Managing intermittency in the electricity market

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Motivation

- To reduce greenhouse gas emissions, it is recommended to shift to renewables-based electricity production
- Renewables such as wind and solar are **intermittent** (variable + uncertain)
- Renewables-based electricity is **intermittent** and **inflexible**
- Renewables intermittency challenges the "supply-matching-demand" exercise of the electricity industry
- Disruptions in this balance have technical and economical impacts
- **Flexibility** on the supply and/or **demand side** of the electricity market as a solution to managing renewables intermittency

Related Literature - Demand flexibility

To manage demand intermittency and optimal capacities

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Can we take into account more diversified retail contracts to integrate intermittent renewable technologies?

This paper

What we do?

- Theoretical framework for integrating intermittent renewable technologies into an electricity mix with conventional energy
- Demand-side flexibility be implemented through retailers offering diversified electricity delivery contracts at different prices
- Diversity of the contracts be depicted through **base state-contingent electricity delivery contracts**

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What we find?

- Model is consistent with a partial equilibrium model
- Welfare is constraint efficient
- Conditions when changing the base delivery contracts improves: welfare, integration of the renewable capacity and both

1. Introduction
2. **Main assumptions**
3. Results
4. Conclusion

General features

Intermittency:

- Set of states of nature: $s \in \{1, \ldots, S\}$
- State-contingent electricity production traded on perfectly competitive state-contingent wholesale markets
- State-contingent expected prices: $\mathbf{p} = (p_1, \ldots, p_S) \in \mathbb{R}^S$

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Decision making:

Ex-ante	States of nature	Ex-post
Investment in renewable capacity	|	
Production plan from conventional technology	|	Electricity
Retailers	|	Delivery
Consumers	|	

Electricity Retailing (1)

- Retailers propose diversified delivery contracts built as from **base state-contingent delivery contracts**

- Example:
  - Time-of-Use retail contract
  - 1 off-peak period: night (s_1)
  - 1 peak period: day(s_2)
  - The base contracts can then be:

$$\begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} k_1 \\ \begin{pmatrix} a_1 \\ 0 \end{pmatrix} \\ price : q_1 \end{array} \qquad \begin{array}{c} k_2 \\ \begin{pmatrix} 0 \\ a_2 \end{pmatrix} \\ price : q_2 \end{array}$$

  - Linear combination of k_1 and k_2 can give a Flat delivery contract:

$$\begin{array}{c} \\ s_1 \\ s_2 \end{array} \begin{array}{c} k_3 \\ \begin{pmatrix} a_1 \\ a_1 \end{pmatrix} \\ price : q_3 \end{array}$$

Electricity Retailing (2)

Description	Notation
Random electricity of 1 unit delivery contract k	$\mathbf{a}_k = (a_{1k}, \ldots, a_{Sk}),\ a_{sk} \geq 0$
K contracts	$K = \{1, \ldots, K\}$
Electricity delivery of the K contracts	$\mathbf{A} = [\mathbf{a}_k]_{k=1}^{K} \in \mathbb{R}_+^{SK}$
Portfolio of contracts offered	$\boldsymbol{\theta}_r = (\theta_1, \ldots, \theta_K) \in \mathbb{R}^K$
Random electricity flow induced by portfolio	$\mathbf{A}\boldsymbol{\theta}_r \in \mathbb{R}^S$
Less contracts than states of nature	$K < S$
No redundant contract	$rank(\mathbf{A}) = K$
Always an asset delivering electricity in a state	$\forall s,\ \exists k,\ a_{sk} > 0$
Objective program	$\boldsymbol{\theta}_r^* \in \arg\max_{\theta_r \in \mathbb{R}^K} \quad (\mathbf{q}^*)' \boldsymbol{\theta}_r - (\mathbf{p}^*)' \mathbf{A}\boldsymbol{\theta}_r$

