The structural impact of renewable portfolio standards and feed-in-tariffs on electricity markets

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Joint work with:
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June 25, 2015
(1) Motivation for research project

(2) Modeling approach

(3) Discussion of results

(4) Conclusion
RES\(^1\) – in particular wind and solar PV – are fast growing technologies for electricity generation.

Annual investment in RES capacity\(^2\)

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind</th>
<th>Solar</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>40</td>
<td>65</td>
<td>65</td>
<td>170</td>
</tr>
<tr>
<td>2005</td>
<td>100</td>
<td>65</td>
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<td>2006</td>
<td>146</td>
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<td>54</td>
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</tr>
<tr>
<td>2007</td>
<td>172</td>
<td>146</td>
<td>82</td>
<td>390</td>
</tr>
<tr>
<td>2008</td>
<td>168</td>
<td>172</td>
<td>92</td>
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<tr>
<td>2009</td>
<td>227</td>
<td>168</td>
<td>112</td>
<td>507</td>
</tr>
<tr>
<td>2010</td>
<td>279</td>
<td>227</td>
<td>142</td>
<td>648</td>
</tr>
<tr>
<td>2011</td>
<td>244</td>
<td>279</td>
<td>137</td>
<td>660</td>
</tr>
<tr>
<td>2012</td>
<td>140</td>
<td>244</td>
<td>116</td>
<td>490</td>
</tr>
</tbody>
</table>

Global RES capacity\(^2\)

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind</th>
<th>Solar</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>99</td>
<td>115</td>
<td>99</td>
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<tr>
<td>2005</td>
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<td>2006</td>
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<td>433</td>
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<tr>
<td>2007</td>
<td>200</td>
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<td>165</td>
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<td>2008</td>
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<td>2009</td>
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<td>250</td>
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<td>2010</td>
<td>390</td>
<td>315</td>
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<td>1020</td>
</tr>
<tr>
<td>2011</td>
<td>480</td>
<td>390</td>
<td>390</td>
<td>1260</td>
</tr>
</tbody>
</table>

\(^1\) Renewable energy sources for electricity generation; 2 Excluding large hydro power

FIT schemes are employed in
- 71 countries
- 28 states and provinces

FITs are the most widespread RES support schemes in 2013 present in 71 countries

SOURCE: REN21 (2013)
RPS\(^1\) are the second most widespread RES support scheme present in 22 countries and 54 states/provinces.

RPS / quota schemes are employed in:
- 22 countries
- 54 states and provinces

SOURCE: REN21 (2013)

1 Renewable portfolio standards and quota systems
(1) The electricity sector is the main energy consumer and carbon emitter in the US

### Share of energy expenditures in US GDP

<table>
<thead>
<tr>
<th>Year</th>
<th>Residential, commercial</th>
<th>Industrial</th>
<th>Transportation</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>7</td>
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<td>2009</td>
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<tr>
<td>2010</td>
<td>8</td>
<td></td>
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</tr>
</tbody>
</table>

### Split of US total energy consumption

<table>
<thead>
<tr>
<th>Sector</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<th>2008</th>
<th>2009</th>
<th>2010</th>
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<td></td>
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<tr>
<td>Industrial</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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<td>21%</td>
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<tr>
<td>Transportation</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28%</td>
</tr>
<tr>
<td>Electricity</td>
<td>40%</td>
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<td></td>
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</table>

### Split of US total CO₂ emissions

<table>
<thead>
<tr>
<th>Sector</th>
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<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential, commercial</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11%</td>
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<tr>
<td>Industrial</td>
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<td></td>
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<td>14%</td>
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<tr>
<td>Transportation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>31%</td>
</tr>
<tr>
<td>Electricity</td>
<td>38%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

(1) RES\textsuperscript{1,2} account for an increasing share in global electricity generation and capacity

**RES share in new global capacity**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>26</td>
<td>23</td>
<td>29</td>
<td>36</td>
<td>42</td>
<td></td>
</tr>
</tbody>
</table>

**Split between RES and conventional power**

<table>
<thead>
<tr>
<th>Category</th>
<th>Conventional</th>
<th>Renewable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global final energy consumption</td>
<td>81</td>
<td>19</td>
</tr>
<tr>
<td>Global electricity production</td>
<td>78</td>
<td>22</td>
</tr>
<tr>
<td>Installed electricity generation capacity</td>
<td>74</td>
<td>26</td>
</tr>
</tbody>
</table>

\textsuperscript{1} Renewable energy sources for electricity generation; \textsuperscript{2} Excluding large hydro power

Renewable Portfolio Standard Policies

www.dsireusa.org / March 2013

29 states, plus Washington DC and 2 territories, have Renewable Portfolio Standards (8 states and 2 territories have renewable portfolio goals).

