Effectiveness of decarbonisation policies in an electricity system with intermittent renewables

Aimilia Pattakou, ETH Zurich, +41 44 632 57 30, apattakou@ethz.ch
Aryestis Vlahakis, ETH Zurich, +41 44 632 06 12, aryestis@ethz.ch

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1 Introduction

Many electricity generation systems are very carbon intensive: internalising the externality caused by CO_2 emissions has become a keystone climate change policy in many countries. How can a subsidy for intermittent renewable energy internalise the carbon externality and achieve first best? Policy makers use subsidies to renewable energy to help expand the penetration of a generation technology, hence reducing overall CO_2 emissions from electricity production. In many European countries, what matters in the design of renewable energy support policies is that the replaced energy is dirty; there is rarely discrimination as to the degree of dirtiness. We use a modified peak-load pricing model to characterise the social planner's optimum, and then examine whether environmental policies applied to a market equilibrium are successful in restoring first best in a power system comprising of intermittent and dispatchable generation technologies.

Our analysis is most closely related to the literature on peak-load pricing models for the electricity generation market, as summarised by Crew et al. (1995). This literature has subsequently been extended by Chao (2011), who considers uncertainty in demand and supply, or Ambec & Crampes (2012) and Helm & Mier (2016), who analyse the effect intermittent renewable energy has on the equilibrium capacity and energy supply for electricity. Our main contribution is to characterise multiple technologies in electricity production and use this to consider the effectiveness of a subsidy to intermittent renewable energy; this is most similar to Andor & Voss (2016).

2 Model

We modify the canonical peak-load pricing model to explicitly include the intermittency of renewable energy generators and the external costs of carbon. The model is set up to consider the effect of a policy which aims to reduce the carbon externality by offering additional support to carbon free, renewable energy generators. We first determine the optimal quantities of capacity and of energy generated. We then do the same for the decentralised equilibrium. Finally, we characterise how a subsidy succeeds or fails to restore first best.

In the model, electricity can be generated using any combination of three types of technology: two dispatchable, thermal — and CO_2 emitting — technologies, which we represent by natural gas g and coal c, and a non-dispatchable renewable technology, which we represent by wind w. The two CO_2 emitting technologies differ only in their emission intensity. A standard approach in this literature is to separate the production of electricity into two stages: the decision on how much capacity to build and the decision on how much energy to produce with the installed capacity. We call these the investment and dispatch stages, respectively.

The system produces energy q_i, using capacity K_i, from either wind w, coal c or natural gas g; subscript i denotes the full set of technologies, while we use subscript f when specifically considering the subset of fossil based generators $\{c, g\}$. It costs b_i to produce each unit of energy and β_i to install each unit of capacity. In our analysis, the costs accrued within each period are considered within that period, so quantity costs[1] b_i and capacity costs β_i can be considered simultaneously, even though their original units are different. We consider the coal and gas capacities to be known — we are not focusing on system reliability here — while wind generators, being intermittent, are not always fully available. The availability factor of wind α is drawn from a probability distribution function $f(\alpha)$, which we leave general. This is what we represent by limiting installed capacity K_w, by a fraction α, giving available capacity αK_w. Following the canonical peak load pricing model (Crew et al., 1995), we assume costs such that all technologies are installed. In the dispatch

[1] In the social planner solution to the problem, production cost of the thermal technologies also includes the cost of the carbon externality; this externality is absent in the decentralised equilibrium.

stage, welfare is the utility derived from consuming electricity, $U(q(\alpha))$, less the cost of producing said quantity. Given capacities K, a measure of availability α and $b_w = 0$, the problem reads:

$$\max_{q_i(\alpha)\geq 0} \big\{\mathcal{S}_q := U\big(q(\alpha)\big) - \sum_f b_f q_f(\alpha)\big\} \quad \forall f \in \{c, g\} \tag{2.1}$$

such that

$$\begin{aligned} &q(\alpha) = \sum_i q_i(\alpha) \quad \forall i \in \{c, g, w\} \\ &K_f \geq q_f(\alpha) \quad \forall f \in \{c, g,\} \\ &\alpha K_w \geq q_w(\alpha) \end{aligned} \tag{2.2}$$

