Solar-assisted trigeneration: Primary energy efficiency and cost performance of a new system concept

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Abstract
In this study, a solar cooling and trigeneration application were combined to a new system concept called solar-assisted trigeneration. To examine the concept annual simulations and economic efficiency calculations were performed. Thermal and electrical loads of all main and auxiliary components were considered. If properly designed, the solar-assisted trigeneration reaches higher energy efficiency than the reference systems solar cooling, trigeneration and conventional system with simultaneous consideration of equal overall costs.

Introduction
Solar cooling and trigeneration applications with sorption chillers reach high Primary Energy Ratios (PER) [1,2]. The PER is calculated by the quotient of the useful energy and the used primary energy of an energy system:

$$\text{PER} = \frac{\text{useful energy}}{\text{used primary energy}}$$

In Table 1 typical PERs are shown for different energy systems. The conventional system with a gas burner for heating and a compression chiller for cooling reaches a PER of about 1 for heating, cooling and combined. Solar cooling systems benefit from cooling; the heating is comparable to solar-assisted heating systems, where most of the useful energy is generated by the gas burner. By contrast, trigeneration systems benefit from heating; the PER of cooling is comparable to the conventional system.
### Table 1: Typical Primary Energy Ratios (PER) of different energy systems

<table>
<thead>
<tr>
<th></th>
<th>Heating</th>
<th>Cooling</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional system</td>
<td>0.98</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Solar cooling</td>
<td>1.1</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Trigeneration</td>
<td>1.9</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Solar-assisted trigeneration</td>
<td>2.1</td>
<td>1.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

1: Load ratio = 1:2 (cooling : heating), SEER = 3.0, efficiency of gas burner = 98 %
2: Load ratio = 1:2 (cooling : heating), COP = 0.57, Solar ratio = 70 % (cooling)
3: Load ratio = 1:2 (cooling : heating), COP = 0.57, Cogeneration ratio = 80 %
4: Load ratio = 1:2 (cooling : heating), COP = 0.57, Solar ratio = 24 % (cooling), Cogeneration ratio = max. 80 %

In this study, the solar cooling and trigeneration applications were combined to a new system concept called solar-assisted trigeneration. In cooling mode, the solar collector and a cogeneration unit drive an adsorption chiller and reach a PER comparable to solar cooling. In heating mode, the solar collector and cogeneration unit directly supply the heating system and reach a PER comparable to trigeneration. The aim of the present new system concept was to combine the advantages of solar cooling and trigeneration applications to an all-year energy efficient energy system and to evaluate, whether it is possible to omit the typically used inefficient backup heater.

Beside the energy efficiency, the cost performance was analyzed. Here we set out to find the most energy efficient combinations of each energy system, while simultaneously considering equal overall costs.

### Method

To examine the system concept a test facility was built at the University of Applied Sciences Kempten. Heating cartridges were used to emulate the heat sources solar collector, cogeneration unit and cooling load of a building (see Figure 1). With this flexibility, it was possible to change type and size of the different heat sources easily. The test facility was used to run characteristic testing days with different sets of parameters; one parameter was changed while all other conditions, for instance pathway of radiation and temperature of heat rejection, were kept constant. Among others, the influence of different collector sizes was analyzed. Also, different recooler types were tested under same conditions.

Based on the test facility, simulation models were built to perform annual simulations of the new system concept and the reference systems. For this, Matlab/Simulink 2007b [3] and partly Carnot Blockset r2009 [4] were used. The overall models of the energy systems apply both physical and parametric models. To increase simulation performance, physical models were used only for components, whose internal effects were important for the system or for which no measurement data were available. The parametric models were based on characterized values, which were validated by
measurements of the test facility. The dynamic calculation of the annual primary energy consumption took into account both the thermal and electrical loads of all main and auxiliary components.

With the results of the parametric studies on energy balance, we made parameter studies on cost performance according to VDI 2067 to check the equality of costs. The process of calculating the energy balance and the cost performance by changing the sizes of the main components was made iteratively for the solar cooling, trigeneration and solar-assisted trigeneration systems. The aim was to find the most energy efficient energy systems with the same cost performance as the conventional system. A summary of the methodology is shown in Figure 2.

**Figure 1:** Test facility at the University of Applied Sciences. Top left: dry water driven recooler, dry water/glycol driven recooler and open wet recooler. Right: heat and cold storage. Down left: hydraulic wall with heating cartridges, measurement equipment and adsorption chiller.