- WA: 15% x 2020*
- MT: 15% x 2015
- MN: 25% x 2025 (Xcel: 30% x 2020)
- ND: 10% x 2015
- SD: 10% x 2015
- WI: Varies by utility; ~10% x 2015 statewide
- MI: 10% & 1,100 MW x 2015*
- NY: 29% x 2015
- OH: 12.5% x 2024
- VA: 15% x 2025*
- WV: 25% x 2025†
- NC: 12.5% x 2021 (IOUs)
- NM: 20% x 2020 (IOUs)
- OK: 15% x 2015
- TX: 5,880 MW x 2015*
- CA: 33% x 2020
- AZ: 15% x 2025
- OR: 25% x 2025 (large utilities)*
- 5% - 10% x 2025 (smaller utilities)
- NV: 25% x 2025*
- CO: 30% by 2020 (IOUs)
- 10% by 2020 (co-ops & large munis)*
- IA: 105 MW
- IL: 25% x 2025
- KS: 20% x 2020
- MO: 15% x 2021
- UT: 20% by 2025*
- HI: 40% x 2030
- VT: (1) RE meets any increase in retail sales x 2012; (2) 20% RE & CHP x 2017
- ME: 30% x 2000 New RE: 10% x 2017
- NH: 24.8% x 2025
- MA: 22.1% x 2020 New RE: 15% x 2020 (+1% annually thereafter)
- RI: 16% x 2020
- CT: 27% x 2020
- PA: ~18% x 2021†
- NJ: 20.38% RE x 2021 + 4.1% solar x 2028
- MD: 20% x 2022
- DE: 25% x 2026*
- DC: 20% x 2020

- Renewable portfolio standard
- Renewable portfolio goal
- Solar water heating eligible
- Minimum solar or customer-sited requirement
- Extra credit for solar or customer-sited renewables
- Includes non-renewable alternative resources

www.dsireusa.org / March 2013

16 states + Washington DC have Renewable Portfolio Standards with Solar and/or Distributed Generation provisions

- WA: double credit for DG
- OR: 20 MW solar PV x 2020; double credit for PV
- NV: 1.5% solar x 2025; 2.4 - 2.45 multiplier for PV
- CO: 3.0% DG x 2020; 1.5% customer-sited x 2020
- IL: 1.5% PV x 2025; 0.25% DG by 2025
- OH: 0.5% solar-electric x 2025
- MI: triple credit for solar-electric
- NH: 0.3% solar-electric x 2014
- MA: 400 MW PV x 2020
- NY: 0.4092% customer-sited x 2015
- NJ: 4.1% solar-electric x 2028
- PA: 0.5% PV x 2021
- DE: 3.5% PV x 2026; triple credit for PV
- MD: 2% solar x 2020
- DC: 2.5% solar x 2023

- AZ: 4.5% DG x 2025
- NM: 4% solar-electric x 2020; 0.6% DG x 2020
- UT: 2.4 multiplier for solar-electric
- TX: double credit for non-wind (non-wind goal: 500 MW)
- NC: 0.2% solar x 2018
- WV: various multipliers

Delaware allows certain fuel cell systems to qualify for the PV carve-out

Renewable portfolio standard with solar / distributed generation (DG) provision

Renewable portfolio goal with solar / DG provision

Solar water heating counts toward solar / DG provision
Governments support RES deployment through different policy mechanisms – we focus on FIT and RPS

**RES support schemes**

<table>
<thead>
<tr>
<th>Description</th>
<th>Country examples</th>
<th>Focus of paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price-based</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed-in-tariffs (FIT)</td>
<td>Canada, Denmark, Germany, India, Spain, South Africa</td>
<td></td>
</tr>
<tr>
<td>▪ Purchase guarantee of RES electricity at subsidized rates for a predetermined period of time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Typical designs either as fixed FIT or FIT premium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production tax credits (PTC)</td>
<td>U.S.</td>
<td></td>
</tr>
<tr>
<td>▪ Grant of tax credits for RES electricity generated for a predetermined period of time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Scheme often combined with other RES support systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity-based</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable portfolio standards (RPS)</td>
<td>U.S. (e.g. IL, CA, TX), UK, Sweden, Belgium, Australia</td>
<td></td>
</tr>
<tr>
<td>▪ RES quota requirement for utilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Typically market-based system using tradable renewable energy certificates (RECs) as additional revenue source for RES developers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tender regimes (TR)</td>
<td>China, Denmark, France, Ireland, UK, U.S.</td>
<td></td>
</tr>
<tr>
<td>▪ Reverse auction of specific (larger) RES projects for a predetermined period of time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Long-term power purchase agreements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Only operation-oriented, excluding environmental protection or emission reduction schemes such as EU ETS

A research gap exists for the comparison of RES support schemes accounting for market effects.

Comparisons:
- Mendonça et al. (2009)
- Haas et al. (2010 & 2011)
- Mormann (2012)

Single analyses:
- Cory et al. (2009)
- Chen & Cliff (2009)
- Couture & Gagnon (2010)
- Jensen & Skytte (2002)
- Tanaka, Chen (2013)

Detailed numerical assessments:

Full market models:
- Eager et al. (2012)
- DECC (2013)

Research question:
What is the impact of renewable portfolio standards (RPS), feed-in-tariffs (FIT) and market premia (MP) on affordability, security of supply, and sustainability of the electricity generated?
(1) Motivation for research project

(2) Modeling approach

(3) Discussion of results

(4) Conclusion
We compare RES support schemes using a quantitative generation capacity expansion model.