The Lagrangian then is:

$$\mathcal{L}_q = U\big(q(\alpha)\big) - \sum_f b_f q_f(\alpha) + \sum_f \lambda_f(\alpha)[K_f - q_f(\alpha)] + \lambda_w(\alpha)\big[\alpha K_w - q_w(\alpha)\big] + \xi_i q_i(\alpha) \tag{2.3}$$

In the investment stage the total expected welfare is considered. Investment costs are assumed to be quadratic in order to have increasing marginal investment costs. The problem is then written as:

$$\max_{K_i > 0} \Big\{\mathcal{S}_K := \int_0^1 \mathcal{S}_q^*(K_i, \alpha_i) f(\alpha) d\alpha - \sum_i \frac{1}{2}\beta_i K_i^2\Big\} \tag{2.4}$$

The Lagrangian — subscript K denotes that this is the one for the capacity problem — is:

$$\mathcal{L}_K = \int_0^1 \mathcal{S}_q^*(K_i, \alpha_i) f(\alpha) d\alpha - \sum_i \frac{1}{2}\beta_i K_i^2 \tag{2.5}$$

3 Results & Further Work

Using our basic model, we show that available wind capacity can never be idle, and derive the equations that determine optimal installed capacities. Note that due to unsuitable environmental conditions, installed and available wind capacity might not be equal, but the capacity that is available will be fully used. To show this, we assume that wind is installed, $K_w > 0$, and consider the case when it is only partially used: $\alpha K_w > q_w^* > 0 \therefore \lambda^*(\alpha) = 0$. From the first order condition for the quantity of wind, we have $f(\alpha)\big[\mathrm{U}'(q^*(\alpha)) - b_w\big] = 0$. However, this cannot hold, as we know $f(\alpha) \neq 0$, $\mathrm{U}'(q^*(\alpha)) \neq 0$, and $b_w = 0$. It must be that $\alpha K_w = q_w^* > 0$. We will not deal with the cases in which fewer than three generation technologies are installed: in these cases the problem of a subsidy to renewables for environmental reasons is not interesting. In addition, assuming a uniform distribution for α, the equations that define capacities are:

$$\frac{U(K_w + K_c + K_g) - U(K_c + K_g)}{K_w} = b_c + \beta_c K_c \tag{3.1}$$

$$\frac{U(K_w + K_c + K_g) - U(K_c + K_g)}{K_w} = b_g + \beta_g K_g \tag{3.2}$$

$$\frac{U(K_w + K_c + K_g) - \int_0^1 U(\alpha K_w + K_c + K_g) d\alpha}{K_w} = \beta_w K_w \tag{3.3}$$

In the paper's extension, we will demonstrate how a subsidy that does not discriminate between dirty energies fails to restore first best, because it either replaces an insufficient amount of dirty energy, or does not replace the most carbon intensive energy source. Finally, we illustrate our theoretical insights with a numerical example based on realistic data.

References

Ambec, S., & Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, *34*(3), 319–336.
URL http://dx.doi.org/10.1016/j.reseneeco.2012.01.001

Andor, M., & Voss, A. (2016). Optimal renewable-energy promotion: Capacity subsidies vs. generation subsidies. *Resource and Energy Economics*, *45*(nil), 144–158.
URL https://doi.org/10.1016/j.reseneeco.2016.06.002

Chao, H. (2011). Efficient pricing and investment in electricity markets with intermittent resources. *Energy Policy*, *39*(7), 3945–3953.
URL https://doi.org/10.1016/j.enpol.2011.01.010

Crew, M. A., Fernando, C. S., & Kleindorfer, P. R. (1995). The theory of peak-load pricing: A survey. *Journal of Regulatory Economics*, *8*(3), 215–248.
URL http://dx.doi.org/10.1007/BF01070807

Helm, C., & Mier, M. (2016). Efficient diffusion of renewable energies: A roller-coaster ride. *University of Oldenburg, Department of Economics Working Papers*, *389*(16).