The cost of undisturbed landscapes

Towards designing energy systems from a social perspective

Sebastian Wehrle, Johannes Schmidt

University of Natural Resources and Life Sciences, Vienna

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① Background & Motivation

② Method

③ Results

④ Sensitivity

⑤ Discussion & Conclusion

State of the Art

Power system models used to

- demonstrate the feasibility of highly renewable energy systems
- determine the system cost-minimizing mix of renewable energy technologies

find significant capacities of renewable energy technologies (RET), in Central Europe largely wind power, need to be added.

Researchers are increasingly aware that social and political restrictions on such large-scale RET expansions must be recognized.

- RET deployment in power system models often limited on the upside by results from analyses of land availability, e.g. by excluding areas for technical or legal reasons, or because they are contested by stakeholders

Yet, this neglects the trade-offs faced by a social planner deciding on RET expansion.

Motivation

- So far, analysis of *system cost* minimizing energy systems
  - Investment cost
  - Operation and maintenance cost (including fuel and emission cost)

  → includes external effects of RET on power system, such as
    - Profile cost
    - Transmission expansion cost
    - Balancing cost

- We need analysis of ***social cost*** minimizing energy systems, including
  - Local external cost, such as visual impact on landscape, harm to wildlife, noise, glaring, . . .
  - Benefits of system transition, such as avoided cost of local air pollution

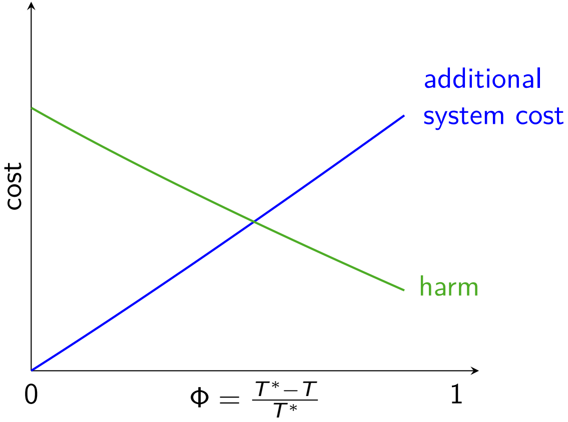
  → includes external effects of RET beyond power system

Framework

Consider a renewable energy technology T that

- is deployed at the *system cost* minimizing level T^*, i.e. it saves system cost relative to its best alternative P, but
- comes at *social cost*, e.g. due to unaccounted negative external effects

A social planner should substitute T with P up to the point where the increase in system cost equals the reduction in harm (from T's negative externality which is unaccounted for in system cost)



Approach

Focus on the social cost of power systems, including local externalities of *wind power*

- Seems to be at center of societal debate currently
- Local externalities well researched (compared to externalities of open-space PV)

An assessment of socially optimal renewables expansion must be based on two pillars

1. **The cost of undisturbed landscapes**
   - energy system costs of substituting wind power with other RET
   - the *opportunity cost* of wind power (versus its best alternative)
2. The benefit of undisturbed landscapes
   - avoided (local) negative external effects of wind turbines
   - avoided (local) external cost of wind power

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Estimating the opportunity cost of wind power

To determine the opportunity cost of wind power versus solar PV, we

1. derive the unrestricted system cost-minimizing deployment of wind and solar power
2. restrict deployment of wind power by a small margin (so that the next best RET substitutes for wind power) and observe net system cost c_{net} in the country of interest (calculated as total system cost including air pollution cost net of trade balance)
3. repeat 2 till no wind power can be deployed anymore
4. the opportunity cost of wind power is approximated by the change in c_{net} in response to a change in wind power capacity w deployed.

$$OC_w = \frac{\Delta c_{net}}{\Delta w}$$

The case of Austria

- Policy goal: $100\,\%^1$ of electricity demand from domestic renewable sources on annual balance by 2030
  - → Ideal frame for studying substitution / opportunity cost
- necessarily turns Austria into a net exporter of electricity
- Official expectation: additional generation of $27\,\mathrm{TW\,h}$ sufficient

