Heterogeneity of Intermittent Energy Sources and Cost-effective Renewable Policies

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15th IAEE European Conference 2017
September 3-6, 2017

Motivation & Focus

- Carbon mitigation in the electricity sector is a major concern of climate change regulation. Market-based policies (carbon pricing) have garnered limited political support.

- Renewable energy (RE) subsidies have been politically popular program over past decade ➔ have led to explosive growth in capacity investments in wind & solar (e.g., in Europe and U.S.)
  - Feed-in tariff (FIT)
  - Market premium
  - Green quota (RPS), Clean Energy Standard
  - Financing of RE subsidies?

- Heterogeneity of RE resources in terms of environmental value, i.e. emissions offset per added MWh of RE (Cullen, 2013; Novan, 2015)
  - Abrell, Kosch, Rausch (2017) for Spain & Germany: implicit cost per ton CO_2 abated through subsidies on wind and solar €8-260 and €528-1800

Instrument choice & design for RE policies?

This paper: research questions

- How should policies for promoting RE supply from variable resources (i.e., wind and solar) be optimally designed in presence of environmental externalities associated with fossil fuel use**?**

- Key policy design choices: structure & financing of RE subsidies, e.g.
  - fixed tariff, premium
  - Technology-neutral or -differentiated
  - refinancing through (non) revenue-neutral tax on consumers, production taxes on “dirty” generation**?**

- Comparison of (non-)optimal RE policies (FIT, market premium, green quota) and carbon pricing in terms of market value and environmental value

- Ways to improve current RE policy design**?** How close can improved policies get to 1st-best policy outcomes (i.e., carbon pricing)**?**

Related literature (brief!) & key 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 (Joskow, 2010; 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)

- Theoretical analysis focusing on design features of optimal RE support schemes

- Quantitative empirical assessment of different (non-)optimal RE policy designs ➔ numerical policy optimization model with equilibrium constraints describing German electricity market

Quantitative framework: overview

- Given social cost of carbon (Γ), regulator seeks to maximize social welfare by choosing RE policies (**b**)

$$\max_{b} W(p(b), x(b); \Gamma)$$
$$s.t. \qquad p(b), x(b) \in \mathcal{A}$$

- Welfare function:

$$W(p(b), x(b); \Gamma) = \underbrace{\sum_{t \in \mathcal{T}} \left(\int_0^{\sum_{i \in \mathcal{I}} X_{it}} [D^{-1}(Q) - S^{-1}(Q)] dQ \right)}_{= \text{Market surplus}} - \underbrace{\Gamma E(x(b))}_{= \text{Environmental damage}}$$

- Prices **p(b)** and quantities **x(b)** in set of feasible equilibrium allocations **A** derived from a partial equilibrium model of the electricity sector

- Computational strategy: Mathematical Program under Equilibrium Constraints (MPEC) through grid search of Mixed Complementarity Problems (MCPs) over policies **b**

Lower-level problem: partial equilibrium model of electricity market

Key model features

- Generation dispatch and endogenous capacity investments
- Multiple technologies: conventional (nuclear, hydro, lignite, hard coal, natural gas, others) + green (wind, solar)
- One year with hourly resolution to capture diurnal & seasonal variation: time-varying demand, resource availability (wind & solar)
- Price-responsive linear demand function for each hour, marginal cost pricing

Model parametrization based on 2014 German electricity market data

- “Brownfield” approach w/ existing capacities for conventional generators
- Resource availabilities for wind, solar, hydro based on observed generation from German TSOs
- Hourly electricity demand from ENTSO-E
- Technology characteristics:
  - Heat efficiency + variable O&M (Schröder et al., IEA)
  - Quadratic investment costs: graded resources & max potential by state + observed investment costs

Representation of RE policies in lower-level equilibrium problem

- Different RE policies are represented in terms of the following policy variables:

$$b = (S, \omega_i, \kappa_i, \Theta)$$

  - RE subsidies: S
  - Technology differentiation of RE subsidies: ω_i
  - Energy demand tax: Θ
  - Energy production tax: κ_i

