Assessment of hydrogen based long-term electrical energy storage in residential energy systems

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Context

Companies are proposing electrical energy storage systems based on hydrogen

• Small modular components
  – To exploit economies of scale

• For residential sector and small businesses

• A few examples:
  – Picea (Germany)
  – LAVO (Australia)
  – Enapter (Germany)
Aim of the study

• Evaluating the potential of residential hydrogen storage systems in the Italian context
  – Through the analysis of representative case studies
    • To account for the numerous different climatic zones
  – Work in progress!

Structure of the work, tools and work environments

Step 1
Energy demand modelling

Step 2
Dwelling energy system modelling

Step 3
Optimization

Step 4
Optimal configuration analysis and post process
Case study – System configuration

- Electricity produced by PV panels or imported from the grid
- Electrochemical battery
  - For hourly load variations
  - Capacity fixed: 10 kWh
- Hydrogen storage system
  - Electrolyzer
  - H$_2$ tank
  - Fuel cell
- Heat pump system
  - To cover demand of
    - Ambient heating
    - Ambient cooling
    - Domestic hot water

Powered by
Case study – Assumption and hypothesis

- Florence province
  - 43.7799368, 11.1709281
  - 1821 HDD
  - Ambient data have been obtained from Renewables.ninja

- Main hypothesis
  - Electricity price increase of 25%
  - Reference year 2030-2040
  - Interest rate 5%
  - Fully electrified dwelling
  - Rural context

- Optimization
  - Parameter to be optimized: Net Present Value after 20 years
  - Varying: electrolyser size, fuel cell size

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>1300 €/kWₚ</td>
<td>25 years</td>
</tr>
<tr>
<td>Electrolyser</td>
<td>250-2000 €/kW</td>
<td>20 years</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>250-2000 €/kW</td>
<td>20 years</td>
</tr>
</tbody>
</table>
Demand curves

- Demand curves have been obtained through RAMP
  - Open-source bottom-up stochastic model for generating multi-energy load profiles
  - Developed by University of Liege and Politecnico di Milano
    - [https://github.com/RAMP-project/RAMP](https://github.com/RAMP-project/RAMP)
  - Applied to the Italian context using data from ISTAT
    - Italian national institute for statistics
    - Database storing information on energy usage in the residential sector of real dwellings
      - [https://www.istat.it/it/archivio/142173](https://www.istat.it/it/archivio/142173)

5082 kWh/y  H: 15900 kWh/y  C: 5220 kWh/y  3750 kWh/y
Dwelling energy system model

- Energy system modelled through MESS – Multi-Energy System Model
  - Recently developed open-source simulation model by UNIFI, eurac and TU Wien
  - Bottom-up, modular model
  - Analytical programming approach
    - i.e., based on a series of endogenous priorities and pre-defined procedures for simulating the operation of units that are freely dispatchable as defined by Lund et al.
  - Model written in both Julia and Fortran
  - Thoroughly described in [https://www.mdpi.com/1996-1073/14/18/5724](https://www.mdpi.com/1996-1073/14/18/5724)

- Here MESS has been used in a black box optimization procedure
  - Letting the optimizer work only on input and output files
  - Analysing then the optimal solution
Results – Optimization

- FC size always < 1kW
- EL to FC sizes ratio increases with decreasing components cost
  - \( 3.5 < \frac{P_{EL}}{P_{FC}} < 7.7 \)

\[ \begin{align*}
\text{PV area} &= 50\,\text{m}^2 \\
\text{FC size: } 0\,\text{kW} < P_{FC} < 1\,\text{kW} \\
\text{EL size: } 0.5\,\text{kW} < P_{FC} < 4.5\,\text{kW} \\
\text{Tank volume: } 2\,\text{m}^3 < V < 13\,\text{m}^3
\end{align*} \]
Results - Optimization

- FC optimal sizes increase more than EC sizes
  - $2.5 < \frac{P_{EL}}{P_{FC}} < 3.0$
- Tank size reaches unfeasible volumes

PV area = 100m²
- FC size: $0.5 \text{ kW} < P_{FC} < 2 \text{ kW}$
- EL size: $1 \text{ kW} < P_{FC} < 5.5 \text{ kW}$
- Tank volume: $5 \text{ m}^3 < V < 25 \text{ m}^3$
Results – Optimal solutions analysis

• \( t_0 \) time when \( H_2 \) tank is emptied
  \( t_1 \) time when \( H_2 \) production starts
to increase steadily
• If PV area = 50 m\(^2\)
  – \( t_1 - t_0 \) decreases with decreasing
    components’ prices
• If PV area = 100 m\(^2\)
  – \( t_1 - t_0 \) approx. constant
• When PV area = 100 m\(^2\) fuel cell
  requires all winter to discharge
  – Around May battery is enough to
    balance production and demand
  – Why \( P_{EL}/P_{FC} = 3 \)?
Results – Optimal solutions analysis

- **Summer day: H₂ tank charging**
  - When excess PV and battery is full, central hours of the day

- **Winter day: H₂ tank discharging**
  - Low PV production, battery does not reach maximum SoC, H₂ discharging for most hours of the day

- **H₂ tank discharges for more hours during winter days than charges during summer ones**
  - Ratio of about 3:1
Conclusions

• Optimization has given relevant EL and FC sizes for components’ costs < 1000 €/kW
• Tank volume of approx. 6 m$^3$ and 14 m$^3$ when optimizing for 1000 €/kW
• EL optimal size always > FC optimal size
  – Might be due to more hours/day discharging in winter with respect to hours/day charging in summer
  – Ratio varies for 50 m$^2$ and is constant for 100 m$^2$ of PV panels

Future work

• Sensitivity analysis on the assumptions made
• Extension to other Italian climatic zones
  – To evaluate the impact of
    • Different insolation
    • Different ambient heating and cooling load curves
• Extension to different household types
  – Single vs multi-family houses
  – Different dwelling types
  – New constructions vs renovated buildings
• Evaluation of the impact of incentives on the system economics
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Thank you for your attention!

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Backup slides
Electrolyzer model

Linear regression to approx V-I curve of the electrolyzer

Finding the working point of the electrolyzer by explicitly solving the system:

\[ \text{PowerInput} = \text{CellCurrDensity} \times \text{CellActiveArea} \times \text{Vstack} \]

\[ \text{Vstack} = B \times \text{CellCurrDensity} + A \]

Checking if resulting current density is high enough for the electrolyzer to start, otherwise hydrogen prod = 0

Computing electrolyzer's efficiency and hydrogen energy output (eta faraday → eta el)

Hydrogen production
Fuel cell model

Linear regression to approx V-I curve of the fuel cell
Finding the working point of the electrolyzer by explicitly solving the system:

\[ \text{ReqPower} = \text{FC_CellCurrDensity} \times \text{FC_CellArea} \times \text{FC_Vstack} \]
\[ \text{FC_Vstack} = \text{coeffBfc}(i\text{loc}) \times \text{FC_CellCurrDensity} + \text{coeffAfc}(i\text{loc}) \]

Computing FC's efficiency and hydrogen energy demand
Hydrogen demand
Optimization

DUAL ANNEALING
Stochastic approach
Taken from the Scipy library:
https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.dual_annealing.html#scipy.optimize.dual_annealing
Given: function, bounds, max number of iterations
Results

50 m², tank SoC

![Graph showing SoC over months from Jan 2019 to Dec 2019 with three line graphs representing different costs per kW: 500 €/kW, 1000 €/kW, and 1500 €/kW.]
Results

100 m², tank SoC