Curtailment-storage-penetration nexus in the energy transition

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Agenda

- Motivation
- Methodology and data
- Transition Results
- Curtailment-storage-penetration nexus and its role
- Summary and Conclusions
Motivation

- Several studies show that energy system transitions require a continued increase in the use of Variable Renewables Energy (VRE)
- With an increased use of VRE resources, such as Wind and Solar, follows an increased use of energy storage technologies.
- The required storage size was found to depend on various factors, such as level of energy penetration, curtailment, resource complementarity, etcetera.
- Thus, understanding the role of various factors in energy transition is important to set proper target and provide good scientific ground to guide transition policy and system design.
- Some of the key questions of this study include:
  - How does the storage technology mix and capacity requirement relate to VRE penetration?
  - What is the economic opportunity/penalty of curtailment?
  - What are the factors that will define storage dispatch merit order?
- In summary, how does various factors interact and how they affect transition?
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Methodology and data:
LUT Energy System Transition Model

LUT Energy model, key features
- linear optimization model
- hourly temporal resolution
- 0.45° x 0.45° spatial resolution
- multi-node approach
- flexibility and expandability

For simplicity and the opportunity to model the system with better certainty because of the absence of existing or planned electricity trade with neighbouring countries as well as the possibility to perform high spatial and temporal resolution modelling of the power grid, Israel was chosen for this study.
Methodology and data:
An overview of Israel’s electricity system

- The present Israeli energy system depends on hydrocarbon fuel. In 2015, crude oil, coal and natural gas supplied 43%, 26% and 30% of Israel’s energy need, respectively. The remaining 1% is obtained from RE.
- Specifically, the Israel Electric Corporation (IEC) had a total generating capacity of 13.6 GW (4.8 GW coal and the remaining being gas) with annual electricity sales of 50.6 TWh.
- Electricity supply in Israel is very reliable with an average consumption per capita of approximately 6600 kWh in 2015, higher than Italy but lower than Germany.
## Methodology and data:

### Transition Scenarios

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Base Case (BC)</strong></td>
<td>➢ Assumes that cost of carbon per ton of CO$_{2eq}$ is 9 € in 2015, which progressively increases to 28, 52, 61, 68, 75, 100 and 150 € at every 5-year time step following the base case values in the LUT model.</td>
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<td></td>
<td>➢ Except specific data related to Israel, all other inputs remain typical of the LUT Energy System Transition model.</td>
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<td>➢ This scenario represents the fastest transition. The curtailment level in this scenario is set by the model itself.</td>
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<td><strong>Current Policy (CP)</strong></td>
<td>➢ set a target of a 10% RE (mainly obtained from wind and solar) share of its 2020 electricity demand, which will increase to 17% of the national demand as per the nationally determined emission reduction plan.</td>
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<td>➢ The post-2030 share of RE is not clear but in the present study, a generous increase in RE penetration of 1%/year was assumed. Due to this limit, the maximum PV prosumer market potential was reduced from 20% to 7% for this particular case.</td>
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<td>➢ The use of natural gas is expected to increase and coal will fully phased out by 2050.</td>
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<td>➢ The first nuclear power plant of 500 MW will be built by 2030, with another 1 GW and 1.4 GW being built in 2035 and 2050, respectively.</td>
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<td>➢ The Current Policy was taken while also applying the carbon cost as in the BC. The curtailment level is set by the model itself.</td>
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<td><strong>No Carbon Cost (NCC)</strong></td>
<td>➢ Assumed that the carbon cost for emissions in the electricity sector remains zero throughout the transition period. This scenario does not ban fossil fuel by 2050 contrary to the BC. All other assumptions are similar to the BC scenario.</td>
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<tr>
<td><strong>Base Case without Curtailment (BCWC)</strong></td>
<td>➢ similar to the BC scenario. But curtailment is limited to approximately 0.1% throughout most of the transition. But, all post 2040 runs were performed at a relaxed curtailment limit of 0.2%.</td>
</tr>
<tr>
<td><strong>No Carbon Cost without Curtailment (NCCWC)</strong></td>
<td>➢ similar to NCC scenario. But curtailment is limited to approximately 0.1% throughout most of the transition. Thus, all post 2040 runs were performed at a relaxed curtailment limit of 0.2%.</td>
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Transition Results: Levelized cost of Electricity for various Scenarios

Key insights:

- Projected RE technology cost could lead to fast transition without carbon cost
- Present policies may lead to multiple risks including increased cost of electricity

For more details on policy lessons see:
Solomon A. A., D. Bogdanov, C. Breyer, Solar driven net-zero emission electricity supply with negligible carbon cost, Israel as a case study. Energy - International Journal, under review (final stage)

- Contrary to intuition, LCOE for scenarios without Curtailment was higher than the corresponding years scenario with curtailment. E.g. LCOE for the BCWC scenarios in 2045 and 2050 were 10.3% and 8.6% higher than the BC. Similarly, NCCWC is 8.5% and 8.4% higher than the NCC scenario, respectively.