	2018 [GW]	2018[2] [TWh]	Policy [TWh]	2030 [TWh]	2030 [GW]
Solar PV	1.44	1.23	+11	12.23	14.27
Wind (onshore)	3.05	6.14	+10	16.14	8
Hydro (run-of-river)	5.72	28.34	+5	33.34	6.73
Biomass	~ 1	4.78	+1	5.78	< 2

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[1] excluding system services and industry own consumption. At current levels this equals 10% of consumption, i.e. actual target is around 90%.

[2] meteorological conditions as in 2016

The case of Austria

Some Stylized Facts

- Social conflict around the large-scale expansion of onshore wind power
- Solar PV is the only feasible large-scale substitute for wind power
  - Use of nuclear power banned in a 1978 referendum
  - Hydro power potential largely exploited
  - Biomass neither ecologically nor economically sustainable
- Germany is Austria's most important electricity trading partner, by far

- Resemble prospective power system in Austria in 2030
- Set policy target of meeting at least 90% of demand in 2030 from domestic renewable sources

- Include most important electricity trading partner Germany
- Incorporate announced electricity system targets for Germany in 2030
    - nuclear phase-out
    - partial coal exit
    - expansion of renewable capacities in line with EEG 2017

- Simulate operation of and investment in prospective electricity system with *medea*

Power system model *medea*

Objective

- minimize total system cost
  - fuel and CO_2 cost
  - O&M cost
  - capital cost

Decision variables

- hourly dispatch
- inter-zonal electricity trade
- investment in power plants, storages, and transmission

Constraints

- market clearing
- capacity constraints
- co-generation & fuel use
- system service requirement
- inter-zonal electricity trade

Economic assumptions

- perfect competition
- perfect foresight
- price-inelastic demand

Resolution

- hours (one year)
- bidding zones
- 41 technologies

Implementation

- linear program
- python & GAMS

medea is available on github.com/inwe-boku/medea (MIT license)

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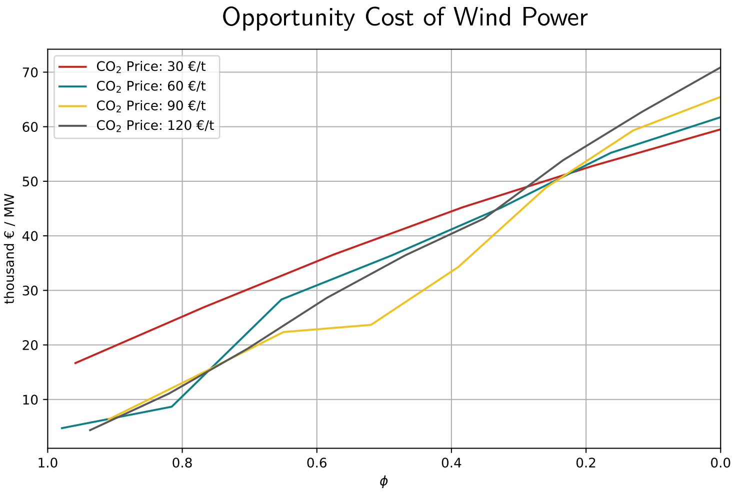
Relative measure of substitution



Capital cost of solar PV	630 $€/\mathrm{kWp}$

$\rightarrow$ about $^2/_3$ rooftop PV, $^1/_3$ open space PV

At $\Phi = 1$ RET deployment is as in the unconstrained system cost minimum.

At $\Phi = 0$ the least cost technology is fully substituted by its best alternative.