Research question
What is the impact of renewable portfolio standards (RPS), market premia (MP), and feed-in-tariffs (FIT) on the three key electricity policy dimensions of

- **Affordability** approximated by total cost and electricity prices
- **Security of supply** approximated by lost load occasions and electricity price volatility
- **Sustainability** approximated by CO$_2$ emissions

Model requirements

<table>
<thead>
<tr>
<th>Reflection of market reactions and strategic investor behavior</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market instead of central command-and-control perspective needed</td>
<td></td>
</tr>
<tr>
<td>Need to account for price sensitivity of demand instead of only generation-focused cost-minimization perspective</td>
<td></td>
</tr>
<tr>
<td>Strategic bidding required and profitability/project value approach needed instead of pure cost focus on investor level</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reflection of long-term investments and real-time supply and demand matching</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended time horizon exceeding lifetime of most plants</td>
<td></td>
</tr>
<tr>
<td>High granularity of time steps required given increasing intermittent generation as well as ramping constraints</td>
<td></td>
</tr>
</tbody>
</table>

Focus on comparison between support schemes
- Setting in liberalized electricity market with stable regulatory and economic environment allowing to use deterministic inputs
- Investors deciding rationally and using profitability considerations
- Abstraction from transmission constraints and technical feasibility
The three support schemes analyzed exhibit different degrees of market-integration.

\[
\begin{align*}
\tilde{x} &= \text{endogenous variable} & P &= \text{electricity price} & P_{REC} &= \text{REC price} & \text{FIT} &= \text{feed-in-tariff} \\
\bar{x} &= \text{exogenous, constant variable} & \pi &= \text{total revenue per unit of electricity} & MP &= \text{market premium} & E &= \text{electricity}
\end{align*}
\]

<table>
<thead>
<tr>
<th>High</th>
<th>Level of market integration</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPS</td>
<td>Renewable generators</td>
<td>FIT</td>
</tr>
<tr>
<td></td>
<td>$E$</td>
<td>$E$</td>
</tr>
<tr>
<td></td>
<td>$REC$</td>
<td>$FIT$</td>
</tr>
<tr>
<td></td>
<td>$\pi = \tilde{P} + \tilde{P}_{REC}$</td>
<td>$\pi = \bar{F}I\bar{T}$</td>
</tr>
</tbody>
</table>

- RES generators’ revenue depends on electricity market prices under RPS and MP
- RES generators are perfectly isolated from electricity prices under FIT

1 Renewable energy certificates
The three support schemes analyzed exhibit different degrees of market-integration.

- **RPS**: RECs are priced as follows: \( P_{REC} = \max(\text{LC} - P + \text{MC}; 0) \) and thus fully compensate for price decreases.
- **Market premium**: Market premium guarantees a fixed premium over \( P \).
- **FIT**: FITs are constant and fully independent of \( P \).

\[ \begin{align*}
\text{Revenues at market prices} & \quad P = \text{electricity price} & P_{REC} = \text{REC price} & \quad \text{FIT} = \text{feed-in-tariff} \\
\text{Revenues under support scheme} & \quad \pi = \text{total revenue per unit of electricity} & \quad \text{MP} = \text{market premium} & \quad E = \text{electricity}
\end{align*} \]

1 Which is identical as we still abstract from the effects of different risk profiles under the three schemes.
In a stylized RPS market model we endogenously derive electricity/REC\(^1\) prices and capacity investments.

**Example of RPS scheme**

1. **Conventional generators** (annual invest & hourly dispatch per standard plant & technology)
2. **Electricity market** (hourly dispatch)
3. **Retailers / obliged entities**\(^2\) (hourly aggregate demand curve)
4. **Electricity consumers**\(^3\) (not simulated explicitly)
5. **Renewable generators** (annual invest & hourly dispatch per standard plant & technology)
6. **REC\(^1\) market** (annual clearance)
7. **Regulator** (ex ante announcement of all annual quotas)

**Key Features**
- Investor behavior
- Market reactions
- Strategic bidding
- (Long-term focus)
- High granularity

---

1. Renewable energy certificates; 2 Utilities, transmission and distribution operators or others depending on local regulation; 3 Households, industry, and others; sometimes these are also the obliged entities depending on regulation.
(2) We first compute an initial forecast and then iterate actual updates

**Initial forecast**
- Cost-optimal conventional generation portfolio

**Actual iterations**
- Electricity market
- Electricity prices
- REC market
- REC prices

**Repeat**
- Repeat $T$ times for $i$ iterations

**Updated generation portfolio**

**Investor decisions on capacity**

**Investors decisions include**
- Plant retirements at end of useful life
- Divestitures given lacking profitability based on initial forecast/prior iteration
- New investments given positive expected NPV based on initial forecast/prior iteration

**Stopping after convergence**

- Investor behavior
- Market reactions
- Strategic bidding
- Long-term focus
- High granularity
- Tractability

---

1 given a specific RES quota
We derive price-quantity equilibria on an hourly basis for the electricity and annually for the REC market.

- Prices are determined through equilibrium models both for the electricity and REC markets.
- Demand curves and quotas are exogenously given and deterministic according to energy agency forecasts / regulatory announcements.
- Supply curves account for ramping constraints and renewable intermittency.
In a stylized MP model we endogenously derive electricity prices and capacity investment.

Example of market premium

- Conventional generators
- Renewable generators
- Retailers / obliged entities

- Electricity market
- Regulator

- Market premium (payment for non-energy part of renewable electricity production)

- Investor behavior
- Market reactions
- Strategic bidding
- (Long-term focus)
- High granularity

1 Renewable energy certificates; 2 Utilities, transmission and distribution operators or others depending on local regulation
In a stylized FIT market model we endogenously derive electricity prices and capacity investment.

Example of FIT scheme:

- **Conventional generators**
  - $E$
  - Priority dispatch
  - $E$

- **Electricity market**
  - $E$
  - $E_{\text{priority\ dispatch}}$
  - $E$

- **Retailers / obliged entities**
  - $E$
  - $E$

- **Renewable generators**
  - $E$
  - Feed-in-tariff
    - (payment for renewable electricity production)
  - $E$

- **Regulator**
  - $E$
  - Info
  - $E$

- **Market**
- **Endogenous player**
- **Exogenous player**

- Investor behavior
- Market reactions
- Strategic bidding
- (Long-term focus)
- High granularity

1 Renewable energy certificates; 2 Utilities, transmission and distribution operators or others depending on local regulation
The load duration curve provides first insights on the technology mix needed to meet demand.
We model investment and divestiture decisions on a technology level.

