



The Economics of Renewable Energy Support

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Background

- Carbon mitigation in the electricity sector is a major concern of climate change regulation
- Two major strategies for public policy:
 - Carbon pricing (taxes, emission trading)
 - Renewable energy support (subsidies, feed-in, green quotas)

Carbon pricing often faces strong political opposition



Massive support for renewables → explosive investment in wind & solar



How to optimally design support schemes for renewable energy sources (wind, solar)?

Design of Renewable Energy (RE) Support

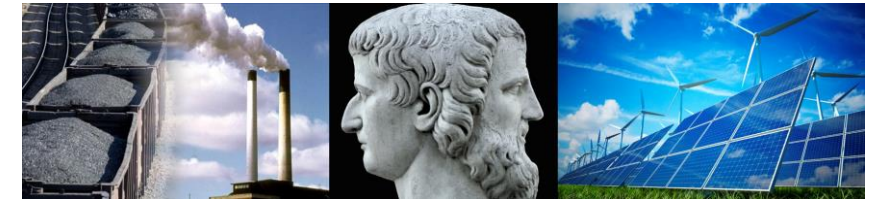
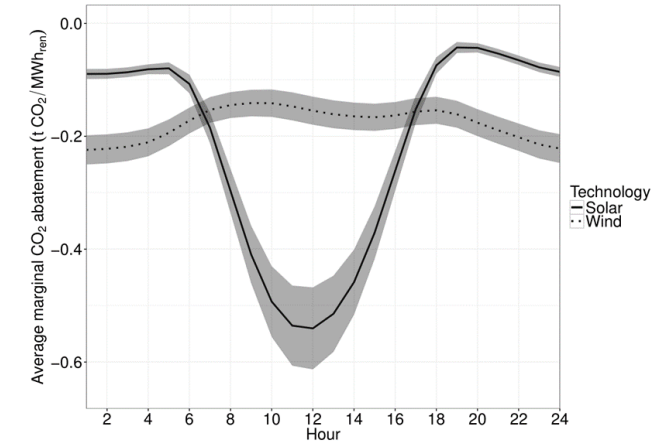
- Renewable Support Scheme = RE subsidies + tax to finance subsidies

Financing of RE Subsidies

Structure of RE Subsidies		Tax on Energy Demand	Tax on Energy Production
	Guaranteed Output Price	Feed-in Tariff (FIT)	Technology Standards: - Green Quota - Renewable Portfolio Standards
	Output Subsidy	Market Premium	

Designing RE Support: Three Major Issues

1. Technology-neutral or –differentiated subsidies?
→ Heterogeneity in production profiles
2. Revenue neutrality: subsidy expenses = tax revenues?
→ Subsidies usually recovered in revenue neutral way
3. Large enough incentives for carbon mitigation?
→ Risk of “Janus Faced” electricity system: dirty coal and clean renewables



How to optimally design renewable support schemes?
Can renewable support schemes achieve the social optimum?

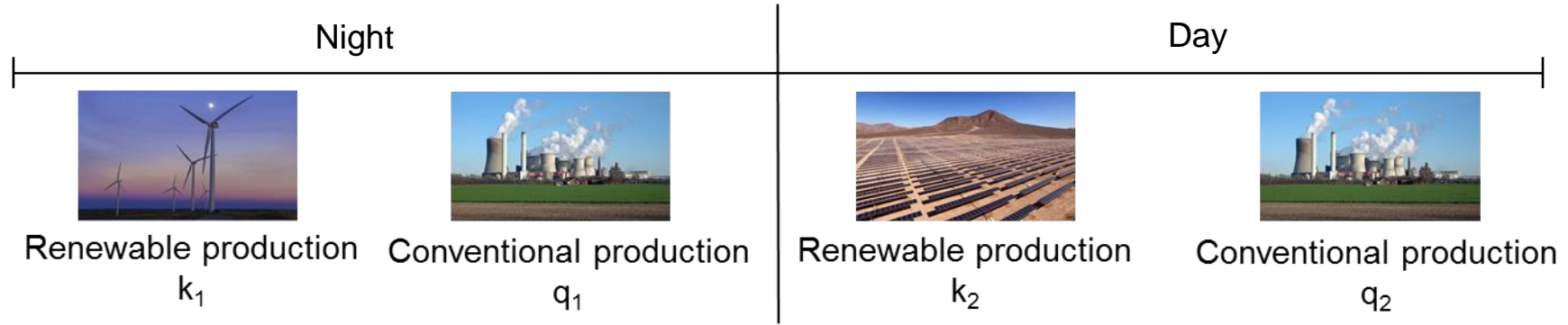
Related Literature and Contributions

- Surprisingly small literature on instrument choice & policy design for promoting RE supply in presence of environmental externality
 - Heterogeneity of spatio-temporal availability of renewable resources and implications for emissions offset (Cullen, 2013; Kaffine et al., 2015; Novan, 2015; Abrell et al., 2017)
 - Optimal energy mix of reliable and intermittent energy sources (Ambec and Crampes, 2012,2015; Helm and Mier, 2016)
 - Comparing cost-effectiveness of RE policies vs. carbon pricing (Fischer and Newell, 2008; Palmer et al., 2008; Morris et al., 2010; Fell & Linn, 2013; Rausch & Mowers, 2014; Goulder et al., 2016)
- First analysis of support schemes for RE sources investigating
 - optimal policy design
 - conditions when RE support can achieve social optimum
 - proposal for alternative policy design

Overview

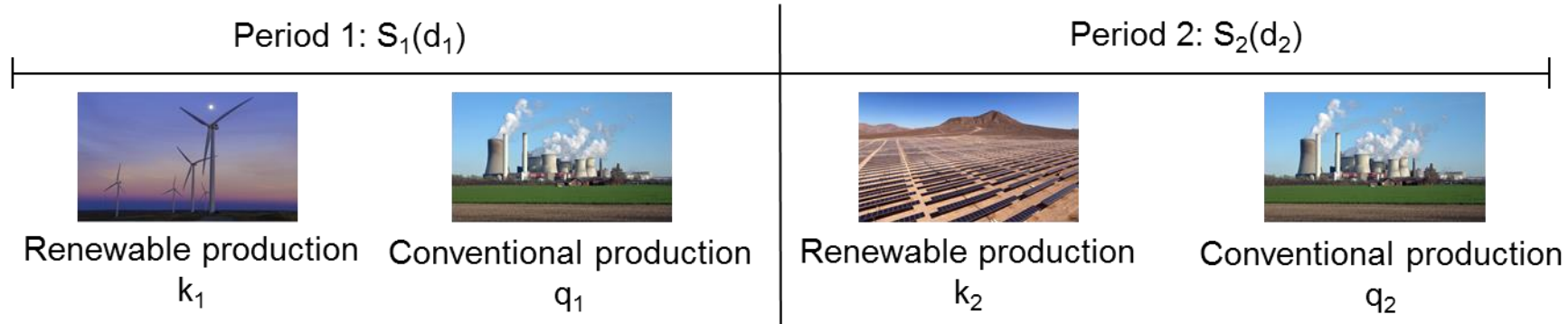
- Motivation
- Theoretical Analysis
- Quantitative Results
- Conclusions