Electricity Production

Intermittent Technology

Description	Notation
Ex-ante capacity	$\kappa \in \mathbb{R}_+$
State-contingent production per unit capacity	$\mathbf{g} = (g_1, \ldots, g_S) \in \mathbb{R}_+^S$
Increasing and convex investment cost function	$\mathcal{K}(\kappa)$ $(\partial\mathcal{K}(\kappa) > 0,\ \partial^2\mathcal{K}(\kappa) > 0\ \&\ \mathcal{K}(0) = 0)$
Objective program	$\kappa^* \in \arg\max_{\kappa \in \mathbb{R}_+} \quad \kappa\,(\mathbf{p}^*)'\,\mathbf{g} - \mathcal{K}(\kappa)$

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Conventional Technology

Description	Notation
State-contingent electricity production	$\mathbf{y} = (y_1, \ldots, y_S) \in \mathbb{R}_+^S$
Increasing and convex production expected cost	$\sum_{s=1}^{S} c_s(y_s)$ $(\partial c_s(q_s) > 0,\ \partial^2 c_s(q_s) > 0,\ c_s(0) = 0)$
Objective program	$\mathbf{y}^* \in \arg\max_{\mathbf{y} \in \mathbb{R}_+^S} (\mathbf{p}^*)' \mathbf{y} - \sum_{s=1}^{S} c_s(y_s)$

Electricity consumption

Description	Notation
Random electricity consumption	$\mathbf{x} = (x_1, \ldots, x_S) \in \mathbb{R}_+^S$
Budget	$m_0 \in \mathbb{R}$
Money spent on other goods	$m \in \mathbb{R}$
Increasing and strictly concave utility function	$\mathcal{U}(\mathbf{x})$
Portfolio of contracts demanded	$\boldsymbol{\theta}_c \in \mathbb{R}^K$
Random electricity flow induced by portfolio	$\mathbf{x} = \mathbf{A}\boldsymbol{\theta}_c$
Objective program	$(\boldsymbol{\theta}_c^*, m^*) \in \underset{(\theta_c, m) \in \mathbb{R}^{K+1}}{\arg\max} \quad \mathcal{U}\left(\mathbf{A}\boldsymbol{\theta}_c\right) + m$
	$s.t. \quad \begin{cases} \mathbf{A}\boldsymbol{\theta}_c \geq 0 \\ (\mathbf{q}^*)' \boldsymbol{\theta}_c + m = m_0 \end{cases}$

Partial Equilibrium: Definition

Equilibrium is $(m^*, \boldsymbol{\theta}_c^*, \boldsymbol{\theta}_r^*, \mathbf{y}^*, \kappa^*, \mathbf{p}^*, \mathbf{q}^*) \in \mathbb{R}^{K+1} \times \mathbb{R}^K \times \mathbb{R}_+^S \times \mathbb{R}_+ \times \mathbb{R}_+^S \times \mathbb{R}_+^K$ whereby:

- ex-ante, the consumers maximize utility and the retailers and producers maximize their profits
- the contract and contingent electricity markets clear:

$$\boldsymbol{\theta}_r^* = \boldsymbol{\theta}_c^* \quad \text{and} \quad \mathbf{y}^* + \kappa^* \mathbf{g} = \mathbf{A}\boldsymbol{\theta}_r^*$$

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Partial Equilibrium: Existence and Uniqueness

- No-arbitrage condition shows that $\mathbf{q} = \mathbf{A}'\mathbf{p}$ with $\mathbf{p} \in \mathbb{R}^S_{++}$

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- The state contingent demand of electricity is a differentiable function $\mathbf{D} : \mathbb{R}^S_{++} \to \mathbb{R}^S$ with the property that $\partial \mathbf{D}(\mathbf{p})$ is a symmetric and negative semi-definite matrix and the boundary conditions are defined.

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- The contingent electricity supply $\mathbf{S} : \mathbb{R}^S_{++} \rightarrow \mathbb{R}^S_{+}$ is a differentiable function with the property that $\partial \mathbf{S}(\mathbf{p})$ is positive definite and the boundary conditions are defined.