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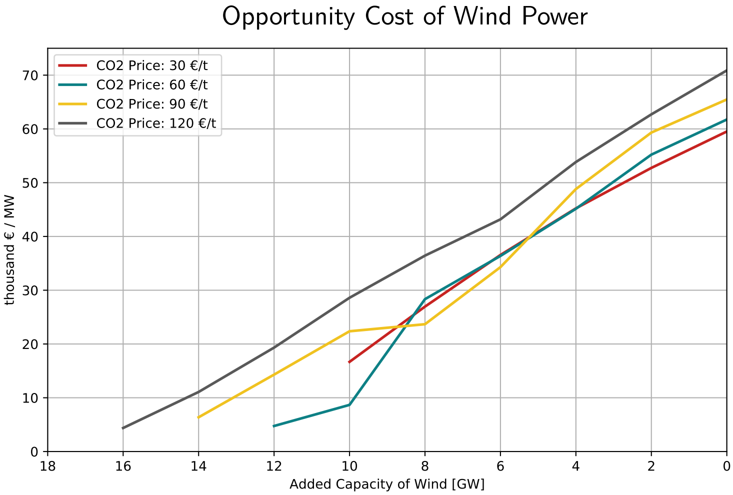
Absolute measure of substitution



Capital cost of solar PV	630 €/kWp

→ about $^2/_3$ rooftop PV, $^1/_3$ open space PV

← more wind power

more solar PV →

wind power and solar PV are substitutes

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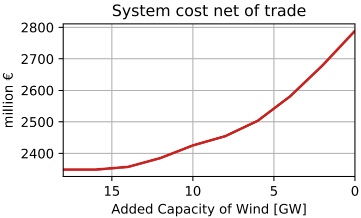
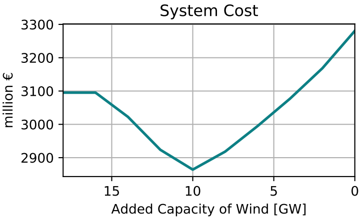
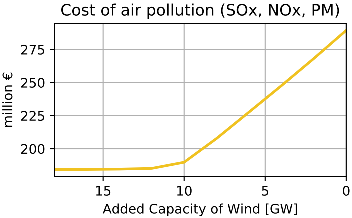
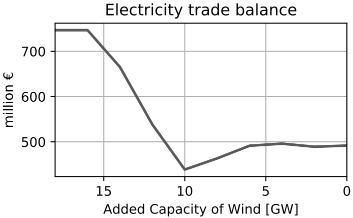
Cost with restricted wind power


System cost net of trade


System Cost


Cost of air pollution (SOx, NOx, PM)


Electricity trade balance

Capital cost of solar PV	630 €/kWp
CO_2 price	90 €/MWh

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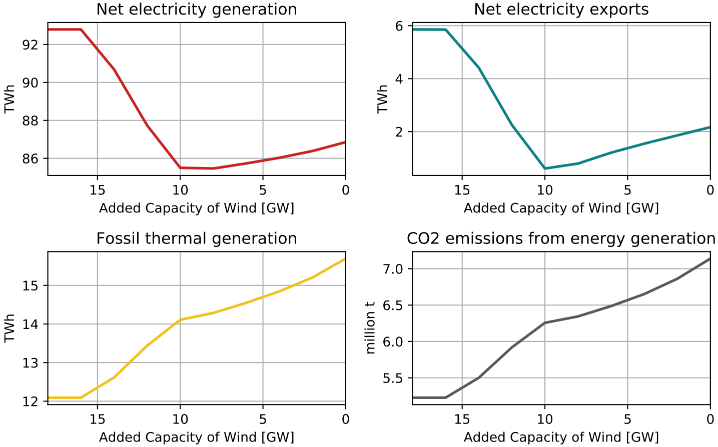
System operation with restricted wind power



