Greenhouse gas reductions and primary energy savings via adoption of hybrid plants in place of conventional ones

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Abstract

With the Kyoto agreement, there has been a greater emphasis on lowering energy waste and supporting low-emissions systems such as fuel cells (FC), photovoltaic (PV) systems or solar thermal systems (STS). These technologies produce environmental benefits since non-renewable energy can be preserved and environmental pollution can be drastically reduced. In addition to this, the decentralization of the electricity production plants mitigates the grid distribution losses. This paper develops a theoretical analysis focused on the environmental benefits achievable through a shift from the conventional systems, normally operating in hospitals, to different hybrid plants. The model site is a hospital located near Ferrara (Italy). At first, a numerical procedure has been adopted in order to calculate the energy requirements of the existing plant. Then several hybrid schemes have been investigated and compared: PAFCs (phosphoric acid fuel cells), STS, PV systems. An energy analysis is developed for each option assuming the conventional systems, operating in the medical center, as the reference. At the same time, an economic study is developed for all the retrofit scenarios in terms of annual return, simple payback period and IRR. The results are presented with reference to the primary energy requirements and the pollutant emissions; it is demonstrated that in the case the existing conventional systems would be upgraded with these hybrid plants, overall greenhouse emissions could be abated with a significant reduction in primary fossil energy consumptions.

Keywords: hybrid plants, pollutant reductions, primary energy savings, fuel cells, solar thermal systems, photovoltaic systems.
1 Introduction

Human activities, primarily the combustion of coal, oil and natural gas, are important contributors to the climate changes. To respond to this problem, Italy and other countries have signed the Kyoto Protocol (1997). The Protocol will commit Italy to reduce its emissions of greenhouse gases (GHGs) to 6.5% below their 1990 levels within the years 2008-2012. However, the most recent projection of Italy’s GHG emissions shows that the gap between Italy's Kyoto commitment and the total projected emissions is becoming alarmingly large [1]. At the same time, scientists have made it clear that reductions of about 20-50% in global GHG emissions are needed just to stabilize the atmospheric concentrations of GHGs at double their pre-industrial levels. This fact underlines that the Kyoto Protocol has to be considered just as a small, but important, first step. The dimension of the problem highlights that the solutions to the climate change must begin at the local level. In Italy, the local governments’ environmental policies have a profound influence on environment, economy, social fabric and quality of life. In theory they have the potentiality to control, both directly and indirectly, more than half of the GHG emissions released in Italy. Generally, these emissions come from the heating and cooling plants of public buildings (municipalities, hospitals, etc.) and from providing basic services such as transportation, water, waste management. Actions to reduce GHG emissions save money, minimize local air pollution (contributing to lower smog, acid rain, and health problems), create jobs, and provide better overall quality of life. Hence, the local governments are uniquely positioned to affect broad reductions in GHG emissions. Regulatory, fiscal, and voluntary mechanisms can all be used effectively to reduce GHG emissions in the wider community. A concrete action that the local governments can use in order to sensibly reduce GHG emissions in their community is to upgrade their buildings’ plants (municipalities, hospitals, decisional centers) shifting away from the use of conventional fossil fuels toward cleaner, renewable energy sources. Besides, improving energy efficiency can contribute to community’s economic renewal by freeing up more money to reinvest within the local economy. Recently, Van Shijndel [2] showed how the optimization of the primary energy consumption associated with the hospitals’ thermal plants operation can be compatible with the constraint of a positive economic profit. Bizzarri and Morini [3] demonstrated that a fuel cell hybrid plant in a hospital can lead to considerable primary energy saving and consistent pollutant emission reduction.

This paper investigates the real opportunities in terms of primary energy and money savings and environmental benefits offered by the energy retrofit of a typical Italian hospital. The retrofit policies here studied consist in a shift from a conventional plant configuration (normally operating in the hospitals), to different hybrid schemes (PAFCs, STS, PV systems).

In particular, the hospital of Lagosanto, near Ferrara (Italy), has been chosen as the model to test the efficacy of these retrofit strategies.
2 Constraints of retrofit

The monthly electric requirements $Q_E$ of the Lagosanto’s hospital were reconstructed acquiring its electricity bills database [4], whereas the corresponding thermal consumptions were evaluated through ad hoc developed procedures since no reliable databases were available. The first step consisted in the creation of a digital model of the hospital. Then the monthly heating and cooling needs, $Q_H$ and $Q_C$, were determined exploiting this model, initially simulating the heat transfer phenomena both in transient and steady-state conditions, then processing the data obtained through properly developed spreadsheet procedures [4,5]. At the end of this investigation, the monthly energy requirements of Lagosanto hospital were completely identified (Table 1).

