced level of risk aversion ($\Omega = 0.9$)

References

Dimanchev, E., Gabriel, S. A., Reichenberg, L., & Korpaas, M. (2023). Consequences of the missing risk market problem for power system emissions [MIT CEEPR Working Paper Series]. https://ceepr.mit.edu/workingpaper/consequences-of-the-missing-risk-market-problem-for-power-system-emissions/

Gurobi. (2020). Non-Convex Quadratic Optimization. Retrieved September 27, 2023, from https://www.gurobi.com/events/non-convex-quadratic-optimization/

Munoz, F. D., van der Weijde, A. H., Hobbs, B. F., & Watson, J.-P. (2017). Does risk aversion affect transmission and generation planning? A Western North America case study. *Energy Economics*, *64*, 213–225. https://doi.org/10.1016/j.eneco.2017.03.025

Sepulveda, N. A., Jenkins, J. D., de Sisternes, F. J., & Lester, R. K. (2018). The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*, 1–18. https://doi.org/10.1016/j.joule.2018.08.006