<table>
<thead>
<tr>
<th>Level of decision making</th>
<th>Description</th>
<th>Investor 1</th>
<th>Investor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undifferentiated</td>
<td>Entire generation park</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>By technology cluster</td>
<td>Renewables</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>By technology</td>
<td>Conventionals</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>By plant</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

On average and in the long run, non-profitable technologies will be divested and investment in profitable technologies takes place despite different investor portfolios.
The installed capacity is updated in three steps through age retirement, divestitures and new investments.

<table>
<thead>
<tr>
<th>Step</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Age retirement</strong> of all plants reaching their end of life</td>
<td>( LF_{i,j,t}^{act} \geq LF_i )</td>
</tr>
<tr>
<td>2. <strong>Divestiture</strong> of all plants with negative profitability below certain threshold</td>
<td>( \Pi_{i,j,t} = -FC_{i,t} + (\alpha \times P_{i,t}^{avg} + (1 - \alpha) \times P_{i,t-1}^{avg} - MC_{i,t}) \times Q_{i,j,t} \leq \Theta_i )</td>
</tr>
<tr>
<td>3. <strong>Investment</strong> in new plants with NPV exceeding specific thresholds</td>
<td>( NPV_{inv,i,t} = -IC_{i,t} + \sum_{t_{LF}=1}^{LF_i} \Pi_{i,t} / (1 + d_{inv})^{t_{LF}} \geq \Theta_i ) ( K_{i,t}^{new} = \sum_{inv=1}^{n_{inv}} \phi_{inv} \times K_{i}^{new,\max} \forall inv \text{ with } NPV_{inv,i,t}(d_{inv}) \geq \Theta_i )</td>
</tr>
</tbody>
</table>
Supply: The merit order shows available electricity generation capacity in order of increasing marginal costs

- Nuclear and lignite as “classic” base load suppliers run all the time
- OCGT and Oil as “classic” peak load suppliers only run a fraction of the year

Sources: Forschungsstelle für Energiewirtschaft e. V. (FfE)
Market prices are derived based on the supply curve from the merit order and the inelastic demand curve.

- Through marginal costs pricing efficient short-term dispatching of available electricity supply and demand is achieved with profits for all plants dispatched before the marginal supplier.

**Sources:** Forschungsstelle für Energiewirtschaft e. V. (FfE)
Renewables are dispatched first given their (near) zero-costs, shifting the supply curve right. By pushing the prior marginal supplier out-of-the-money, wholesale prices are reduced.

SOURCES: Forschungsstelle für Energiewirtschaft e. V. (FfE)
Content

(1) Motivation for research project

(2) Modeling approach

(3) Discussion of results

(4) Conclusion
The California electricity market is dominated by gas-fired and hydro generation as well as broad regulation.

**Californian electricity market**

**Key facts**
Ranking compared to other U.S. States

- #1 in terms of population with 38.3 million people in 2013
- #1 in terms of GDP with 1.96 trillion USD in 2011
- #5 in terms of net electricity generation with 201 TWh in 2011
- #2 in terms of non-hydro RES generation with 27 TWh in 2011

**Installed capacity**

<table>
<thead>
<tr>
<th>Source</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>2.3</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>6.5</td>
</tr>
<tr>
<td>Geothermal</td>
<td>2.6</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.6</td>
</tr>
<tr>
<td>OCGT</td>
<td>38.4</td>
</tr>
<tr>
<td>CCGT</td>
<td>8.1</td>
</tr>
<tr>
<td>Nuclear</td>
<td>2.2</td>
</tr>
<tr>
<td>Hydro</td>
<td>13.5</td>
</tr>
</tbody>
</table>

**Relevant key regulation**

- Resource adequacy provisions: Long-Term Procurement Plans, Resource Adequacy Requirements, and the Capacity Procurement Mechanism
- CO₂ cap-and-trade scheme
- Renewable portfolio standards (RPS)
- Production tax credits
- Investment tax credits

## (3) Model assumptions – technology factors

<table>
<thead>
<tr>
<th>Technology type</th>
<th>Size GW</th>
<th>Life years</th>
<th>Invest Mio. USD</th>
<th>Fixed cost Th. USD</th>
<th>Mrg. cost USD/MWh</th>
<th>Heat rate GJ/MWh</th>
<th>Learning %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>1.0</td>
<td>25</td>
<td>2.2</td>
<td>39.6</td>
<td>-2.3</td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>0.2</td>
<td>25</td>
<td>2.7</td>
<td>24.7</td>
<td>0</td>
<td></td>
<td>2.1</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.1</td>
<td>25</td>
<td>5.6</td>
<td>132.0</td>
<td>-1.6</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Biomass</td>
<td>0</td>
<td>25</td>
<td>4.1</td>
<td>105.6</td>
<td>56.9</td>
<td>14.2</td>
<td>0.8</td>
</tr>
<tr>
<td>OCGT</td>
<td>0.5</td>
<td>100</td>
<td>2.9</td>
<td>14.1</td>
<td>9.0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>CCGT</td>
<td>2.2</td>
<td>40</td>
<td>5.5</td>
<td>93.3</td>
<td>2.1</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.6</td>
<td>35</td>
<td>0.9</td>
<td>13.2</td>
<td>42.9</td>
<td>7.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.2</td>
<td>35</td>
<td>0.7</td>
<td>7.0</td>
<td></td>
<td>53.7</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**SOURCE:** EIA (2013), NREL (2010)
### (3) Model assumptions – generation park