Model Overview



- Regulator concerned with management of externality associated with use of fossil fuels in electricity supply
- Partial equilibrium model of electricity market (perfect competition, homogenous outputs, marginal cost pricing)
- Two periods
- Production of conventional power plants is always available but causes emissions
- Heterogeneity of production profiles
 - Wind available only in the night
 - Solar available only in the day

Model Setup



- Private surplus $S_t(d_t)$ for demand d_t
- Renewable generation k_t :
 - 2 technologies
 - Technology t fully available in period t
 - Zero marginal cost
 - Increasing (marginal) investment cost: $G_t(k_t)$
- Conventional generation q_{it} :
 - Two technologies: dirty, cleaner (d,c)
 - Capacity is given and fixed
 - Fully dispatchable in all periods
 - Increasing (marginal) cost: $C_i(q_{it})$
 - Emissions: $E_i(q_{it})$ cause damage δ

Regulator: Maximize Social Surplus

- Policy instruments
 - s_t : Subsidy for renewable available in period t
 - τ_t : Demand tax in period t
 - κ_i : Emission tax technology i

$$\max_{\mathbf{b}=\{s_t, \tau_t, \kappa_i\}} \mathcal{W} := \underbrace{\sum_t \left[S_t(d_t) - G_t(k_t) - \sum_i C_{it}(q_{it}) \right]}_{=\text{Economic surplus}} - \underbrace{\delta \sum_t \sum_i E_{it}(q_{it})}_{=\text{Environmental damage}}$$

s.t. (d_t, k_t, q_{it}, p_t) solve market equilibrium conditions

$$\begin{aligned} C'_{it} + \kappa_i E'_{it} &\geq p_t & \forall t, i & (q_{it}) \\ G'_t &\geq \psi_t & \forall t & (k_t) \\ \psi_t &= \begin{cases} p_t + s_t & \text{if premium for RE} \\ s_t & \text{if feed-in tariff for RE} \end{cases} \\ p_t + \tau_t &\geq S'_t & \forall t & (d_t) \\ k_t + \sum_i q_{it} &= d_t & \forall t & (p_t) \end{aligned}$$

Optimal RE Support: Structure of Subsidies & Financing

- Subsidy reflects *market value* (p_t) and *environmental value* ($\delta E'_{dt}$)
 - Feed-in: $s_t^* = p_t + \delta E'_{dt}$
 - Premium: $s_t^* = \delta E'_{dt}$

➔ Optimal RE subsidy is differentiated by resources

- Optimal demand tax: $\tau_t^* = \delta E'_{dt}$

➔ Optimal RE support is not revenue neutral

Can We Achieve the Social Optimum Using RE Support?

Proposition

The optimal RE support scheme implements the social optimum if and only if a switch between the dirty and clean fossil-based energy technologies is not required.

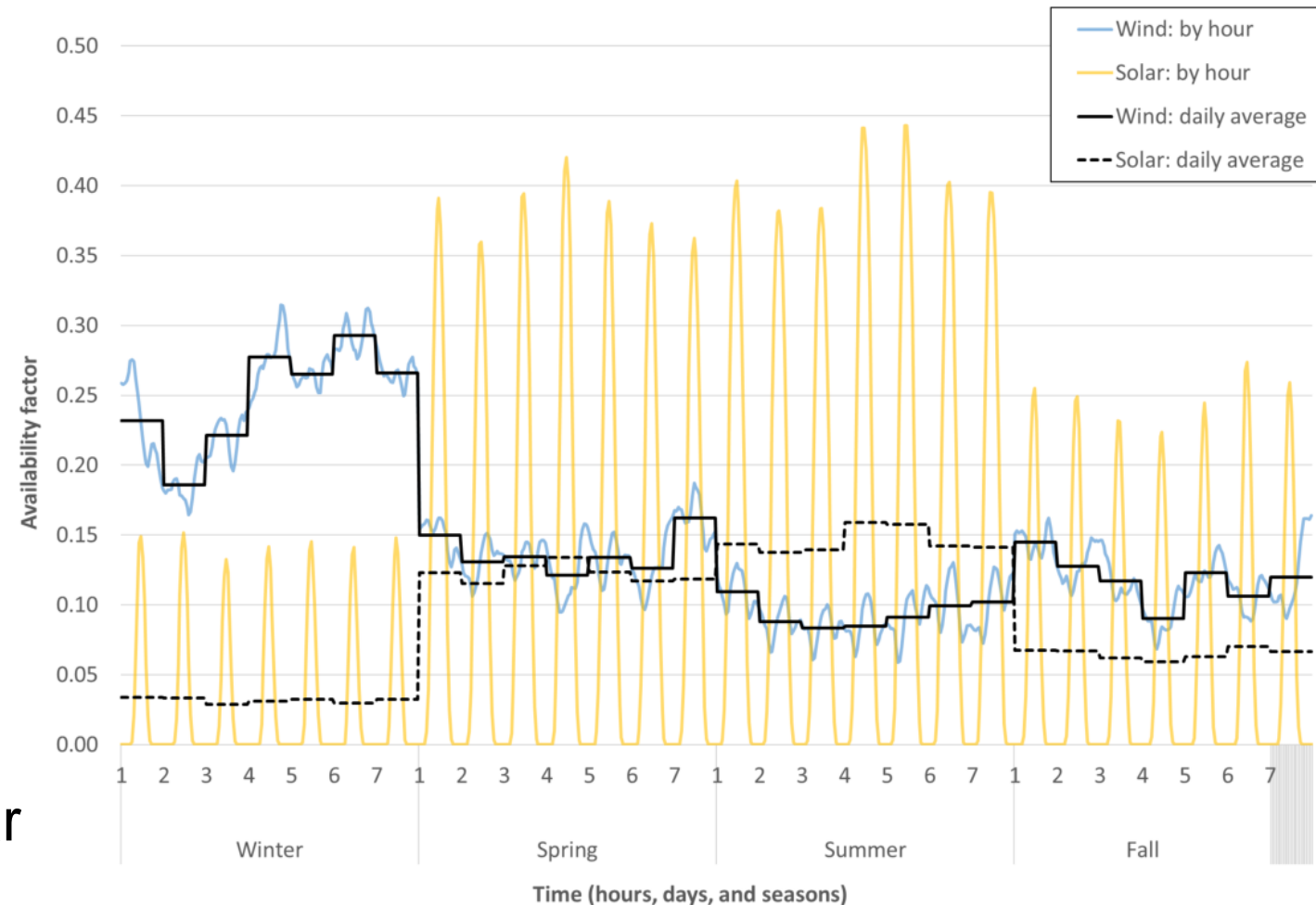
- A renewable support scheme **can** implement
 - an efficient level of renewable capacity: $s_t^* = p_t + \delta E'_{dt}$
 - an efficient level of demand: $\tau_t^* = \delta E'_{dt}$
- A renewable support scheme **cannot** alter the relative cost of polluting technologies