- Zero-profit conditions for firm-specific energy supply:

$$\frac{d}{dX_{it}} c^{g}_{it}(X_{it}) + \kappa_i + P^{I}_{it} \geq \tau_{it} \quad \perp \quad X_{it} \geq 0 \quad \forall i, t$$

  - With per-unit sales price (inclusive of RE subsidies):

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

- Hourly electricity market clearing conditions:

$$\sum_i X_{it} + \underbrace{R_t - J_t}_{\text{=net release from storage}} = D_t(P_t, \Theta) \quad \perp \quad P_t \text{ “free”} \quad \forall t$$

Taxonomy of alternative RE policy designs

Technology-neutral or -differentiated RE subsidies (S, ω_i)	Refinancing of RE subsidies	
	Tax on energy demand (Θ)	Taxes on energy production (κ_i)
Fixed tariff	*FIT*	*Green offsets with FIT*
Market premium	*Premium*	*Green quota* *Green offsets with premium*

x revenue neutrality (yes/no)

Policies:

- Benchmark case: carbon pricing $\kappa_i = \theta_i \Gamma$ with carbon intensity θ_i (ton CO_2/MWh)
- RE subsidies financed through demand tax (FIT and Premium):
  - Technology-neutral or technology-differentiated
  - Subsidies fully refinanced by demand tax…
  - …<u>or</u> demand tax can be chosen optimally without requirement to finance subsidies
- RE subsidies financed through taxes on energy production (green quota or RPS, green offsets):
  - Differ in terms of (1) how RE subsidies are structured (2) how RE subsidies are financed
  - Are always revenue-neutral within electricity sector

Overview: Theoretical results

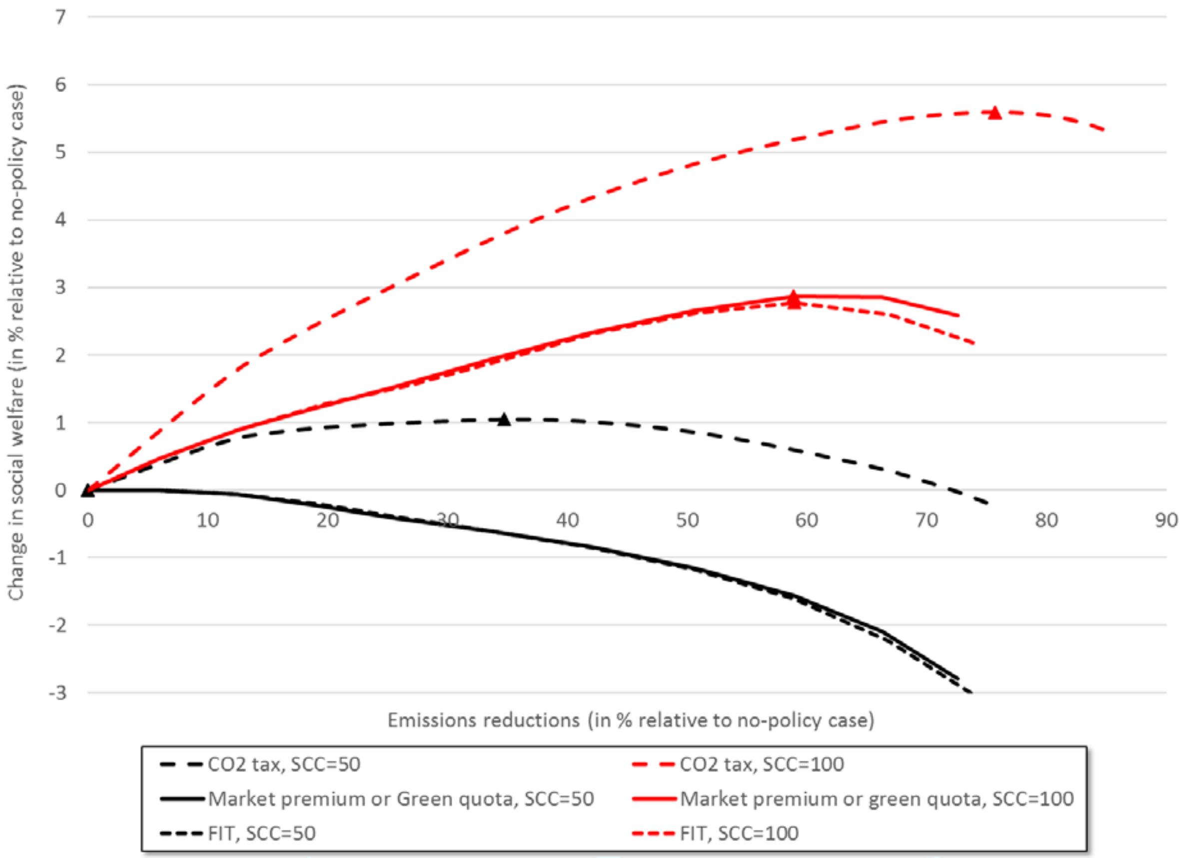
- **Proposition 1:** An emissions tax equal to the marginal social cost of carbon implements the first-best allocation.

