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Optimization of stand-alone hybrid renewable energy systems for total energy supply of households in Mediterranean environment

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1. SIMULATION MODEL OF off-grid mCCHP SYSTEM BASED ON PEMFC WITH RENEWABLES

1.1. INPUT DATA

- Referent residential object (single-family isolated household, 70 m²) in the Mediterranean region, Split (43°16′N; 16°52′E)
METEOROLOGICAL DATA:
- The average monthly temperature and solar energy, *Split, DHMZ*
- Wind speed hourly profile, *Split, DHMZ*
1.2. ELECTRICAL HOUSEHOLD PROFILE

From real profile of 4-member household:

- electricity consumption of 10 kWh/day,
- hourly peak power demand of 3.8 kW
- the electricity requirement is varied throughout the day
- family members are not at home in the afternoon (17:00 – 19:00)
- in the morning (7:00-9:00) and at noon (15:00-17:00) family is together (breakfast / lunch / rest) → the electricity demand is increase
- maximum demand → at night (21:00-23:00).
1.3. THERMAL HOUSEHOLD PROFILE

a) Domestic Hot Water / DHW

- providing of DHW according to the real profile of 4-member household
- thermal energy consumption: 8.9 kWh/day,
- hour peak consumption of thermal energy: 4.57 kW,
- average consumption of thermal energy for DHW: 0.367 kW
b) operating modes for heating/cooling

From real household seasonal profile:

a) Space heating: \( \theta_{\text{avg}} < 14 \, ^\circ\text{C} \)
   - Average operating hours: 8h/day

b) Space cooling: \( \theta_{\text{avg}} > 21 \, ^\circ\text{C} \)
   - Average operating hours: 6h/day

---

<table>
<thead>
<tr>
<th>Month</th>
<th>Days</th>
<th>( \Theta_{\text{avg}} )*</th>
<th>Heating kWh/day</th>
<th>Cooling kWh/day</th>
<th>Monthly kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>31</td>
<td>8.2</td>
<td>16.8</td>
<td>no</td>
<td>520.8</td>
</tr>
<tr>
<td>Feb</td>
<td>28</td>
<td>8.3</td>
<td>16.8</td>
<td>no</td>
<td>470.4</td>
</tr>
<tr>
<td>Mar</td>
<td>31</td>
<td>11</td>
<td>16.8</td>
<td>no</td>
<td>520.8</td>
</tr>
<tr>
<td>Apr</td>
<td>30</td>
<td>14.5</td>
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<td>no</td>
<td>0</td>
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<td>May</td>
<td>31</td>
<td>19.8</td>
<td>no</td>
<td>no</td>
<td>0</td>
</tr>
<tr>
<td>Jun</td>
<td>30</td>
<td>23.9</td>
<td>12.24</td>
<td>no</td>
<td>367.20</td>
</tr>
<tr>
<td>Jul</td>
<td>31</td>
<td>26.6</td>
<td>no</td>
<td>12.24</td>
<td>379.44</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>26.4</td>
<td>no</td>
<td>12.24</td>
<td>379.44</td>
</tr>
<tr>
<td>Sep</td>
<td>30</td>
<td>21.2</td>
<td>no</td>
<td>12.24</td>
<td>367.20</td>
</tr>
<tr>
<td>Oct</td>
<td>31</td>
<td>17.3</td>
<td>no</td>
<td>no</td>
<td>0</td>
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<td>Nov</td>
<td>30</td>
<td>12.7</td>
<td>16.8</td>
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<td>504</td>
</tr>
<tr>
<td>Dec</td>
<td>31</td>
<td>9.1</td>
<td>16.8</td>
<td>no</td>
<td>520.8</td>
</tr>
</tbody>
</table>

*\( \Theta_{\text{avg}} \) - the monthly average ambient temperature in Split
1.4. MODEL OF off-grid HYBRID SYSTEM

Diagram showing a hybrid energy system with components such as WT/AC, PV/DC, AC load, Battery bank, Converter, Electrolyzer, PEMFC/DC, THERMAL STORAGE, and heat exchanger, indicating the integration of renewable energy sources and waste heat recovery for households.
### 1.5. SYSTEM CONTROL INPUTS