Overview

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- Quantitative Results
- Conclusions

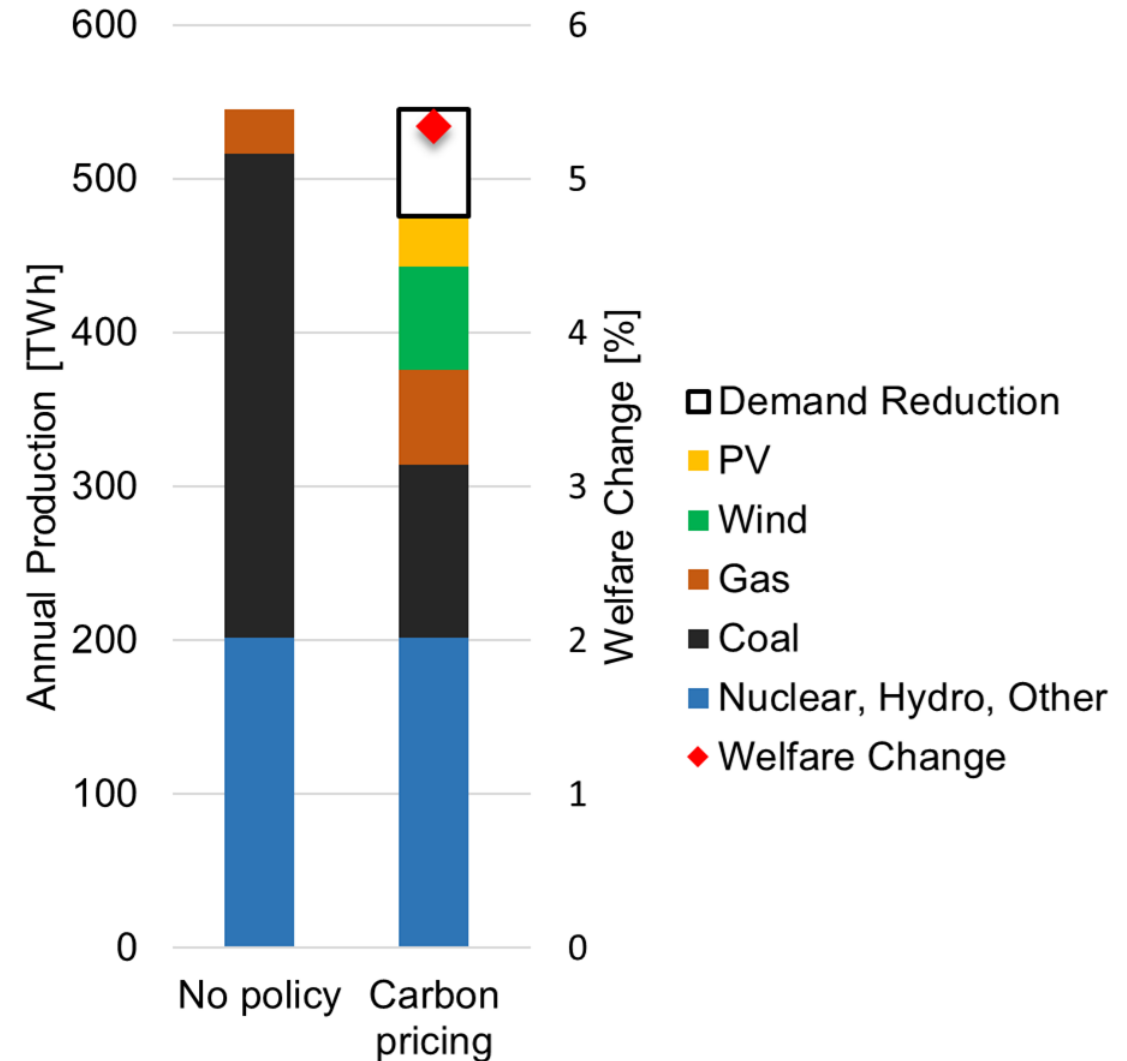
Quantitative Framework

- Quantification of relative performance of alternative policy designs
- Relaxes assumptions
 - Hourly resolution
 - Multiple technologies (lignite, hard coal, natural gas, nuclear, hydro, biomass)
 - Joint availability of wind and solar