- **Proposition 2:** Under a FIT or a market premium with time-dependent demand taxes, the clean technology does not enter the market.
  - FIT or market premium cannot induce a fuel switch
  - Demand tax cannot alter relative production costs across techs

- **Proposition 3:** Under the optimal FIT or market premium, the revenues raised from the demand tax exceeds the total payments for RE subsidies.
  - ➔optimal FIT or market premium should not be designed in a revenue-neutral way

- **Proposition 4:** The optimal FIT or market premium (with optimal demand tax) implements the 1st-best allocation if and only if the clean conventional technology is not required to enter the market.
  - If fuel switch is required ➔ optimal FIT or market premium does not implement 1st-best optimum

Optimal and sub-optimal polices for FIT, Premium (= Green quota), and carbon pricing for different SCC



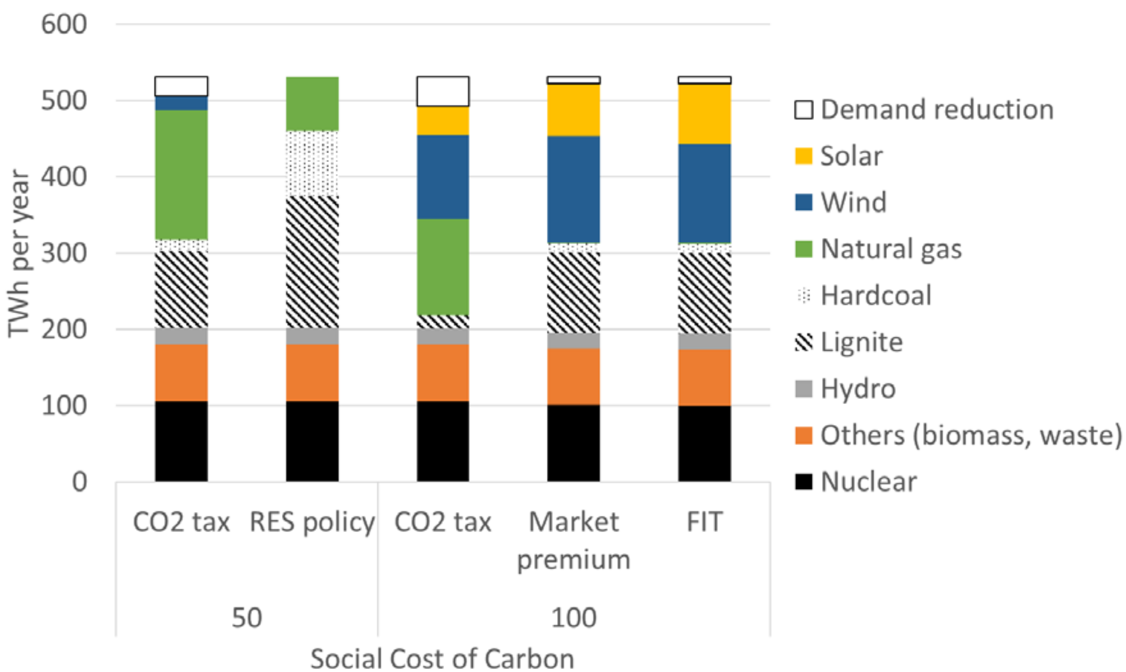
Triangles denotes optimal policies

Assumption here: RE subsidies are fully refinanced through demand tax (or green quota system)

- Unsurprisingly, carbon pricing largely outperforms RE support schemes (for optimal and non-optimal policies)
- For low SCC (=€50), optimal investment in RE sources is zero
- Premium is slightly better than FIT but differences are small

Why do RE support schemes perform worse?