<table>
<thead>
<tr>
<th>Technology type</th>
<th>Init. Capa. GW</th>
<th>Age 1-10</th>
<th>Age 11-20</th>
<th>Age 21-30</th>
<th>Age 31-40</th>
<th>Age 41-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>6.5</td>
<td>41</td>
<td>12</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wind onshore</td>
<td>2.3</td>
<td>11</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Geothermal</td>
<td>2.6</td>
<td>1</td>
<td>26</td>
<td>25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biomass</td>
<td>1.6</td>
<td>12</td>
<td>36</td>
<td>34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>OCGT</td>
<td>8.1</td>
<td>9</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>CCGT</td>
<td>2.2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nuclear</td>
<td>13.5</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Hydro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(3) Model assumptions – sample year used

(3) Model assumptions – time-series data used

RES quota

CO₂ price

Natural gas price

Biomass price

Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results.

Key assumptions:
- Homogeneous investors
- Identical risk profiles and discount rates for all schemes
- Identical support rates for all technologies under MP and FIT

Key results:
- (Nearly) identical results across most dimensions
- Much higher electricity price volatility under FIT scheme
Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results.
(3) Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results

Key assumptions
- Homogeneous investors
- Identical risk profiles and discount rates for all schemes
- Identical support rates for all technologies under MP and FIT

Key results
- (Nearly) identical results across most dimensions
- Much higher electricity price volatility under FIT scheme
- Results converge after 3-6 iterations
Depending on the regulator's assessment of market dynamics and investors, support scheme results differ depending on whether regulatory risk is abstracted from.

### Key assumptions / assumptions differing from base case
- Homogeneous investors
- Identical risk profiles
- No support differentiation

- Heterogeneous investors
- Different risk profiles
- Differentiated support rates under MP and FIT – highest for geothermal
- Increased support rates under MP and FIT by 2%
- 1 percentage point decrease in annual learning rate for solar

### Key results / differences in results compared to base case
- Similar results across dimensions
- Higher electricity price volatility for FIT scheme

- More diverse RES investment across support schemes
- Lower electricity price volatilities
- Lower total cost (in particular support scheme cost) under MP and FIT schemes
- Lower volatility but higher electricity prices under MP and FIT
- Steep RES investment increase under FIT rendering electricity market dysfunctional
- Drop in solar investment
- Less RES investment and lower volatility under MP and FIT

---

1 Abstracting from regulatory risk
This assessment crucially impacts which support scheme is most advantageous.

<table>
<thead>
<tr>
<th>Key findings</th>
<th>RPS</th>
<th>MP</th>
<th>FIT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base case</strong></td>
<td><img src="%E2%9C%93" alt="Low volatility" /></td>
<td><img src="%E2%9C%93" alt="Low volatility" /></td>
<td><img src="%E2%9C%97" alt="High volatility" /></td>
</tr>
<tr>
<td><strong>Heterogeneous investors</strong></td>
<td><img src="%E2%9C%93" alt="Reduced volatility" /></td>
<td><img src="%E2%9C%93" alt="Reduced volatility" /></td>
<td><img src="%E2%9C%93" alt="Reduced volatility" /></td>
</tr>
<tr>
<td><strong>Different risk profiles(^1)</strong></td>
<td><img src="%E2%9C%97" alt="Identical cost" /></td>
<td><img src="%E2%9C%93" alt="Reduced cost" /></td>
<td><img src="%E2%9C%93" alt="Greatly reduced cost" /></td>
</tr>
<tr>
<td><strong>Differentiated support</strong></td>
<td><img src="%E2%9C%97" alt="Not easily possible(^2)" /></td>
<td><img src="%E2%9C%93" alt="Reduced volatility" /></td>
<td><img src="%E2%9C%93" alt="Reduced volatility" /></td>
</tr>
<tr>
<td><strong>Increased support by 2%</strong></td>
<td><img src="%E2%9C%93" alt="High robustness" /></td>
<td><img src="%E2%9C%97" alt="Low robustness" /></td>
<td><img src="%E2%9C%97" alt="No robustness" /></td>
</tr>
<tr>
<td><strong>Lower solar learning rate by -1pp</strong></td>
<td><img src="%E2%9C%93" alt="High robustness" /></td>
<td><img src="%E2%9C%97" alt="Low robustness" /></td>
<td><img src="%E2%9C%97" alt="No robustness" /></td>
</tr>
</tbody>
</table>

1 Abstracting from regulatory risk; 2 only possible through separate market or different numbers of RECs allocated per RES electricity generated contingent on technology used.
Content

(1) Motivation for research project
(2) Modeling approach
(3) Discussion of results

(4) Conclusion
While our results provide first insights, further research is needed to understand impact of RES support schemes.

Key findings

- RPS, MP, and FIT lead to increasing RES generation and decreasing conventional generation as well as CO₂ emissions.
- MP and in particular FIT can achieve these results at lower total cost when accounting for different risk profiles but lead to higher electricity price volatility.
- MP and FIT can be more easily adjusted to support specific technologies with potentially beneficial impacts on the overall market.
- RPS deliver more robust results in terms of RES buildup and distort markets less in case of inaccurate parameter estimations.

Future research

- Account for uncertainty and ambiguity factors such as RES generation.
- Analyze and compare support scheme robustness in more depth.
- Investigate the impact of less static / more flexible MP and FIT designs.