Social Optimum: Carbon Pricing

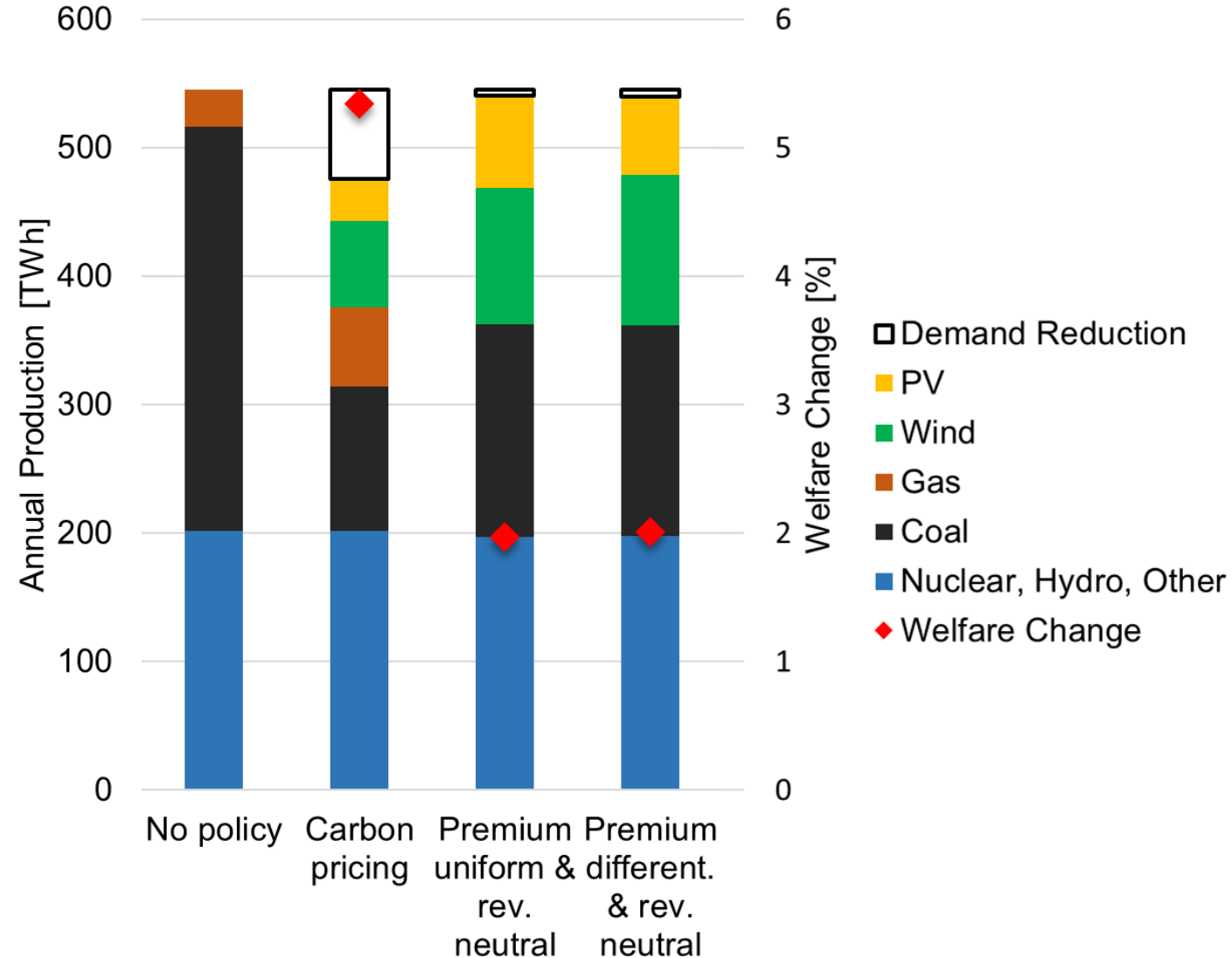
- Welfare gain: 5.3%
- **Three abatement channels**
 1. Investment into RE
 2. Energy conservation
 3. Fuel switch



Revenue-Neutral RE Support

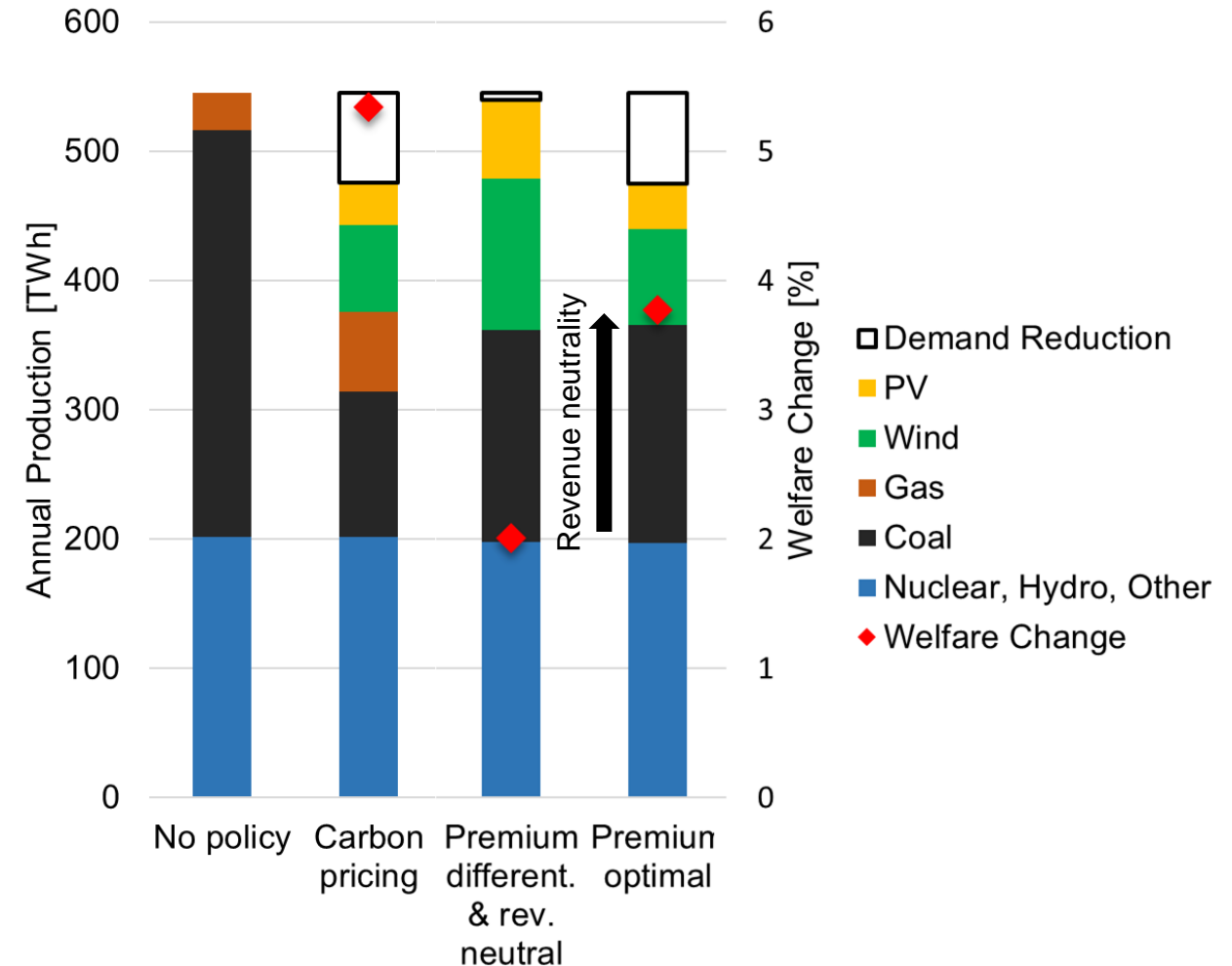
- Carbon pricing clearly outperforms RE support
- Minor improvement by differentiated premium
- RE support fails to implement
 - energy conservation
 - fuel switch

➔ Over-investment into RE



Revenue Neutrality Blocks Energy Conservation

- Welfare increases but social optimum not reached
- Relaxing revenue neutrality
 - induces energy conservation
→ less over-investment into RE
 - does not incentivize fuel switch



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Summary

- How should policies for promoting RE supply from variable resources be optimally designed in the presence of externalities associated with fossil fuel use?
 - **Structure of subsidies: Differentiate according to market and environmental value**
 - **Financing: Revenue neutrality blocks energy conservation**
- Can RE support schemes implement the social optimum? Under which conditions?
RE support achieves social optimum if and only if no switch from coal to natural gas is required.