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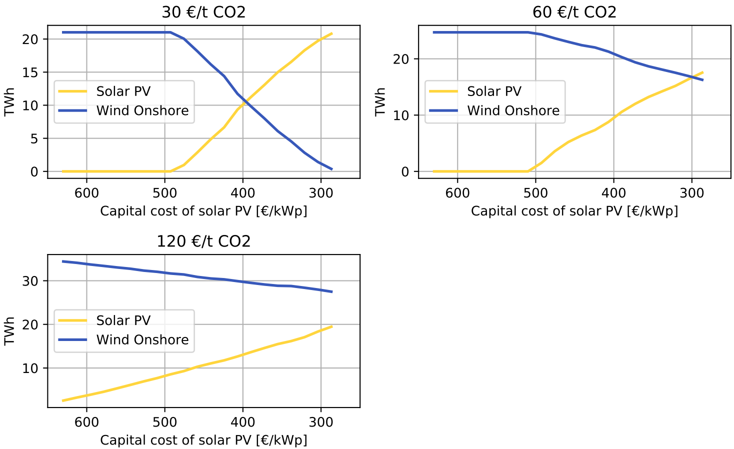
Sensitivity to capital cost of solar PV

Least Cost Technology Mix



Capital cost estimates for solar PV in 2030

Small-scale rooftop	830 $€/\mathrm{kWp}$
Utility-scale open space	280 $€/\mathrm{kWp}$

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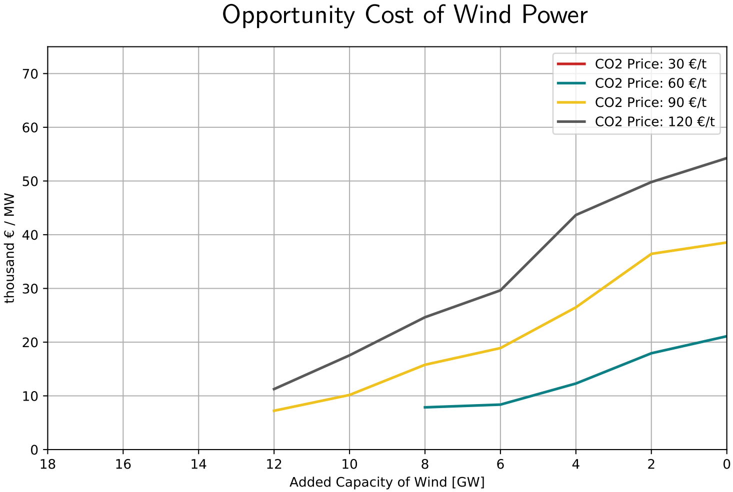
Sensitivity to capital cost of solar PV



Capital cost of solar PV	$280 \text{ €}/\mathrm{kWp}$

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Discussion of results

- Renewable resource quality held constant as capacity is expanded
- Sub-national electricity transmission and distribution grids neglected
- Technical operation of generators not fully represented
  (e.g. no unit commit, simplified balancing)
- Electricity market-splitting has increased market concentration
- Announced policy necessarily turns Austria into a net exporter of electricity
  → "loop-flows" potentially avoided
  → artificial transmission restriction between DE and AT could be eliminated

Conclusions

- We demonstrated that restricting wind power can come at significant opportunity cost
- Socially optimal wind power deployment depends on cost and benefits of undisturbed landscapes
- Our analysis constitutes one of two pillars needed to determine a spatially explicit, socially optimal renewables expansion
  - → need to complement findings with a spatially resolved assessment of the negative externalities of wind turbines, for example approximated by wind turbine impact on property prices

- For the case of Austria, we find
  - little social value lost from substituting onshore wind power with utility-scale, open-space solar PV, *if* CO_2 emissions are valued at $30\,€/\mathrm{MWh}$ or lower
  - potential gains from wind power *if* (i) there is a preference for rooftop solar PV or (ii) the cost of CO_2 emissions exceeds $30\,€/\mathrm{MWh}$
  - Gains from wind power deployment could be used to compensate individuals affected by local wind turbine externalities

Thank you!

https://refuel.world
https://github.com/inwe-boku/medea
sebastian.wehrle@boku.ac.at

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