Key challenges

- At least two stochastic variables representing uncertain annual output from wind and solar.
- Multiple scenarios to represent all possible states contingent on wind and solar power generation as well as installed capacity.
Working paper and contact details

---

**Working paper**

The Structural Impact of Renewable Portfolio Standards and Feed-in-Tariffs on Electricity Markets;


---
Backup
Facts
Model approach
We derive the forecasted installed capacity in five steps:

<table>
<thead>
<tr>
<th>Step</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Establish <strong>load duration curve</strong> by putting hourly load in descending order</td>
<td>[ LDC_t = L_t^{total}(Q_t) \forall L_t^{total}(Q_t) \leq L_t^{total}(Q_{t+1}) ]</td>
</tr>
<tr>
<td>2. Develop <strong>residual load duration curve</strong> by deducting RES feed-in from LDC</td>
<td>[ RLDC_t = L_t^{residual}(Q_t) \forall L_t^{residual}(Q_t) \leq L_t^{residual}(Q_{t+1}) ]</td>
</tr>
<tr>
<td>3. Compute <strong>total cost per unit of capacity</strong> dependent on run-time</td>
<td>[ TC_{i,t}(Q_t) = CC_{i,t} + FC_{i,t} + MC_{i,t} * Q_t ]</td>
</tr>
<tr>
<td>4. Define <strong>screening curve</strong> representing the least cost technology per run-time</td>
<td>[ SC(Q_t) = \min[TC_{i,t}(Q_t)] = \begin{cases} TC_{1,t}(Q_t) &amp; \forall 0 \leq Q_t \leq Q_{1,t} \ TC_{2,t}(Q_t) &amp; \forall Q_{1,t} \leq Q_t \leq Q_{2,t} \ \vdots \ TC_{n,t}(Q_t) &amp; \forall Q_{n-1,t} \leq Q_t \leq Q_{n,t} \end{cases} ]</td>
</tr>
<tr>
<td>5. Map RLDC on SC to derive cost-optimal <strong>installed capacity</strong> per technology and year</td>
<td>[ K_{i,t} \forall i = 1, 2, \ldots, n ]</td>
</tr>
</tbody>
</table>
We compute hourly electricity prices in five steps

<table>
<thead>
<tr>
<th>Step</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. <strong>Compute available capacity</strong></td>
<td>( K_{i,t,y}^{av} = K_{i,t} \cdot \vartheta_{i,t,y} )</td>
</tr>
<tr>
<td>2. <strong>Compute marginal cost</strong></td>
<td>( MC_{i,t} = \eta_{i,t} \cdot P_t^{fuel} + \iota_t \cdot P_t^{CO2} + MC_{i,t}^{other} )</td>
</tr>
<tr>
<td>3. <strong>Establish supply curve as step function</strong></td>
<td>( MC_{market}^{t,y}(L_{t,y}) = \begin{cases} MC_{1,t,y}(L_{t,y}) &amp; \forall \ 0 \leq L_{t,y} \leq K_{1,t,y}^{av} \ MC_{2,t,y}(L_{t,y}) &amp; \forall \ K_{1,t,y}^{av} \leq L_{t,y} \leq \sum_{i=1}^{2} K_{i,t,y}^{av} \ \vdots \ MC_{n,t,y}(L_{t,y}) &amp; \forall \ \sum_{i=1}^{n-1} K_{i,t,y}^{av} \leq L_{t,y} \leq \sum_{i=1}^{n} K_{i,t,y}^{av} \end{cases} )</td>
</tr>
<tr>
<td>4. <strong>Define hourly demand curve</strong></td>
<td>( P_{t,y}(L_{t,y}) = D_{t,y}^{0} - \beta_{t} \cdot L_{t,y} )</td>
</tr>
<tr>
<td>5. <strong>Intersect supply and demand functions to establish hourly electricity price</strong></td>
<td>( P_{t,y}(L_{t,y}) = MC_{market}^{t,y}(L_{t,y}) = D_{t,y}^{0} - \beta_{t} \cdot L_{t,y} )</td>
</tr>
</tbody>
</table>
When accounting for ramping constraints we need to adjust available capacity and marginal cost.

<table>
<thead>
<tr>
<th>Step</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Adjust maximum available capacity</td>
<td>( K_{i,t,y}^{av}(K_{i,t,y-1}^{ut}) = K_{i,t,y-1}^{ut} + \gamma_i^{up} \cdot K_i^{plant} \cdot m_{i,t} )</td>
</tr>
<tr>
<td>2. Compute minimum utilized capacity</td>
<td>( K_{i,t,y}^{min}(K_{i,t,y-1}^{ut}) = K_{i,t,y-1}^{ut} - \gamma_i^{down} \cdot K_i^{plant} \cdot m_{i,t} )</td>
</tr>
<tr>
<td>3. Adjust marginal cost if utilized capacity for a specific technology falls below its minimum utilized level</td>
<td>( MC_{i,t,y}(K_{i,t,y}^{ut}, K_{i,t,y-1}^{ut}) = \eta_{i,t} \cdot P_t^{fuel} + \nu_i \cdot P_t^{CO2} + MC_{i,t}^{other} - RC_{i,t} )</td>
</tr>
</tbody>
</table>
When accounting for strategic bidding, we compute an electricity price mark-up depending on capacity scarcity.