Conclusions

- Demand tax is key to incentivize energy conservation
- RE support schemes may not be a bad choice in
 - world with low natural gas prices (e.g., shale gas)
 - countries with monolithic “clean” fossil-based energy supply (e.g., Middle East, future Swiss system?)
- If coal remains cheap
 - ➔ Additional policies needed to avoid Janus-faced energy system



Thank you for your attention

Questions, Comments?

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Literature

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-
- Additional Material

Alternative Policy Design: Green Offsets

- **Main idea**

Emissions have to be offset by a certain amount of green production

- System of tradable certificates:

- Per unit of production each RE receives one credit
- Each producers has to hold credits according to carbon (θ_i) and offset intensity (γ)

- Market clearing condition determines RE subsidy (s)

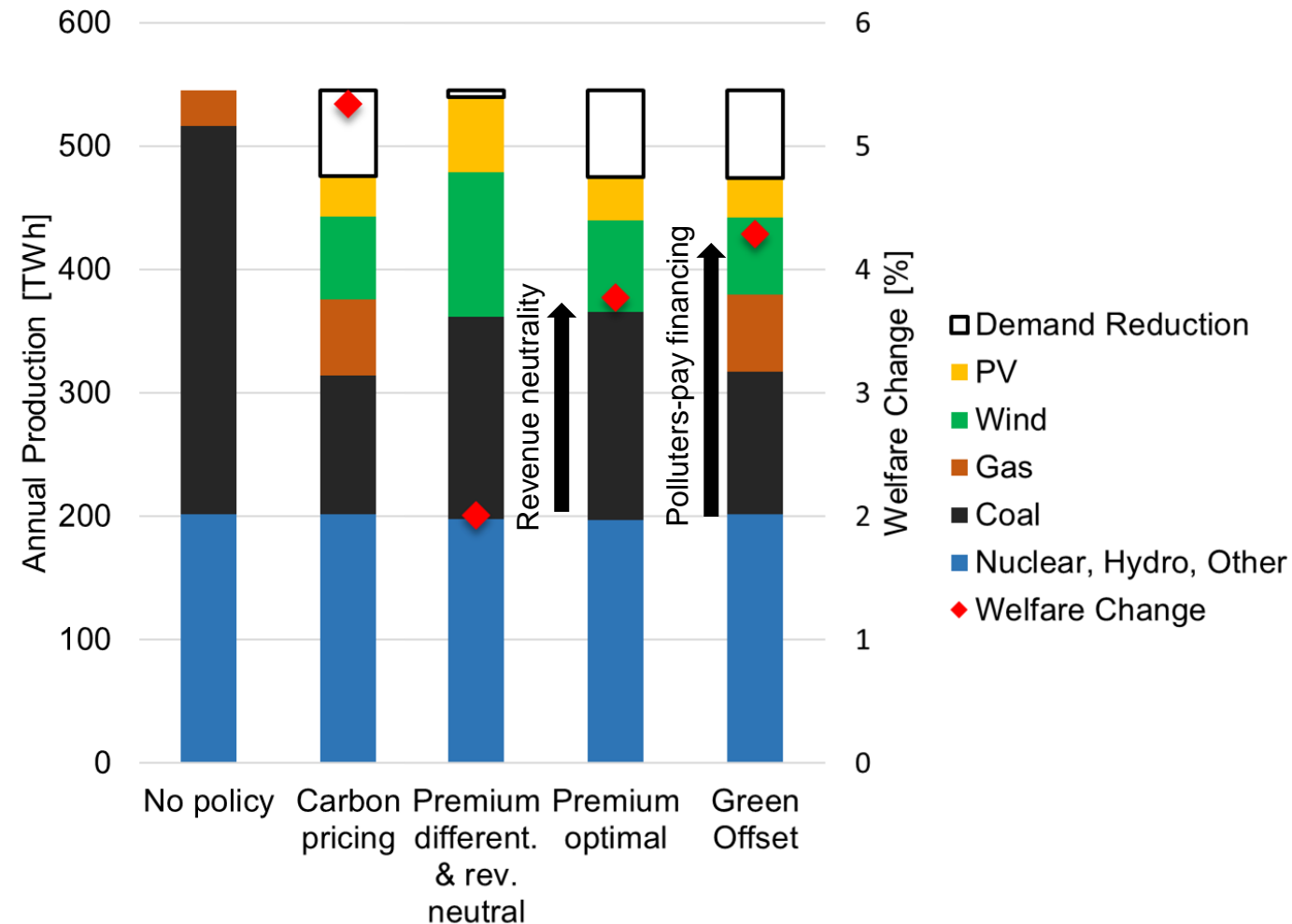
$$\underbrace{\sum_{i \in \mathcal{G}, t} X_{it}}_{\text{Green energy supply}} \geq \underbrace{\gamma}_{\text{Offset intensity}} \times \underbrace{\sum_{i, t} \theta_i X_{it}}_{\text{System-wide CO}_2 \text{ emissions}} \quad \perp \quad s \geq 0$$

- Alters relative price of polluting producers according to emission

But: Revenue neutral

Green Offsets

- Further welfare improvement but still no social optimum
- Green offsets incentivize
 - RE investments
 - energy conservation
 - fuel switch from coal to gas
- Revenue neutrality hinders reaching social optimum