Annual electricity generation by technology for optimal policies



- Relative to 1st-best carbon pricing, RE policies induce
  - insufficiently small fuel switch between coal and natural gas
  - too large investments in renewables (especially solar)
  - too small reduction in energy demand
- FIT worse than premium (or green quota) as under FIT renewable energy producers do not see market prices

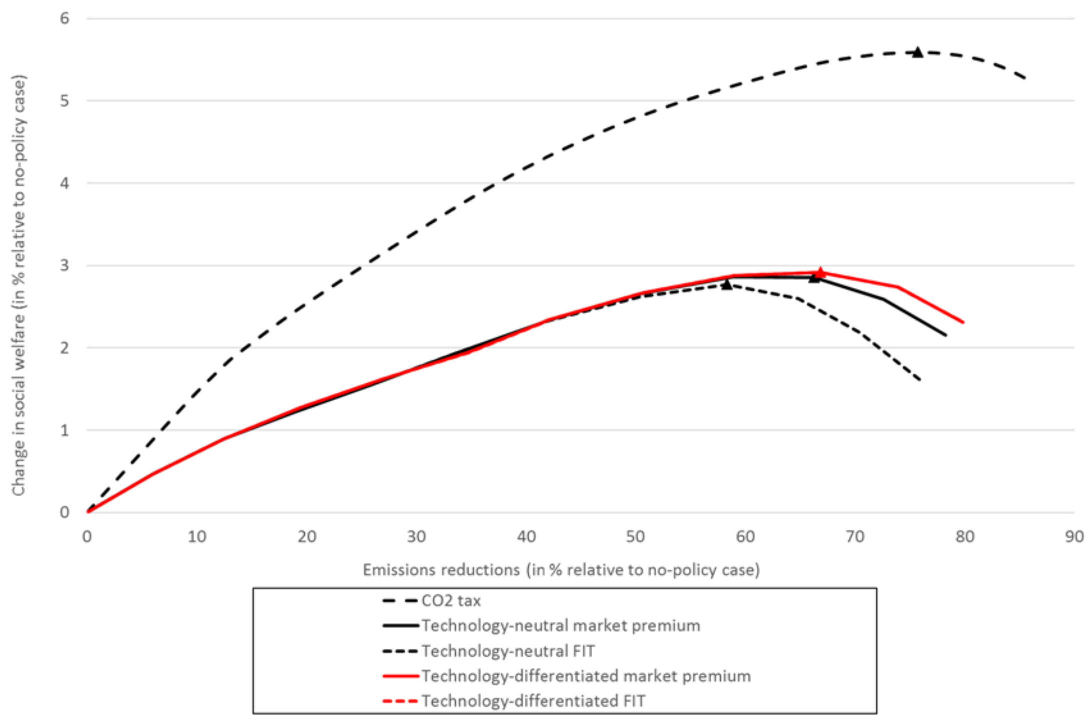
How can RE policy designs be improved?