Table 1: Estimated monthly electrical ($Q_E$), heating ($Q_H$) and cooling ($Q_C$) demands of Lagosanto’s hospital.

<table>
<thead>
<tr>
<th>Month</th>
<th>$Q_E$ [MWh]</th>
<th>$Q_H$ [MWh]</th>
<th>$Q_C$ [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>476</td>
<td>1715</td>
<td>-</td>
</tr>
<tr>
<td>Feb</td>
<td>476</td>
<td>1449</td>
<td>-</td>
</tr>
<tr>
<td>Mar</td>
<td>505</td>
<td>1270</td>
<td>-</td>
</tr>
<tr>
<td>Apr</td>
<td>481</td>
<td>894</td>
<td>-</td>
</tr>
<tr>
<td>May</td>
<td>537</td>
<td>460</td>
<td>-</td>
</tr>
<tr>
<td>Jun</td>
<td>669</td>
<td>232</td>
<td>154</td>
</tr>
<tr>
<td>Jul</td>
<td>690</td>
<td>134</td>
<td>322</td>
</tr>
<tr>
<td>Aug</td>
<td>711</td>
<td>139</td>
<td>533</td>
</tr>
<tr>
<td>Sep</td>
<td>496</td>
<td>233</td>
<td>468</td>
</tr>
<tr>
<td>Oct</td>
<td>518</td>
<td>637</td>
<td>292</td>
</tr>
<tr>
<td>Nov</td>
<td>493</td>
<td>1167</td>
<td>-</td>
</tr>
<tr>
<td>Dec</td>
<td>488</td>
<td>1600</td>
<td>-</td>
</tr>
</tbody>
</table>

From Table 1 it is evident that the monthly electric demand during summer grows significantly following a common pattern distinctive of many North Italian hospitals [4]. This growth is the result of the high utilization of compression chillers supporting the HVAC systems during the hot season. A peak cut policy, pursuing the optimization of the electrical requirements around the monthly values characteristic of the cold season, could even lead to economical benefits since the contracts with the electricity companies are normally set to the peak of consumption.

Besides, it has been proved that, for hybrid solar thermal power plants, the major fossil energy saving and greenhouse gases reduction are obtained when the solar collectors provide an amount of electricity consistent with the summer growth of consumptions [5].

In the hospital of Lagosanto, heat and power requirements are provided by “conventional” systems. Electricity is imported from the grid whereas heating is completely supplied by gas-fired boilers. Cooling needs are normally satisfied with compression chillers.

The retrofit scenarios presented in this article have been developed considering two main constraints. The first constraint is that the monthly electricity self production from the “not-conventional” part of the plant should at least equal the gap existing between the average monthly electrical requirement characteristic of summer months (from June to August) and those characteristic of the other months. It means that the “not-conventional” part of the plant achieves the peak cut. Such a choice well suits with solar technologies since these systems achieve their peak of production in correspondence of the peak of demand during the hottest sunny days of the summer. The second constraint
descends from the type of data available for the analysis. Since there were no data concerning the dynamic behaviour of the energy demand throughout the “typical day”, it was impossible to simulate the operations in progress of the different plants examined. Hence, at this step of the research, it has been decided to focus the study only on the monthly integral consumptions.

In conformity with the constraints defined above, the following assumptions have been considered.

- Trigeneration is pursued: if low enthalpy heat recoveries are available they are used first to feed absorption chillers for cooling (only in summer), then to mitigate boilers’ operations (directly or indirectly, making absorption chillers operate as heat pumps during the cold season).
- Absorption chillers are sized such to be fed always by the whole of the energy recoveries when these are available. It means that their cooling output has been computed considering a continuous energy production throughout the operating hours of the typical day of July (19.18 hours for fuel cells, 9.6 hours for solar collectors).
- In the peak mode, the energy requirements in deficit are provided by the “conventional” systems: electricity is imported from the grid, heat and cold are generated respectively using gas-fired boilers and compression chillers.
- Electricity from the grid is assumed to have been derived from a oil fired power station [6].
- The heat loss in the plant network are neglected.

3 Scenarios definitions

Four different scenarios have been investigated.

- Basic scenario: the “conventional” hospital (Fig. 1), where electricity is imported from the grid, heating is provided by gas-fired boilers and cooling by compression chillers.

In this scheme, the following numerical values have been adopted:

- public utility mean electrical efficiency $\eta_{E,T}=38.25\%$ [6];
- gas-fired boilers thermal efficiency $\eta_B=85\%$;
- compression chiller $COP_C = 3.0$.