Numerical Model: Equations

- Follows theoretical model setup but formulated more generally
- Mathematical Program with Equilibrium Constraints (MPEC)
- Solved using (parallelized) grid search over policy space

$$\max_{s, \omega_i, \tau_t, \kappa_i \geq 0} \mathcal{W} = \underbrace{\sum_t \left[\int_0^{D_t} \tilde{P}_t(\tilde{x}) d\tilde{x} - \sum_i (c_i^i(I_i) + c_{it}^g(X_{it})) \right]}_{=\text{Economic surplus}} - \underbrace{\delta \sum_{i,t} \int_0^{X_{it}} E_i(\tilde{x}) d\tilde{x}}_{=\text{Environmental damage}}$$

subject to:

$$\frac{\partial c_{it}^g(X_{it})}{\partial X_{it}} + \kappa_i \frac{\partial E_i(X_{it})}{\partial X_{it}} + P_{it}^I \geq \tau_{it} \quad \perp \quad X_{it} \geq 0 \quad \forall i, t$$

$$\alpha_{it} (\bar{K}_i + I_i) \geq X_{it} \quad \perp \quad P_{it}^I \geq 0 \quad \forall i, t$$

$$\frac{\partial c_i^i(I_i)}{\partial I_i} \geq \sum_t \alpha_{it} P_{it}^I \quad \perp \quad I_i \geq 0 \quad \forall i$$

$$\sum_i X_{it} = D_t(P_t, \tau_t) \quad \perp \quad P_t \text{ "free"} \quad \forall t$$

$$\pi_{it} = \begin{cases} P_t, & \text{if } i \in \mathcal{B} \\ P_t + \omega_i s, & \text{if } i \in \mathcal{G} \text{ and RE support with a market premium} \\ \omega_i s, & \text{if } i \in \mathcal{G} \text{ and RE support with a feed-in tariff.} \end{cases}$$

Numerical Model: Additional Constraints

- Revenue neutrality

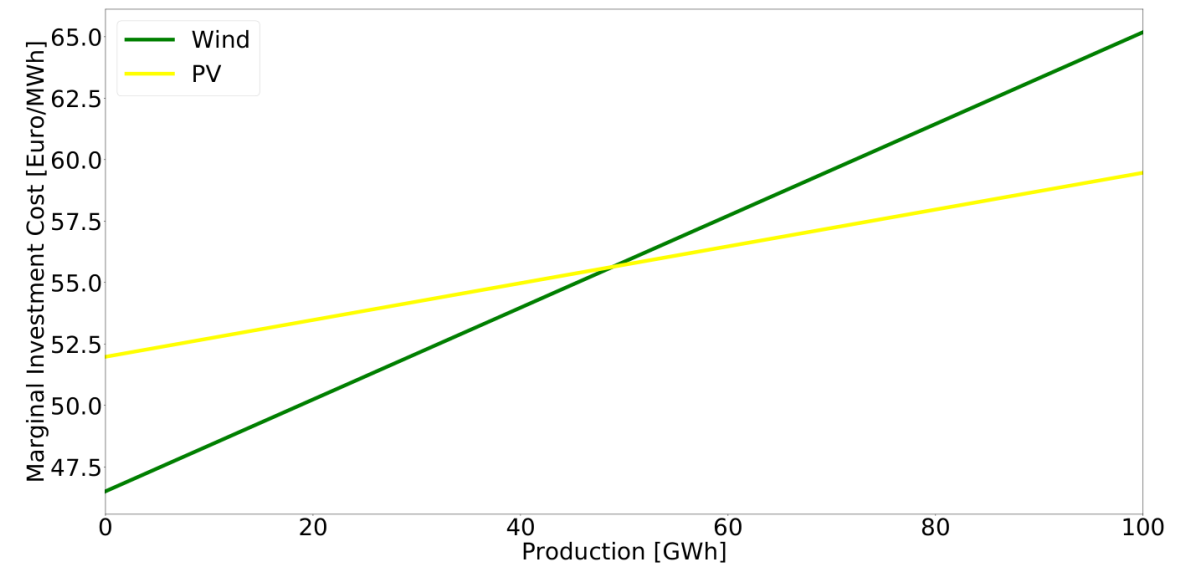
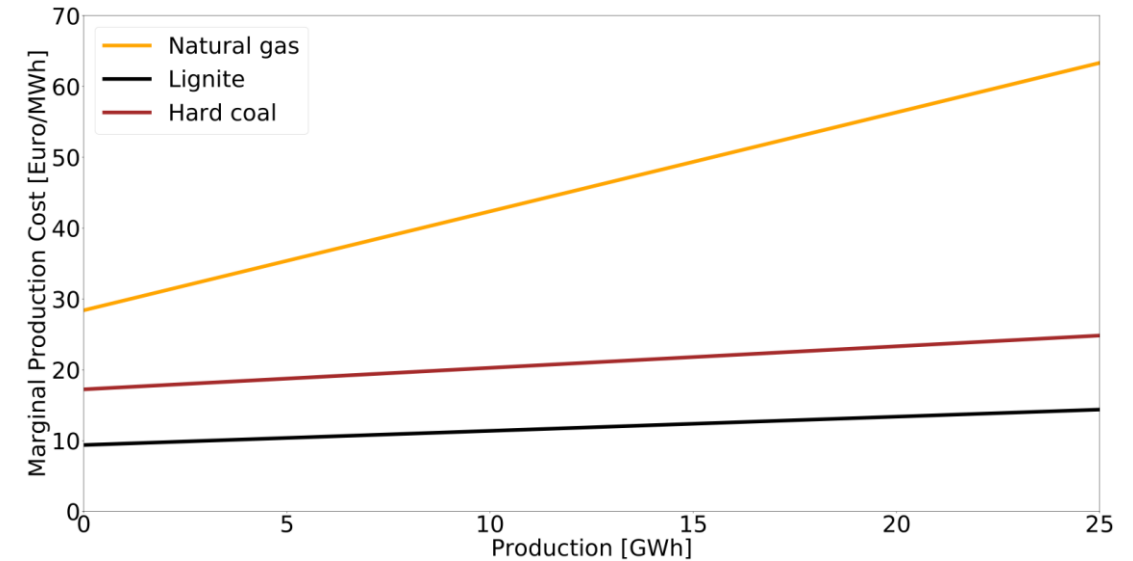
$$\sum_t \tau D_t \geq \sum_{i \in \mathcal{G}} \sum_t (\pi_{it} - P_t) X_{it} \quad \perp \quad \tau \geq 0.$$

- Green offsets and quota

$$\sum_{i \in \mathcal{G}, t} X_{it} \geq \gamma \left\{ \begin{array}{l} \sum_{i,t} \int_0^{X_{it}} E_i(\tilde{x}_{it}) d\tilde{x}_{it} \\ \sum_{i,t} X_{it} \end{array} \right. \quad \perp \quad s \geq 0$$