1. Technology-differentiated RE subsidies?

2. Combining RE subsidies with optimal demand tax?

3. Combining RE subsidies with production taxes?

Technology-neutral vs. technology-differentiated FIT & Premium



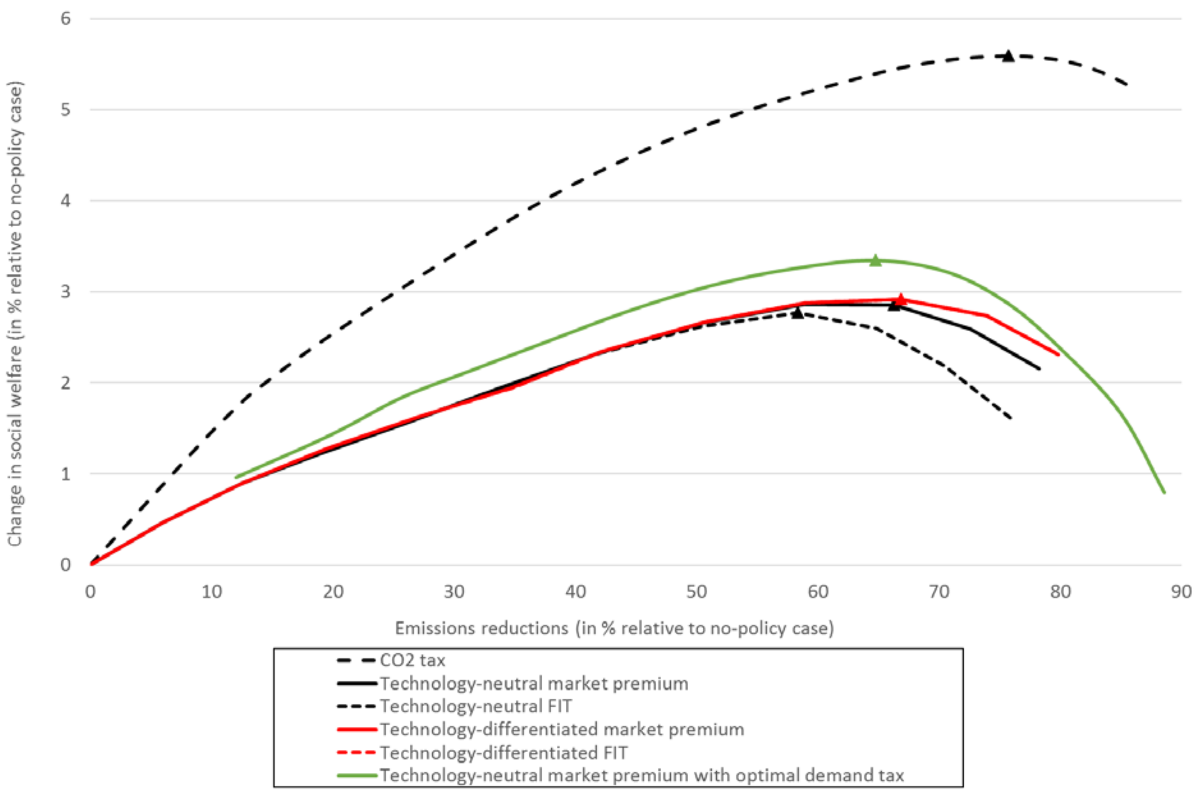
Triangles denotes optimal policies

Assumption here: RE subsidies are fully refinanced through demand tax

For SCC= €100

- Degree of optimal differentiation between wind & solar is small and slightly in favor of wind, i.e. optimal subsidies are lower for solar
  - Market value: favors solar due to stronger positive correlation with demand ➔ solar earns higher prices in peak hours but cannibalizes itself with increasing share of solar generation
  - Environmental value: favors wind due to higher carbon offsets as a result of stronger positive correlation with emission-intensive base load
- Gains from differentiating under FIT are slightly larger relative to Premium
- Optimally differentiated RE subsidies do not bring RE policies much closer to 1st-best carbon pricing

Combining optimal RE subsidies with optimal energy demand tax



Triangles denotes optimal policies

For SCC= €100

- Demand tax can counteract inefficiently high demand induced by RE subsidies but still fails to implement fuel switch from coal to natural gas
- Optimal (uniform) premium + optimal energy demand tax brings RE policy only somewhat closer to 1st-best carbon pricing

Green offsets

		Refinancing of RE subsidies	
		Tax on energy demand (Θ)	Taxes on energy production (κ_i)
Technology-neutral or -differentiated RE subsidies (S, ω_i)	Fixed tariff	*FIT*	*Green offsets with FIT*
	Market premium	*Premium*	*Green quota* *Green offsets with premium*

Green offsets:

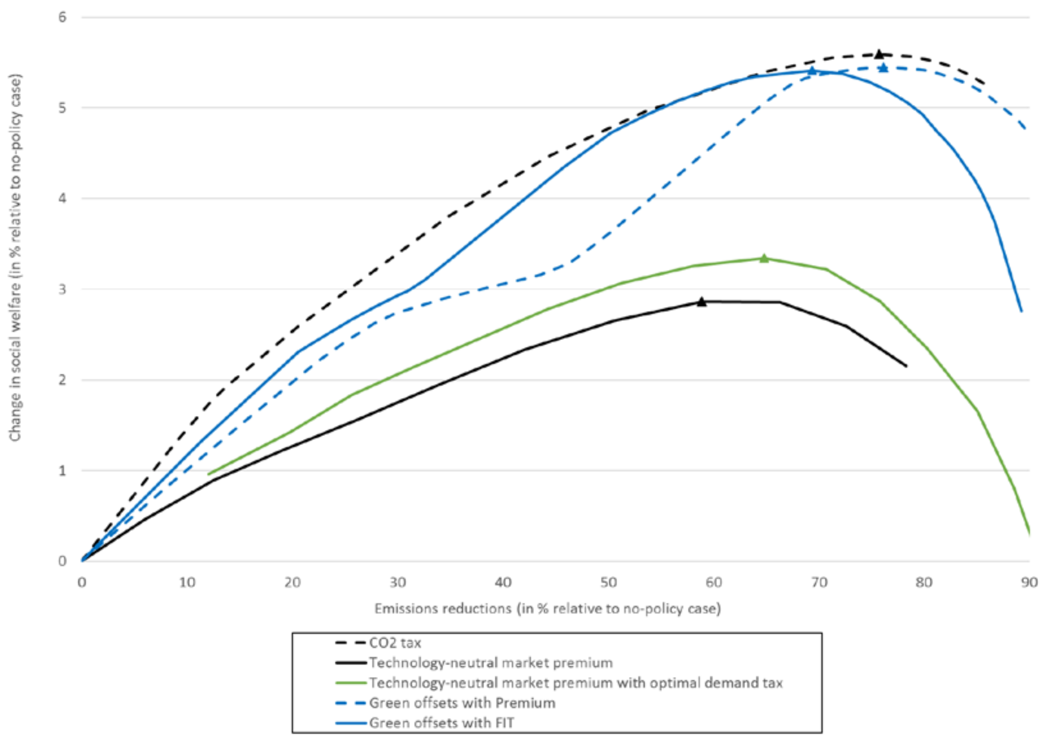
- Main idea: CO_2 emissions have to be compensated or offset by a certain amount of energy supplied from "green" (wind + solar) sources
  - RE subsidies are endogenous
  - Regulator chooses offset intensity γ

$$\underbrace{\sum_{i\in\mathcal{G},t} X_{it}}_{\text{Green energy supply}} \geq \underbrace{\gamma}_{\text{Offset intensity}} \times \underbrace{\sum_{i,t} \theta_i X_{it}}_{\text{System-wide } CO_2 \text{ emissions}} \quad \perp \quad S \geq 0$$

  - Revenue-neutrality implies that technology-specific refinancing taxes are set in proportion to emissions:

$$\kappa_i = \gamma \theta_i S$$

Green offsets with RE subsidies structured as premium or fixed tariff



Triangles denotes optimal policies

For SCC= €100

- Optimal green offset policy yields outcome that closely approximates 1st-best carbon pricing
  - Enables “accessing” production cost in zero-profit condition ➔ incentivizes fuel switch + counteracts too high demand
- To reach 1st-best optimum, RE subsidies structured in form of a premium are better than fixed tariffs
- For carbon taxes below SCC (to the left of social optimum), RE subsidies structured as fixed tariffs are better than premium

Summary of main results

Current RE policy designs

- FIT, premium, and green quota fall a long way short of implementing social optimum

How to improve RE policy design?

1. Taking into account heterogeneity of RE resources

- Optimal subsidies are differentiated across RE technologies to reflect market and environmental value motives...
  - For German case: slightly in favor of wind (generally depends on correlation of resource availability with demand and mix of installed generation capacities)
- ...BUT optimal differentiation does not lead to much improvement in terms of reaching social optimum

2. The way RE subsidies are financed...

- ...is crucial for improving RE policy design
  - Combining RE subsidies with optimal demand tax (i.e., giving up revenue-neutrality requirement within electricity sector) somewhat improves outcome
  - **Green offsets** system (refinancing taxes in proportion to emissions + endogenous subsidies) closely approximates outcomes obtained under 1st-best carbon pricing