![Figure 1: Conventional plant lay-out.](image-url)
- *Retrofit scenario 1*: PAFCs hybrid plant (Fig. 2). The “not-conventional” part of the plant consists in two phosphoric acid fuels cell system also integrated with an absorption cooling system. The heating is supplied partially by heat recovery from the fuel cells and the remainder by gas-fired boilers.

The fuel cells here investigated meet the characteristics of the UTC PC25. This device has been chosen as the reference since it is the sole fuel cells system that has achieved a consistent market penetration.

The main characteristic of this fuel cell hybrid plant [7] are:

- fuel cell electrical efficiency $\eta_{e,FC} = 39\%$;
- fuel cell rated power 200 kW for each installed device;
- average utilization $\approx 7000$ hours/year (19.18 hours/day);
- recoverable heat at rated power $Q_{h,FC}$ 90 kW at $120^\circ$C;
- absorption chiller $COP_{AC} = 0.7$ (heat pump $COP'_{AC} = 1.7$).

- *Retrofit scenario 2*: solar collectors (STS) hybrid plant (Fig. 3). In this scheme, each collector concentrates the sunlight onto the steel pipe located in its focal axis heating a silicone polymer (“organic”) fluid, flowing inside this pipe. This heated fluid is directly employed as the working fluid in a Rankine power cycle generating electricity. Finally, heat recoveries are used first to feed absorption chillers, secondary to diminish the quote of heating in charge of conventional systems (directly, or indirectly through the scheme: absorption chillers-heat pump). For this analysis the Solel-IND300 collector has been chosen as the

![Figure 2: PAFCs hybrid plant lay-out.](image-url)
The plant is sized such to produce an amount of electricity equal to the gap defined above as the constraint. Under this condition, on the basis of the monthly direct radiation $Q'_S$ available at Lagosanto (Table 2), the dimension of the solar field results to be 21343 m².

Table 2: Monthly direct radiation ($Q'_S$) and diffuse radiation ($Q''_S$) on a horizontal surface at Lagosanto (lat. 44.5, lon. 12.1).

<table>
<thead>
<tr>
<th>Month</th>
<th>Unit</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q'_S$ [kWh/m²]</td>
<td>43.1</td>
<td>56.0</td>
<td>96.7</td>
<td>116.4</td>
<td>155.9</td>
<td>165.9</td>
<td>191.9</td>
<td>168.3</td>
<td>122.7</td>
<td>76.9</td>
<td>44.4</td>
<td>36.9</td>
<td></td>
</tr>
<tr>
<td>$Q''_S$ [kWh/m²]</td>
<td>42.5</td>
<td>60.8</td>
<td>97.7</td>
<td>144.0</td>
<td>189.1</td>
<td>200.4</td>
<td>214.2</td>
<td>182.0</td>
<td>133.5</td>
<td>86.5</td>
<td>40.5</td>
<td>33.5</td>
<td></td>
</tr>
<tr>
<td>Intense daylight [h/d]</td>
<td>2.8</td>
<td>3.6</td>
<td>4.7</td>
<td>6.2</td>
<td>7.7</td>
<td>8.6</td>
<td>9.6</td>
<td>8.6</td>
<td>7.0</td>
<td>4.8</td>
<td>2.0</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

The main characteristics of this scheme are summarized below [8]:

- STS electrical efficiency $\eta_{STS}$ computed as the product of the monthly collectors efficiency $\eta_{cSTS}$ (part of monthly direct radiation $Q'_S$ transferable into thermal energy by solar collectors), summarized in Table 3, and the Organic Rankine cycle efficiency ($\eta_{rSTS}$ = 17%);
- absorption chiller $COP_{AC} = 0.7$ (heat pump $COP'_{AC} = 1.7$).

Table 3: Monthly solar collectors efficiency ($\eta_{cSTS}$).

<table>
<thead>
<tr>
<th>Month</th>
<th>Unit</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{cSTS}$ (%)</td>
<td>0.46</td>
<td>5.00</td>
<td>11.58</td>
<td>18.47</td>
<td>28.86</td>
<td>32.91</td>
<td>27.78</td>
<td>28.46</td>
<td>22.17</td>
<td>6.76</td>
<td>0.68</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3: STS hybrid plant lay-out.](image-url)
- **Retrofit scenario 3**: PV hybrid plant (Fig.4); this option is relatively simple consisting in a “conventional” plant integrated by PV systems.

Helios H1000 photovoltaic module has been selected as the reference devices. The plant, sized under the same assumption defined before, considering the monthly direct $Q^\prime_S$ and diffuse solar radiation $Q^\prime\prime_S$ at Lagosanto (Table 2), involves a field of 7831 m² made by 11091 modules.