<table>
<thead>
<tr>
<th>Simulation time step, [min]</th>
<th>60</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load following dispatch strategy</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cycle charging dispatch strategy</td>
<td>20</td>
<td>+</td>
</tr>
<tr>
<td>Battery setpoint state of charge, [%]</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Systems with multiple generators</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Generators operate simultaneously</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Generators capacity less than peak load</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Allow excess electricity to serve thermal load</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Limit excess thermal output (% of load)</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>
1.6. OPTIMIZATION PROCEDURE

- there are three objective functions:
  - different between production/consumption $H_2$ at the end of year is minimum
  - produced excess of thermal energy at the end of year is minimum
  - LOLP in the HRES in all intervals is minimum

<table>
<thead>
<tr>
<th>HRES components</th>
<th>Search interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV, kW</td>
<td>1, 2, 3, 4, 5, 6, 7, 7.5</td>
</tr>
<tr>
<td>WT, kW</td>
<td>1, 2, 2.5, 3, 3.5, 4</td>
</tr>
<tr>
<td>PEMFC, kW</td>
<td>1, 2, 2.5, 3, 3.5, 4</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>1, 2, 2.5, 3, 3.5, 4, 5</td>
</tr>
<tr>
<td>$H_2$ tank, kg</td>
<td>30, 50, 70</td>
</tr>
<tr>
<td>Converter, kW</td>
<td>6, 8, 10, 12</td>
</tr>
<tr>
<td>Battery</td>
<td>1, 2, 4, 5, 6, 7</td>
</tr>
</tbody>
</table>
1.7. LOAD PRIORITY

RES: PV/ WT

Electricity produced on one bus will go:

1. to serve primary load on the same bus,
2. to primary load on the opposite bus,
3. to charge the battery bank,
5. to serve the electrolyzer,
6. to the dump load → serves the thermal load
1.8. DISPATCH STRATEGY

a) there is excess electricity generated from PV/WT

\[ \text{SOC}_{\text{batt}} \rightarrow \text{all the excess electricity can be consumed or } \text{SOC}_{\text{max}} \text{ is reached } \rightarrow \text{the electrolyzer is started to produce } \text{H}_2 \text{ from excess electricity} \]

b) there is energy shortage generated from PV/WT

\[ \rightarrow \text{the lack of energy is taken from the battery until the } \text{SOC}_{\text{min}} \text{ is reached } \rightarrow \text{the PEMFC is powered to serve the electrical profile} \]

- if more power needed than PEMFC can produced /taken from stored \( \text{H}_2 \) \( \rightarrow \) operating reserve
1.9. Software for HRES simulation

<table>
<thead>
<tr>
<th>Feature</th>
<th>HOMER</th>
<th>HYBRID 2</th>
<th>HOGA</th>
<th>HYDROGEMS+ TRNSYS</th>
<th>HYBRIDS</th>
<th>INSEL</th>
<th>ARES</th>
<th>RAPSIM</th>
<th>SOMES</th>
<th>SOLSIM</th>
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<tbody>
<tr>
<td>Free download and use</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>PV, Diesel, Batteries</td>
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<td>+</td>
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<td>+</td>
<td>+</td>
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<td>Mini-Hydro</td>
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<td>+</td>
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<td>+</td>
<td>+</td>
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<tr>
<td>Fuel cell: electrolyzer and H₂ tank</td>
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<td>+</td>
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<td>+</td>
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<td>Hydrogen load</td>
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<td>+</td>
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<tr>
<td><strong>Thermal load</strong></td>
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<td><strong>Control strategies</strong></td>
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<td><strong>Multi-Optimization, Genetic Algorithms</strong></td>
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TRNSYS. Available from: [http://sel.me.wisc.edu/trnsys/](http://sel.me.wisc.edu/trnsys/).


HYBRIDS: Berrill T., 29 Burnett St., Wellington Point, Qld, Australia: Solaris solar powered home; 2005.


SOMES: [http://www.web_co_bw/sib/somes_3_2_description.pdf](http://www.web_co_bw/sib/somes_3_2_description.pdf).

PV produces DC electricity in direct proportion to the global solar radiation incident upon it.

- For grid independent systems, PV optimal slope is the one with highest mean daily insolation value of the weakest month in a year (typically December).

- Selecting 65° slope results in producing 13% less excess electricity compared to 35° slope.