<table>
<thead>
<tr>
<th>Step</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compute <strong>capacity margin</strong></td>
<td>[ K_{t,y}^{\text{margin}}(K_{i,t,y}^{av}, L_{t,y}) = \frac{\sum_{i=1}^{n} K_{i,t,y}^{av} - L_{t,y}}{\sum_{i=1}^{n} K_{i,t,y}^{av}} ]</td>
</tr>
</tbody>
</table>
| 2. Compute **adjusted electricity** price after strategic bidding | \[ P_{t,y}^\varepsilon(K_{i,t,y}^{av}, L_{t,y}) = P_{t,y} \times (1 + \varepsilon(K_{t,y}^{\text{margin}})) \]  
with \[ \frac{\partial \varepsilon}{\partial K_{i,t,y}^{av}} < 0 \] and \[ \frac{\partial \varepsilon}{\partial L_{t,y}} > 0 \] |
We compute annual REC prices in four steps

1. **Compute RES cost gap**

   \[ \omega_{\text{inv},i,t} = \frac{(\Theta_i - NPV_{\text{inv},i,t}) \ast \frac{(1+d_{\text{inv}})^{L_{F_i}} \ast d_{\text{inv}}}{(1+d_{\text{inv}})^{L_{F_i}}-1}}{\vartheta_{i,t} \ast 8760 \ast K_i^{\text{plant}}} \]

2. **Establish REC supply curve as step function**

   \[ MC_t^{\text{REC}} = \begin{cases} (MC_{1,t} - P_{1,t}^{\text{avg}})^+ & 0 \leq \lambda_t \sum_{y=1}^{8760} L_{t,y} \leq \sum_{y=1}^{8760} K_{1,t,y}^{\text{av}} \\ \vdots & \vdots \\ (MC_{r,t} - P_{r,t}^{\text{avg}})^+ & \sum_{y=1}^{8760} \sum_{i=1}^{r-1} K_{i,t,y}^{\text{av}} \leq \lambda_t \sum_{y=1}^{8760} L_{t,y} \leq \sum_{y=1}^{8760} \sum_{i=1}^{r} K_{i,t,y}^{\text{av}} + K_{1,t,y}^{\text{new,av}} \phi_1 \\ \omega_{1,1,t} & \sum_{i=1}^{8760} \sum_{y=1}^{r} K_{i,t,y}^{\text{av}} + K_{1,t,y}^{\text{new,av}} \phi_1 \leq \lambda_t \sum_{y=1}^{8760} L_{t,y} \leq \sum_{y=1}^{8760} \left( \sum_{i=1}^{r} K_{i,t,y}^{\text{av}} + \sum_{i=1}^{r} K_{i,t,y}^{\text{new,av}} \phi_1 \right) \\ \vdots & \vdots \\ \omega_{\text{inv},r,t} & \sum_{y=1}^{8760} \sum_{i=1}^{r} K_{i,t,y}^{\text{av}} + \sum_{i=1}^{n_{\text{inv}}} \sum_{i=1}^{r-1} K_{i,t,y}^{\text{new,av}} \phi_{\text{inv}} \leq \lambda_t \sum_{y=1}^{8760} L_{t,y} \leq \sum_{y=1}^{8760} \left( \sum_{i=1}^{r} K_{i,t,y}^{\text{av}} + \sum_{i=1}^{n_{\text{inv}}} \sum_{i=1}^{r} K_{i,t,y}^{\text{new,av}} \phi_{\text{inv}} \right) \end{cases} \]

3. **Define annual REC demand curve**

   \[ P_t^{\text{REC}} = \begin{cases} (-\infty, \kappa] & \sum_{y=1}^{8760} L_{t,y}^{\text{RES}} \geq \lambda_t \sum_{y=1}^{8760} L_{t,y} \\ \kappa & \lambda_t \sum_{y=1}^{8760} L_{t,y} \geq \sum_{y=1}^{8760} L_{t,y}^{\text{RES}} \end{cases} \]

4. **Intersect supply and demand functions to establish annual REC price**

   \[ P_t^{\text{REC}} = MC_t^{\text{REC}} \]
The six key metrics are computed by summation and averaging over the entire time horizon.

<table>
<thead>
<tr>
<th>Policy goal</th>
<th>Metric</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affordability</td>
<td>Total cost</td>
<td>[ \sum_{t=1}^{T} \sum_{y=1}^{8760} \left( P_{t,y} + \lambda_t \times P_{t,REC} \right) \times L_{t,y} ] for RPS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \sum_{t=1}^{T} \sum_{y=1}^{8760} \sum_{i=1}^{n} \left( P_{t,y} + MP_{t,i} \right) \times L_{t,y,i} ] for MP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[ \sum_{t=1}^{T} \sum_{y=1}^{8760} \left[ P_{t,y} \times L_{t,y} + \sum_{i=1}^{n} \left( FIT_{t,i} - P_{t,y} \right) \times L_{t,y,i} \right] ] for FIT</td>
</tr>
<tr>
<td></td>
<td>Average electricity price</td>
<td>[ \mathbb{E}(P_{t,y}) ]</td>
</tr>
<tr>
<td>Security of supply</td>
<td>Conventional capacity</td>
<td>[ \sum_{i=r+1}^{i} K_{T,i} ]</td>
</tr>
<tr>
<td></td>
<td>Volatility of electricity prices</td>
<td>[ \sqrt{\mathbb{E}[P_{t,y} - \mathbb{E}(P_{t,y})]^2} ]</td>
</tr>
<tr>
<td></td>
<td>Security of supply</td>
<td>[ \sum_{t=1}^{T} \sum_{y=1}^{8760} VOLL ]</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Emissions</td>
<td>[ \sum_{t=1}^{T} \sum_{y=1}^{8760} \sum_{i=1}^{n} \lambda_i \times L_{t,y,i} ]</td>
</tr>
</tbody>
</table>

We compare support schemes along these dimensions and ensure comparability by calibrating schemes to the same level of RES generation.
While uncertainty does not increase at its source, its realizations change the state of the electricity market.