The other basic characteristic of the PV hybrid plant are:

- photovoltaic modules efficiency $\eta_{PV}=12\%$ assuming a BOS efficiency ($\eta_{BOS}$) equal to 80%.

![Figure 4: PV hybrid plant lay-out.](image)

The criteria adopted to compare the viability of the different options are primary fossil energy consumptions, greenhouse gases reductions, economic annual return, simple payback period and IRR.

### 4 Results

The comparison among the four scenarios has produced the following results.

#### 4.1 Primary energy consumptions

From Figure 5 it is clear that there would be a large reduction in the monthly primary energy consumption in each of the three retrofit scenarios here examined. The annual primary energy reduction would be 1865 MWh (6%) for PAFCs plant, 6562 MWh (23%) for STS plant, 3362 MWh (12%) for PV plant. The comparison among the conventional and the hybrid scenarios reveals that the highest reductions would occur in the high-temperature solar plant scenario. This result is first attributable to the large exploitation of solar renewable energy achieved thanks to the collectors, then, on the contrary to what happens in the PV hybrid plant, to the abundant availability of thermal recoveries which can be used to lower the boilers’ use. Fuel cells hybrid plant show a lower reduction since the gas consumption rises significantly. This is due to the choice of feeding fuel cells with natural gas.
4.2 Greenhouse gas reductions

The pollutant emissions from each of the selected systems have been evaluated according to the values summarized in Table 4 [7, 9].

In all the scenarios the emissions were significantly reduced compared to those from the conventional hospital (Fig. 6).

This would be mainly due to the utilization of high efficiency systems directly fed by renewable energy sources or characterized by “clean” energy processes. Secondary, the use of heat recovery to fulfill the heating and cooling needs (together with the consequent significant reduction in boilers and compression chillers use) could also considerably enhance the pollution reduction.

Table 4: Pollutant emissions related to the operation of the investigated systems.

<table>
<thead>
<tr>
<th></th>
<th>CO₂ [g/kWh]</th>
<th>SO₂ [mg/kWh]</th>
<th>NOₓ [mg/kWh]</th>
<th>Powders [mg/kWh]</th>
<th>HC [mg/kWh]</th>
<th>CO [mg/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil-fired power pl.</td>
<td>700</td>
<td>1200</td>
<td>1100</td>
<td>200</td>
<td>50</td>
<td>&lt;30</td>
</tr>
<tr>
<td>PC25 fuel cells</td>
<td>190</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[g/sm³]</td>
<td>[mg/sm³]</td>
<td>[mg/sm³]</td>
<td>[mg/sm³]</td>
<td>[mg/kWh]</td>
<td>[mg/sm³]</td>
</tr>
<tr>
<td>Gas-fired boilers</td>
<td>1988</td>
<td>170</td>
<td>1500</td>
<td>50</td>
<td>40</td>
<td>320</td>
</tr>
</tbody>
</table>

The CO₂ emissions associated with the fulfillment of the energy requirements, would significantly decrease, lowering from 7002 tons/y to 5184 tons/y (26% reduction) for PAFCs hybrid plant, to 5431 tons/y (22% reduction) for STS hybrid plant, to 6102 tons/y (13% reduction) for PV hybrid plant.

The trend followed by the other pollutants confirmed the same pattern: adoption of fuel cells would lead both to a significant decrease in NOₓ (3.3 tons/y, equivalent to 37%), SOₓ (3.6 tons/y, or 37%), and dusts (521 kg/y, or 27%). A high-temperature solar hybrid plant would lower the NOₓ by 1.9 tons/y (22%), SOₓ by 2.1 tons/y (22%), and powders by 426 kg/year (22%). Finally, a
PV hybrid plant could abate the NO\textsubscript{X} by 1.4 tons/y (16%), SO\textsubscript{X} by 1.5 tons/y (16%), and powders by 257 kg/y (13%) Even though high-temperature devices could perform a higher pollutant reduction during summer months, they are almost inoperative during the cold season; on the contrary a fuel cell hybrid plant could achieve a constant pollution reduction throughout the year.

![Graph showing emissions predictions for different scenarios](image)

**Figure 6:** Predicted monthly emissions characterizing the four scenarios.

### 4.3 Economic analysis

The viability of each scenario has been assessed in terms of annual return, simple payback period and IRR considering investment costs, running costs and avoided costs. The last parameter has been computed at the seventh year of life for each hybrid plant. This choice has been made considering that fuel cells have the shortest expected life (7 years) among the selected systems. Both the investment and the maintenance costs were evaluated according to the information obtained from the manufacturers [7,8,10]. The annual interest rate has been assumed at 3% while Italian taxes and/or fiscal incentives were not considered, in order to achieve the most general results as possible.