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Proposition

There exists a unique contingent price vector $\mathbf{p}^* \in \mathbb{R}^S_{++}$ *which clears the different state contingent electricity markets and an associated electricity delivery contract price vector* $\mathbf{q}^* = \mathbf{A}'\mathbf{p}^* \in \mathbb{R}^K_{++}$ *which is free of arbitrage and clears the different contract markets.*

Welfare Analysis

- Contract structure matters as there are less contracts than states of nature
- Potential contingent electricity consumptions restricted to the linear subspace generated by the columns of $\mathbf{A}$, i.e. $\mathbf{x} \in span(\mathbf{A})$
- $\mathbf{x} = \mathbf{A}\boldsymbol{\theta}$
  With 2 contract structures $\mathbf{A}$ and $\tilde{\mathbf{A}}$ with property that $span(\mathbf{A}) = span(\tilde{\mathbf{A}})$, then $\mathbf{A}$ is equivalent to $\tilde{\mathbf{A}}$ in terms of electricity demand, i.e. $\mathbf{A} \sim_e \tilde{\mathbf{A}}$

$$\mathbf{A} = \begin{bmatrix} \mathbf{BC} \\ \mathbf{C} \end{bmatrix} \text{ with } \mathbf{C} \text{ any invertible matrix of dimension } K$$

$$\mathbf{x} = \begin{bmatrix} \mathbf{B} \\ \mathbf{I}_K \end{bmatrix} \boldsymbol{\theta} \Leftrightarrow \begin{cases} \boldsymbol{\theta} = (x_s)_{s=S-K+1}^{K} \\ \begin{bmatrix} \mathbf{I}_{S-K} & -B \end{bmatrix} \mathbf{x} = \mathbf{0} \end{cases}$$

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Welfare Analysis

$$SW(\mathbf{B}) = \max_{(\mathbf{y},\kappa,\mathbf{x})\in\mathbb{R}_+^{\mathbf{2}S+\mathbf{1}}} \mathcal{U}(\mathbf{x}) - \mathcal{C}(\mathbf{y}) - \mathcal{K}(\kappa) \ s.t. \begin{cases} \mathbf{x} - \mathbf{y} - \kappa\mathbf{g} = \mathbf{0} \\ \begin{bmatrix} \mathbf{I}_{S-K} & -\mathbf{B} \end{bmatrix} \mathbf{x} = \mathbf{0} \end{cases}$$

$$\begin{cases} \partial\mathcal{U}(\mathbf{x}) - \boldsymbol{\lambda} - \begin{bmatrix} \mathbf{I}_{S-K} \\ -\mathbf{B}' \end{bmatrix} \cdot \boldsymbol{\mu} = \mathbf{0} \\ -\partial\mathcal{C}(\mathbf{y}) + \boldsymbol{\lambda} = \mathbf{0} \\ -\frac{d\mathcal{K}(\kappa)}{d\kappa} + \mathbf{g}' \cdot \boldsymbol{\lambda} = 0 \end{cases}$$

Proposition

The competitive electricity production plan and allocation $(\tilde{\mathbf{y}}, \tilde{\kappa}, \tilde{\mathbf{x}}) \in \mathbb{R}_+^{S+\mathbf{1}} \times \mathbb{R}_+^S$ is constrained efficient.

Comparative Statics

Improve welfare:

As long as $\boldsymbol{\mu} \neq \mathbf{0}$, any addition of a new contract to $\mathbf{A}$ linearly independent of the existing ones improves welfare

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Improve integration of renewable capacity:
If at least two components of $(\partial_{x_s} U(\mathbf{S}(\mathbf{p})) - p_s)_{s=1}^{S-K}$ are different from 0 and $1 < K < S-1$, all the directions of price changes which improve investment in renewables can be reached, especially the one which is collinear to $\mathbf{g}$ and which "maximizes" the penetration of renewables

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Both of the above:

As long as $\partial_B \kappa^*$ and $\partial_B SW$ are not collinear with a negative coefficient

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Conclusion

- Theoretical framework taking into account intermittency of renewables and demand-side flexibility through diversified retail contracts
- Shown existence and uniqueness of a competitive equilibrium of the contingent wholesale and retail markets
- Welfare is constraint efficient
- Characterized the conditions under which we can improve welfare, renewable capacity investment and both
- The results provide insights on how the role of retailers can be redefined so as to participate in demand-side flexibility
- The paper highlights the importance of accounting for intermittency in order to achieve renewable capacity objectives

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