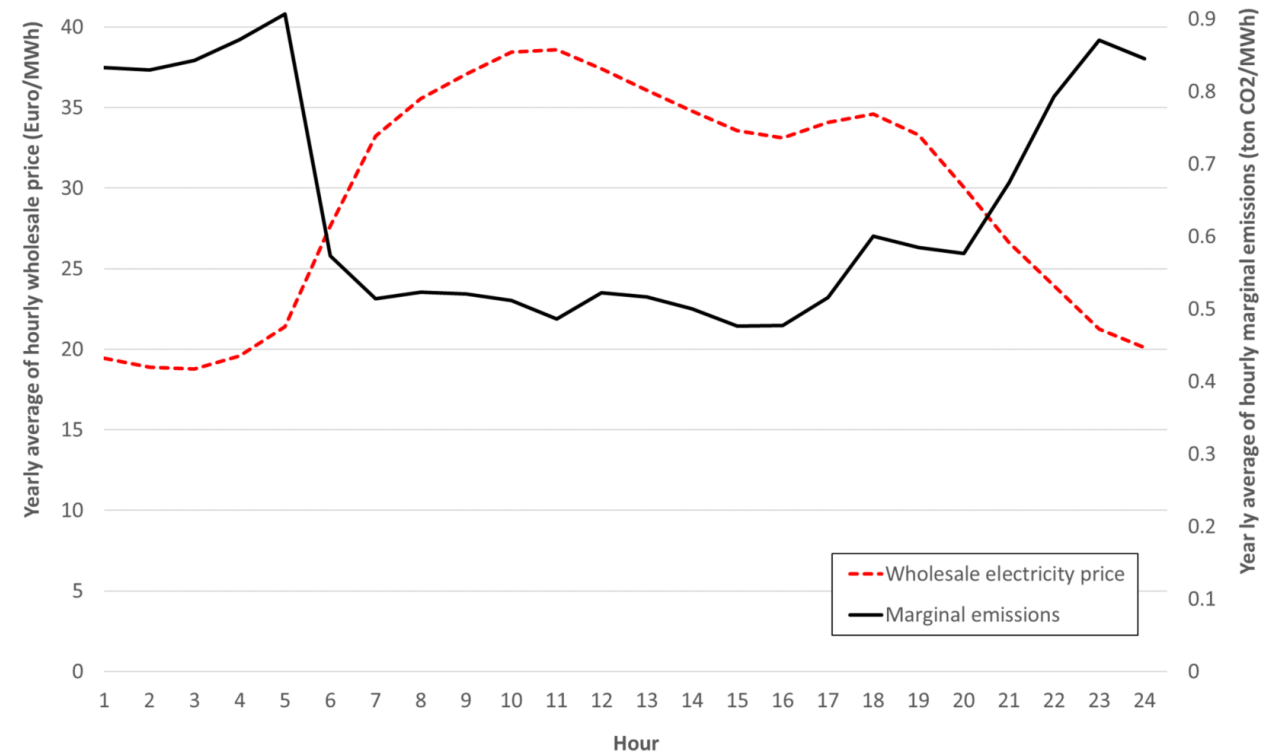
Numerical Model: Calibration

- German electricity market 2014
- Linear demand function based on hourly demand (ENTSOE), prices (EPEX), demand elasticity (-0.15)
- Production and marginal emission functions based on dataset of all German power plants (Open Power System Data)
- Investment cost functions based on
 - historical production profiles (TSO webpages)
 - estimates of potential (Agentur fuer Erneuerbare Energien)
 - Investment cost, interest, and lifetime (Frauenhofer ISE)



Reference Case: No Policy

- No-policy case:
 - No renewable energies
 - Marginal damage: 50€/tCO₂
- Negative correlation of environmental and market value
- Policies
 - Carbon pricing
 - Market premium: revenue-neutral uniform & differentiated
 - Optimal market premium
 - Green offsets



Calibration Base Case

- Demand calibration based on
 - Hourly demand
 - Hourly price
 - Demand elasticity (-0.15)

TABLE 3. Carbon coefficients and fuel prices.

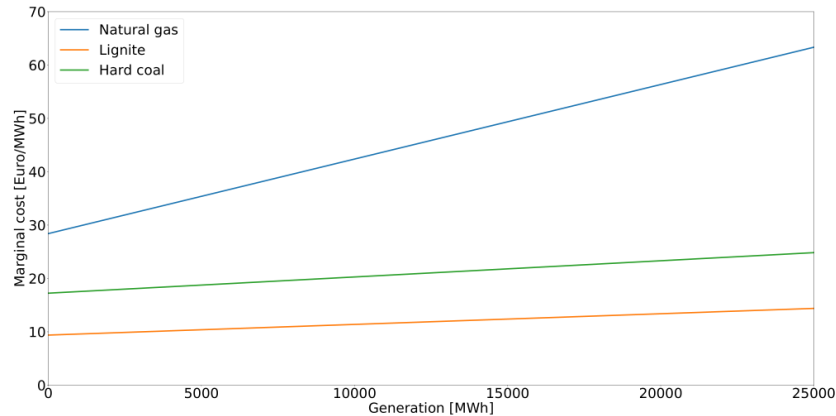
	Hard coal	Natural gas	Lignite
Carbon coefficients ^a (tCO ₂ /MWh)	0.202	0.354	0.364
Fuel price ^b (€/MWh)	8.58	21.16	4.39

Notes:^aBased on IPPC (Eggleston et al., 2006). ^bYearly average of daily spot market prices for 2014 based on price data provided by Bloomberg. For coal and natural gas prices, we use the “ICE CIF ARA Near Month future” and “NBP Hub 1st day futures”, respectively. All prices are converted to 2014 Euros using daily exchange rates provided by the European Central Bank.

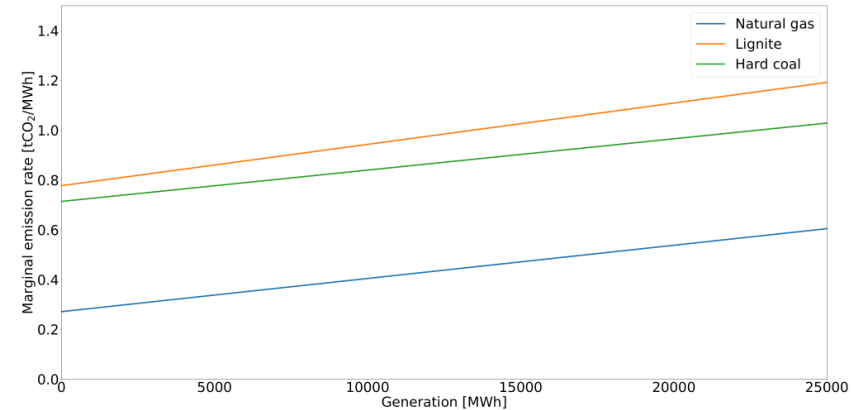
TABLE 4. Benchmark production capacities \bar{K}_i and OLS-fitted quadratic functions for generation cost c_i^g , emissions E_i , and investment cost c_i^i .