**Uncertainty** does not increase in terms of **wind and solar** power generation.

However, **uncertainty increases** in terms of **installed generation** portfolio contingent on all prior states of wind and solar power generation.
Concepts
The power sector has 3 optimization targets: security of supply, sustainability and efficiency.

- **Security of supply** is especially important in countries like Germany where industries rely on very high reliability of supply.
- **Historically less** important e.g. in the U.S. where (industrial) customers often have their own backup supply due to more frequent outages.
- Efficiency is **most important** in developing countries like China, India or Brazil.
- However, growing subsidies in renewables foster the discussion around affordability and social fairness in Germany as well.
- Compared to transportation and heating, the power sector can be switched to **renewables relatively easily**.
- Therefore, the power sector has to **overcompensate** for slow advancements in other sectors.

![Diagram](diagram.png)
Assumptions and inputs
Homogeneous investors & no differences in risk profiles
(3) Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results

**Key assumptions**

- Homogeneous investors
- Identical risk profiles and discount rates for all schemes
- Identical support rates for all technologies under MP and FIT

**Key results**

- (Nearly) identical results across most dimensions
- Much higher electricity price volatility under FIT scheme
(3) Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results.

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Biomass CO2 emissions accounting to be verified both in terms of financials and environmental impact.
Assuming homogeneous investors and no differences in risk profiles, schemes deliver mostly similar results.
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Heterogeneous investors & no differences in risk profiles
(3) Assuming heterogeneous investors and no differences in risk profiles, electricity price volatility decreases

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- (Nearly) identical results across most dimensions
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- Lower volatility across schemes
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Homogeneous investors & differences in risk profiles
Assuming homogeneous investors and differences in risk profiles, costs of FIT and MP decrease

**Key assumptions**
- Homogeneous investors
- Different risk profiles and discount rates for schemes
- Identical support rates for all technologies under MP and FIT

**Key results**
- Decrease in total cost of MP and FIT scheme being driven by a decrease in support scheme cost
(3) Assuming homogeneous investors and differences in risk profiles, costs of FIT and MP decrease

Key assumptions
- Homogeneous investors
- Different risk profiles and discount rates for schemes
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Key results
- Decrease in total cost of MP and FIT scheme being driven by a decrease in support scheme cost
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(3) Assuming homogeneous investors and differences in risk profiles, costs of FIT and MP decrease.
Homogeneous investors & no differences in risk profiles & differentiated support rates
(3) Assuming differentiated support rates, electricity price volatility can be reduced greatly under MP and FIT

**Key assumptions**
- Homogeneous investors
- Identical risk profiles and discount rates for all schemes
- Differentiated support rates under MP and FIT

**Key results**
- (Nearly) identical results across most dimensions
- Greatly reduced electricity price volatility under MP and FIT given shift to non-intermittent RES
(3) Assuming differentiated support rates, electricity price volatility can be reduced greatly under MP and FIT

Key assumptions
- Homogeneous investors
- Identical risk profiles and discount rates for all schemes
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Assuming differentiated support rates, electricity price volatility can be reduced greatly under MP and FIT.
Homogeneous investors & no differences in risk profiles & increased support rates by 2%
Assuming increased support rates by 2%, the electricity market becomes dysfunctional under the FIT scheme.

Key assumptions:
- Homogeneous investors
- Identical risk profiles and discount rates for schemes
- Identical support rates for all technologies increased by 2%

Key results:
- Steep decrease of electricity prices and conventional generation under FIT
- Jump in RES installations and electricity price volatility under FIT
Assuming increased support rates by 2%, the electricity market becomes dysfunctional under the FIT scheme.

Key assumptions:
- Homogeneous investors
- Identical risk profiles and discount rates for schemes
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- Steep decrease of electricity prices and conventional generation under FIT
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TO BE DONE
(3) Assuming increased support rates by 2%, the electricity market becomes dysfunctional under the FIT scheme.
Homogeneous investors & no differences in risk profiles & solar learning -1 percentage point
(3) Assuming decreased learning rates for solar by -1 percentage point, reduce solar investment

**Key assumptions**
- Homogeneous investors
- Identical risk profiles and discount rates for schemes
- Identical support
- Decreased solar learning by 1 pp

**Key results**
- Total costs increase across schemes
- RES installations drop under FIT and MP schemes
- More conventional capacity needed under MP and FIT
Assuming decreased learning rates for solar by -1 percentage point, reduce solar investment

Key assumptions
- Homogeneous investors
- Identical risk profiles and discount rates for schemes
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Assuming decreased learning rates for solar by -1 percentage point, reduce solar investment.
Homogeneous investors & no differences in risk profiles & no adjustment to support rates coming from heterogeneous case
(3) Assuming homogenous support investors, but no support rates adjustment, RES installations drop for FIT

Key assumptions
- Homogeneous investors
- Identical risk profiles and discount rates for schemes
- Identical support rates, not adjusted coming from heterogeneous case

Key results
- Lower RES investment under MP and FIT leading to lower electricity price volatility and more conventional generation needs
Assuming homogenous support investors, but no support rates adjustment, RES installations drop for FIT

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We assume that investors use a symmetrically distributed discount rate.
### Greek Letters

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