<table>
<thead>
<tr>
<th>SOLAR RESOURCE</th>
<th>INPUT</th>
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<tr>
<td></td>
<td>43</td>
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<tr>
<td></td>
<td>16</td>
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<tr>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>4.13</td>
</tr>
<tr>
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<td>90</td>
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<table>
<thead>
<tr>
<th>PHOTO VOLTAIC MODULE PV</th>
<th>DESIGN</th>
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<tr>
<td></td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>47</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>10</td>
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<td></td>
<td>5</td>
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</table>

<table>
<thead>
<tr>
<th>PV CONTROL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location, N [°]</td>
</tr>
<tr>
<td>Location, E [°]</td>
</tr>
<tr>
<td>Clearness indeks, k\textsubscript{T,avg}</td>
</tr>
<tr>
<td>Daily radiation, [kWh/m\textsuperscript{2}/d]</td>
</tr>
<tr>
<td>Derating factor, [%]</td>
</tr>
<tr>
<td>Slope, [°]</td>
</tr>
<tr>
<td>Azimuth, W or S [°]</td>
</tr>
<tr>
<td>Ground reflectance, [%]</td>
</tr>
<tr>
<td>Temperature coeff. of power [%/C]</td>
</tr>
<tr>
<td>Nominal operating cell temperature [°C]</td>
</tr>
<tr>
<td>Efficiency at std. test conditions [%]</td>
</tr>
<tr>
<td>Lifetime, [yr]</td>
</tr>
<tr>
<td>Rated power, DC, [kW]</td>
</tr>
</tbody>
</table>
2.2. WIND TURBINE WT

converts the kinetic energy of the wind into AC electricity according to a particular power curve, which is a graph of power output versus wind speed at hub height.

| Annual average wind speed, $v_{avg}$ [m/s] | 4,1 |
| Weibull shape factor | 1,5 |
| Autocorrelation factor | 0,8 |
| Diurnal pattern strength | 0,2 |
| Hour of peak wind speed | 15 |
| Anemometer height, [m] | 10 |
| Diameter, [m] | 5 |
| Hub height, [m] | 25 |
| Lifetime, [yr] | 15 |
| Rated power: AC, [kW] | 2 |

**INPUT**

**WIND SPEED**

**DESIGN**

**WIND TURBINE WT**

**WT CONTROL**
2.3. MICROTRIGENERATION SYSTEM / mCCHP

2.3.1. Heat Pump HP

- HP is dimensioned according to operating mode during the summertime → simultaneously space cooling and DHW heating

- to start the compressor, HP uses DC electricity generated from PEMFC/ PV/ WT

- the main advantages of a DC brushless motor compressor is its quiet operation, compact, longer life time, energy saving and better capacity control

- DHW preparation under the thermodynamic operating conditions of HP → 1/5 of the total installed compressor power
- system uses a heat exchanger to subcool the refrigerant at the outlet of the hot water heater while heating the refrigerant at the outlet of the evaporator → increasing the both the hot water heating and air cooling capacity of the system

- 1kW compressor operating conditions:
  - the mass flow rate of refrigerant is 0.023 kg/s;
  - the heat exchanger power is 4.41 kW with the COP_{HW} of 4.41
  - the evaporator power is 3.41 kW, with COP_{AC} of 3.41 kW
  - the mass flow rate of the air through the evaporator is 20.4 kg/min.
2.3.2. PEMFC

<table>
<thead>
<tr>
<th>FUEL: stored H₂</th>
<th>INPUT</th>
<th>0.003</th>
<th>Intercept coeff. [kg/hr/kW rated]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM FUEL CELL</td>
<td></td>
<td>0.066</td>
<td>Slope coeff. [kg/hr/kW output]</td>
</tr>
<tr>
<td>PEMFC CONTROL</td>
<td>DESIGN</td>
<td>10</td>
<td>Minimum load, [%]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80</td>
<td>Heat recovery ratio, [%]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
<td>Operating mode: optimized</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
<td>Time period: All week</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15000</td>
<td>Lifetime, [operating hours]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>Rated power, DC, [kW]</td>
</tr>
</tbody>
</table>

![Graph showing fuel consumption vs. output power]