	Energy supply technologies						
	Gas	Coal	Lignite	Hydro	Nuclear	Wind	Solar
<i>Installed production capacities in “no policy” reference case (\bar{K}_i)</i>							
MW	26'900	34'378	23'319	10'320	12'696	0	0
<i>Marginal generation cost functions ($dc_i^g(X_{it})/dX_{it}$)</i>							
Intercept ($\frac{\text{€}}{\text{MWh}}$)	28.41	17.24	9.38	4	9.09	0	0
Slope ($\frac{\text{€}}{\text{MWh}^2}$)	1.4×10^{-3}	3.04×10^{-4}	2×10^{-4}	0	0	0	0
<i>Marginal emissions functions ($dE_i(X_{it})/dX_{it}$)</i>							
Intercept ($\frac{\text{tCO}_2}{\text{MWh}}$)	0.27	0.71	0.78	0	0	0	0
Slope ($\frac{\text{tCO}_2}{\text{MWh}^2}$)	1.33×10^{-5}	1.25×10^{-5}	1.66×10^{-5}	0	0	0	0
<i>Marginal investment cost functions ($dc_i^i(I_i)/dI_i$)</i>							
Intercept ($\bar{\nu}_i, \frac{\text{€}}{\text{MW}}$)	—	—	—	—	—	60'618	41'752
Slope ($\frac{\text{€}}{\text{MWh}^2}$)	—	—	—	—	—	0.24	0.06

Calibrated Functions: Marginal Cost and Emission Rates



Marginal cost functions



Marginal emission rate as function of output

- Calibrated based on dataset for all German power plants (Open Power Systems Data)

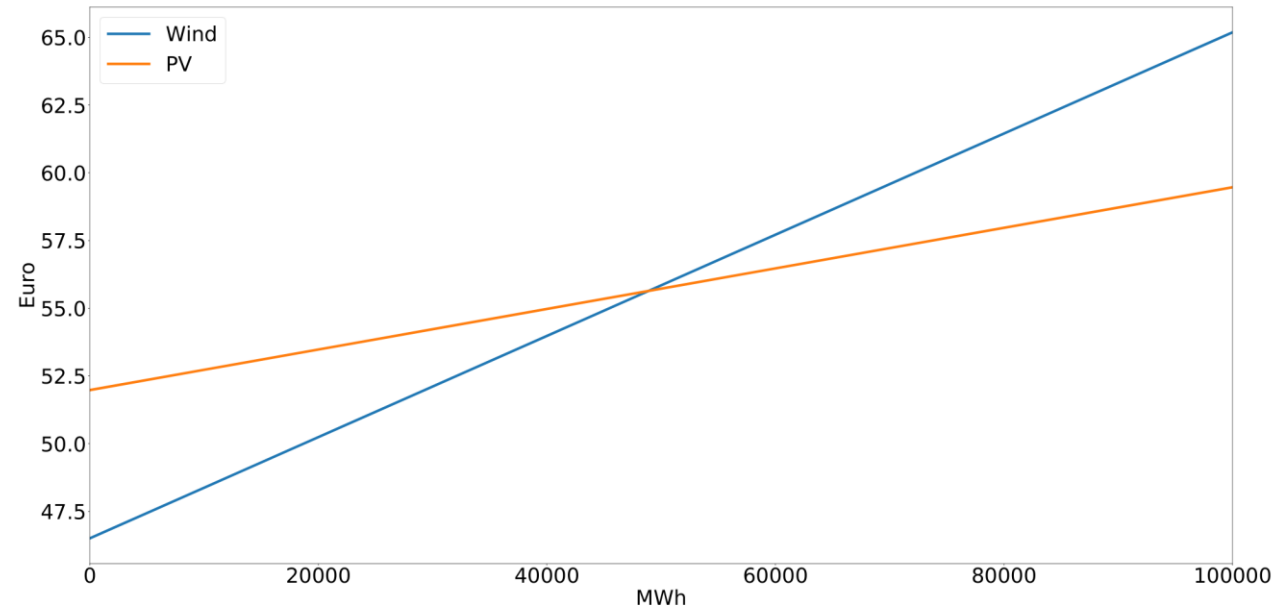
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Calibrated Functions: Investment Cost

- Potential calibrated on average full-load hours for Germany
- Cost, interest rate, and lifetime data from Fraunhofer ISE
 - Wind: 1300 €/kW, 3.8%, 20 years
 - PV: 1000 €/kW, 2.5%, 25 years
- Hourly profiles from electricity transmission system operators



Detailed Results

TABLE 6. Overview of key impacts for alternative efficient RE support policies.

	Abatement efficiency ^a \mathcal{E}^b	Change to unregul. market (%)		Generation share by technology category (%)				Subsidy rate for solar ^c
		Demand	Price ^b	Coal	Gas	Wind	Solar	
Unregulated market outcome	–	–	–	48	5	0	0	–
Carbon pricing	1	-12.7	88.3	26	13	14	7	0
<i>Support schemes based on explicit RE subsidies with refinancing via demand tax</i>								
<i>Technology-neutral RE subsidies & revenue-neutral</i>								
FIT	0.35	-0.8	2.1	30	0	18	15	1
Market premium	0.37	-0.8	2.2	30	0	20	13	1
<i>Technology-differentiated market premium</i>								
revenue-neutral	0.38	-0.9	2.7	31	0	22	11	0.93
optimal refinancing	0.71	-12.9	86.1	36	0	16	7	0.97
<i>Technology or intensity standards</i>								
RE quota	0.37	-0.8	2.2	30	0	20	13	1
<i>Green offsets with RE subsidies paid as</i>								
Market premium	0.72	-7.8	55.4	17	7	23	13	1
FIT	0.80	-13.0	89.7	24	13	13	7	1

Notes: Assumes central case as specified in Section II.D. Reported quantities (demand and generation) refer to annual values. ^aAbatement efficiency \mathcal{E}^b is defined in equation (21). ^bDemand-weighted annual average of hourly tax-inclusive consumer prices for electricity. ^cSubsidy rate relative to wind. A value of 1 indicates equal subsidy rates for wind and solar.

Sensitivity Analysis

- Price responsiveness of demand
 - ➔ If demand becomes more elastic, energy conservation, thus, non revenue-neutral demand tax, becomes more important
- Monolithic fossil fuel systems
 - ➔ Market premium/feed-in nearly achieves first-best
- Higher social cost of carbon
 - ➔ RE support becomes more efficient