The following data were also considered in the analysis:
- electricity cost: 0.07 €/kWh [11],
- natural gas: 0.51 €/kWh for conventional systems [12], 0.34 €/kWh for cogeneration systems [12].

The main results obtained are quoted in Table 5. It is interesting to observe that in all the cases considered here the IRR assumes a negative value and even the simple payback period (SPB) is much longer than the expected life of the systems.
Table 5: Main results of the economic analysis.

<table>
<thead>
<tr>
<th>Costs</th>
<th>unit</th>
<th>PAFC</th>
<th>STS</th>
<th>PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>systems costs</td>
<td>[k€]</td>
<td>2383.3</td>
<td>10401.1</td>
<td>5938.1</td>
</tr>
<tr>
<td>Total</td>
<td>[k€]</td>
<td>2383.3</td>
<td>10401.1</td>
<td>5938.1</td>
</tr>
<tr>
<td>Annual running costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>natural gas needs</td>
<td>[k€/y]</td>
<td>257.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>maintenance</td>
<td>[k€/y]</td>
<td>-</td>
<td>323.9</td>
<td>415.9</td>
</tr>
<tr>
<td>Total</td>
<td>[k€/y]</td>
<td>257.1</td>
<td>323.9</td>
<td>415.9</td>
</tr>
<tr>
<td>Annual savings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electricity self-production</td>
<td>[k€/y]</td>
<td>196</td>
<td>68.4</td>
<td>90</td>
</tr>
<tr>
<td>recovered heat (heating)</td>
<td>[k€/y]</td>
<td>77.6</td>
<td>238.4</td>
<td>-</td>
</tr>
<tr>
<td>recovered heat (cooling)</td>
<td>[k€/y]</td>
<td>8.6</td>
<td>24.8</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>[k€/y]</td>
<td>282.2</td>
<td>331.6</td>
<td>90</td>
</tr>
<tr>
<td>Annual return</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>[k€/y]</td>
<td>25.2</td>
<td>7.7</td>
<td>-325.9</td>
</tr>
<tr>
<td>IRR (7 years)</td>
<td>[%]</td>
<td>-0.43</td>
<td>-0.63</td>
<td>-</td>
</tr>
<tr>
<td>SPB</td>
<td>[y]</td>
<td>93</td>
<td>&gt;1000</td>
<td>&lt;0</td>
</tr>
</tbody>
</table>

At the moment, for these reasons, the feasibility of such a hybrid plants appears to be strongly dependent on the availability of public funds and specific government actions.

However only costs associated with energy processes have been considered in this study. Even though it is not mandatory, the greenhouse gas reduction should be of interest to the politicians considering the amount of hidden cost savings associated to externalities [13]. These externalities, together with the costs associated with the systems’ manufacture, could even completely change the previous results shifting the balance towards the use of these new technologies.

5 Conclusions

This paper develops a theoretical analysis about the feasibility of a hybrid plant applied to a real hospital located in Ferrara (Italy). The solutions here examined consider the utilization of high efficiency systems directly fed by renewable energy sources or characterized by “clean” energy processes. Three retrofit scenarios have been analysed: PAFCs, STS and PV hybrid plants.

The main constraint that has been respected is that the electricity selfproduction in July, from the “not conventional” part of the plant, should equal the gap existing from the average monthly electrical requirement characteristic of summer months (from June to August) and the one characteristic of the other nine months of the year. The energy performance of each hybrid plant has been examined considering as a benchmark the conventional systems now operating in the medical center. The prediction of the yearly primary energy consumptions revealed consistent savings in all the cases investigated up to a 23% decrease in the STS hybrid plant scenario. The results point out that these retrofit policies could offer a significant greenhouse gases emission mitigation. PAFCs hybrid plant, in particular (thanks to the continuity of their operation) could ensure the highest pollutant reductions throughout a whole year.
Finally the economic analysis has confirmed that today the cost of these devices still represents an insurmountable market barrier (negative IRR, unattainable simple payback period). It’s basic to underline that this economic analysis constitutes only a first step being developed only from the energy-processes costs. A definitive, exhaustive comparison among these scenarios will be possible only when also the hidden costs associated with the systems’ manufacture and the externalities will be reliable. At that moment, perhaps, the considerable energy savings and the pollutant emissions reduction, that could be achieved upgrading conventional systems to one of the considered hybrid plants, should suggest the national boards to support the business development of these new technologies, as long as they consolidate a firm market penetration.

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References