![Graph showing efficiency vs. output power]
3. OPERATING PERFORMANCE OF HRES
3.1. Electrical load profile

- PEMFC follows the electrical profile of household, the majority of working hours is in the evening when there's no sun, it operates 715 hr/yr with 580 numbers of starts. \( \eta_{el} = 33.55\% ; \eta_{tot} = 85\% \)

- PEMFC /HP follow the complete thermal profile of household, HP only in the summertime, both operate 4726 hour ; 2274 kWh/yr

- PV uses solar energy in day mode between 7:00 and 18:00 hour, total annual production is 7183.93 kWh/yr with capacity factor of 16.4 %,

- WT generates electricity with annual operating of 5066 hours, wind penetration 68.64 %
  total annual wind electricity production: 2380.11 kWh
D. Čikatić Šanić: Optimization of stand-alone HRES for total energy supply of households in Mediterranean environment
3.2. Thermal storage tank / TS

Thermal storage tank (TS) is filled:

- With excess electricity produced from PV/WT via electrical heater
- Waste heat from the PEMFC via heat exchanger
- Waste heat from the HP via heat exchanger
At 06:00-09:00 am throughout the year, there is a lack of heat produced, so that demand for household DHW is covered from TS.

In the interim period (Apr, May, Oct) household is supplied from TS in the evening on average 3.46 kWh/d.

during the cooling period (May-Sept.) missing only 1.62 kWh/d on average.

during the day 10:00-15:00 throughout the year → excess of produced heat (PV)
4. SIMULATION RESULTS AND DISCUSSION

4.1. Electrical performance of HRES:

- Annually electrical production from PV/WT is 97.66%, from PEMFC is 2.34% of total production.

- Electrolyzer consumptions 57% from PV/WT, while electrical load of household is 43% of total annual electrical consumption.

- The excess electricity produced by the hybrid system always exists, and stored in TS to covering household thermal loads.
4.2. Thermal performance of HRES

- PEMFC produces 53.31% of annually thermal energy, while TS is filled additionally with thermal energy obtained from excess electricity 17.87% and from HP in summertime 28.82%
4.3. Annual energy production/consumption in HRES
## 5. COMPARISON HRES WITH DIFFERENT COMPONENTS

<table>
<thead>
<tr>
<th></th>
<th>OIE/BATT</th>
<th>OIE/PEM</th>
<th>OIE/PEM/BATT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELECTRICITY</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed RES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Sigma P_{\text{RES}}$ kW</td>
<td>9</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>Excess electricity, $E_{\text{el,exc}}$</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>$E_{\text{el,exc}}$ used for:</td>
<td>all for DHW</td>
<td>partially DHW</td>
<td>partially DHW</td>
</tr>
<tr>
<td><strong>HEAT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>waste heat utilization</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Produced excess heat, $E_{\text{th,exc}}$</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>$E_{\text{th,exc}}$ used for</td>
<td>rejected</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENERGY STORAGE</strong></td>
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<td></td>
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</tr>
<tr>
<td>Batery</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>$H_2$ tank</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Thermal storage/TS</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Let the reference HRES be the one that stores energy only in the battery, considering its most commonly used application.

Electricity produced in HRES with RES/BATT is stored in the battery in sufficient quantity to following household electrical demands. There is as much surplus electricity as it is enough to replenish the household needs for the preparation of DHW.

HRES that stores energy only through the H₂ subsystem takes part of installed power from the HRES/BATT due to the supply of electrolyzer needed for H₂ production.

Energy storage via the hydrogen subsystem (electrolyzer, PEMFC and H₂ tank) is a replacement storage for the battery bank, waste heat from PWMFC is used for DHW, produced electricity is used for driven HP compressor.

This eliminates the greatest lack of battery usage since battery life depends on the number of charging/discharging cycles.
6. CONCLUSION

- Optimal electricity and thermal supply for stand-alone household is technically feasible with a 100% renewable system including hydrogen technologies → electrolyser, hydrogen tank and fuel cell
- The application of mCCHP based on PEMFC can easily help renewable energy to get into market, supplying energy when the sun or wind are not available
- mCCHP provides both electricity and thermal energy and fulfills residential load more effectively than conventional systems
- RES / HP/ PEMFC have great perspective in Mediterranean region in cooling season
Thank you for attention

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