A change in LCOE for (a) BC; (b) NCC; (c) CP; (d) BCWC; (e) NCCWC scenarios of the electric power system transition from 2015 to 2050.
Transition Results:
VRE penetration and total loss trend

Trends of (a) VRE energy system penetration and (b) energy loss (both total and curtailment). Due to the existing inflexibility, the loss as a % of total VRE was much higher for all scenarios in 2015. For that particular case, loss is given as percentage of total generation.

Key insights:
➢ Both RE penetration and total loss increases throughout the transition regardless of curtailment policy. The increase for scenarios without curtailment is mainly driven by the increased use of storage.
Transition Results:

Energy storage capacity

Key insights:

- Storage technology mix and its capacity requirement increases with time but scenarios without curtailment needs significantly larger storage. Specifically, the total energy storage capacity by 2050 increased from approximately 11 TWh to about 15 TWh in the BC and from 6 TWh to 11 TWh in the NCC scenarios.

- The battery capacity increased by 9.8% from approximately 255 GWh to about 278 GWh in the BC and by 14.5% from 242 GWh to 277 GWh in the NCC scenarios in the year 2050.

- Massive gas storage is built when VRE penetration approaches or exceeds 90% of the annual demand for scenarios with curtailment and at approximately 70% of the annual demand for scenarios without curtailment (earlier in terms of time).

Energy storage requirement by technology for (a) BC; (b) NCC; (c) CP; (d) BCWC and (e) NCCWC scenarios of the electric power system transition from 2015 to 2050.
Transition Results:
Energy storage capacity

Key insights:
- Despite its large capacity, gas storage is not economically suitable for frequent use due to its low round-trip efficiency, as can be seen from its low energy contribution.
- It can be seen that gas storage started early energy transferring services for no curtailment scenarios.
- Note that the energy contribution of gas storage significantly increases when the no-curtailment policy is enforced.

Fraction of demand supplied by energy coming from various storage technology options for both scenarios without curtailment, namely (a) BC; (b) NCC; (c) CP; (d) BCWC and (e) NCCWC scenarios of the electric power system transition from 2015 to 2050.
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Curtailment-penetration-storage nexus and its role

Key insights:

- Two curves that level off at a VRE penetration of approximately 90% and 70% of the annual demand were obtained for combined curve fits to scenarios with and without curtailment, respectively. These inflection points are not random points.

VRE penetration versus bulk energy storage capacity when storage capacity on x-axis is given (a) in units of GWh and (b) daily average demand. Note that daily average demand value of Israel varies from year-to-year (example 168 GWh by 2015 and 410 GWh by 2050).
Curtailment-penetration-storage nexus and its role:

Key insights:

- The curve for the Israeli system shows an inflection at a VRE penetration of about 70% and energy storage capacity lower than one daily average demand. The inflection for the Californian system is at much lower penetration.

- It was also reported that storage of the order of daily average demand was sufficient to reach to approximately 90% penetration for both power systems with curtailment.

We concluded that the change in trend shows the change in storage application and as a consequence also a change in suitable technology preference resulting due to seasonal and diurnal matching.

VRE penetration (left axis) and UI (right) versus the storage energy capacity

Data source:
Curtailment-penetration-storage nexus and its role

Key Insights:

- VRE penetration increases together with total energy loss even though the magnitude of their interdependence depends on the applied curtailment policy.
- The total energy loss also shows a sharp rise with energy storage capacity before levelling off depending on the applied curtailment policy.
- Note that c) and (d) shows that current policy also does not follow the nexus trend because of inflexibility.

The relationship between VRE penetration and total energy loss, total energy loss and energy storage for various scenarios.
Curtailment-penetration-storage nexus and its role

System dispatch for the first 10 days of various months of the year:
(a) January, (b) April and (c) July.
The positive region represents the output of various generation sources. Notice also the real demand curve. The negative region shows how the excess generation is treated in the model.

Key Insights:
- Batteries, which are classified as diurnal storage, are dispatched in charging mode during day time and discharging mode during night time.
- gas storage, termed as seasonal storage, will be in charging mode on most of spring, summer and autumn days to store SNG to be utilized during winter days and some other days of shortage in the other seasons.
The techno-economic feasibility of each technology depends on Curtailment-storage-penetration nexus versus VRE penetration.

Key Insights:
- The techno-economic feasibility of each technology depends on Curtailment-storage-penetration nexus...
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Summary and Conclusions

- The Curtailment-storage-penetration nexus requires that the three, namely total loss (curtailment plus storage efficiency), penetration and storage capacity, simultaneous increase of in the energy transition

- The nexus was also shown to strongly affect the techno-economic feasibility of a given storage technology, overall storage design and storage dispatch

- The study shows that curtailment is not a simple waste of energy but an important technical factor whose improper use or avoidance carries a penalty

- The observed nexus defines when to deploy and dispatch particular storage

- Thus, it is recommended that policy making is based on a detailed understanding of the requirements of their future energy system, which depend on the local resource and demand characteristics

For more detail please refer to:
A WORLD ELECTRIFIED BY SOLAR AND WIND

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