**Figure 2:** Methodology of the performed studies
Results

The component sizes of the most efficient combinations are shown in Table 2. The solar cooling system had a solar collector surface of 63 m², which matched a specific solar collector surface of 7 m² per kW cooling capacity. The heat storage had a volume of 3.5 m³; the specific storage volume was 56 liter per m² solar collector surface. With this combination the solar cooling system reached an all-year solar ratio between 58 % for Berlin (representative for Northern Germany), 62 % for Kempten (Southern Germany) and 76 % for Milan (Northern Italy); in cooling mode the solar ratio was between 77 % for Milan/Berlin and 97 % for Kempten.

Table 2: Combinations of the analysed energy systems

<table>
<thead>
<tr>
<th></th>
<th>Conventional system</th>
<th>Solar cooling</th>
<th>Trigeneration</th>
<th>Solar-assisted trigeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>solar collector</td>
<td>-</td>
<td>63 m²</td>
<td>-</td>
<td>18 m²</td>
</tr>
<tr>
<td>surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cogeneration</td>
<td>-</td>
<td>-</td>
<td>15 kW</td>
<td>12.5 kW (Kempten)</td>
</tr>
<tr>
<td>(thermal power)</td>
<td></td>
<td></td>
<td></td>
<td>11 kW (Berlin)</td>
</tr>
<tr>
<td>backup heater</td>
<td>gas burner</td>
<td>gas burner</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>chiller</td>
<td>9 kW (compression)</td>
<td>9 kW (adsorption)</td>
<td>9 kW (adsorption)</td>
<td>9 kW (adsorption)</td>
</tr>
<tr>
<td>heat storage</td>
<td>1 m³</td>
<td>3.5 m³</td>
<td>2 m³</td>
<td>2 m³</td>
</tr>
<tr>
<td>cold storage</td>
<td>1 m³</td>
<td>1 m³</td>
<td>1 m³</td>
<td>1 m³</td>
</tr>
</tbody>
</table>

The trigeneration system had a cogeneration unit with a thermal power of 15 kW and an electrical power of 6.8 kW. The ratio of cogeneration was 100 %; no backup heater was needed. To compensate load peaks, a relatively large heat storage with a volume of 2 m³ was used. The solar-assisted trigeneration system had a solar collector surface of 18 m², which matched a specific solar collector surface of 2 m² per kW cooling capacity. The cogeneration unit had a thermal power between 10 kW for Milan, 11 kW for Berlin and 12.5 kW for Kempten. With these heat source sizes it was possible to omit a backup heater. The heat storage had a volume of 2 m³. The solar-assisted trigeneration reached an all-year solar ratio between 22 % for Kempten/Berlin and 28 % for Milan.

We performed sensitivity analyses for energy and cost performance. The impact of the change of heat sources on the cost performance was small compared to predefined economical parameters, e.g. own use of generated electricity, rising prices of fuel and price development of investment costs. With the boundary conditions in Germany, it was possible to obtain combinations, where the cost performance of trigeneration and solar-assisted trigeneration was equal to that of the conventional system (see Figure 3). The costs of solar cooling, however, were 12 % (Kempten/Milan) and 19 % (Berlin) higher compared to the conventional system.
For the analyzed energy systems, the simulated PERs for Kempten are shown in Figure 4. In heating mode, the systems with a cogeneration unit reached the highest PER. The systems with a solar collector had always an advantage compared to each similar system: solar cooling (1.2) compared to conventional system (0.9) and solar-assisted trigeneration (2.4) compared to trigeneration (2.2). In cooling mode, solar cooling (1.5) reached the highest PER, followed by the solar-assisted trigeneration (1.2). The trigeneration (0.9) had almost the same PER as the conventional system (0.8). Combined to an all-year PER, the solar-assisted trigeneration (1.8) reached the highest PER, followed by the trigeneration (1.5), the solar cooling (1.2) and the conventional system (0.9).

For Berlin and Milan the results of the all-year PERs are shown in Figure 5. Except for solar cooling, cooling needs more primary energy than heating. For higher rates
of cold loads to overall loads the PERs decrease. For all three climate regions, PERs of the different systems behave comparably. The PER of solar cooling rises with higher rates of cold load and reaches a similar value as trigeneration for Milan. The solar-assisted trigeneration reaches always the highest PERs in all analyzed climate regions.

![Figure 5: Primary Energy Ratios (PERs) of the analyzed energy systems as a function of the rate of cold to overall load (Kempten, Berlin and Milan).](image)

**Conclusion**

If properly designed, the solar-assisted trigeneration reaches higher energy efficiency than the reference systems solar cooling, trigeneration and conventional system; with the boundary conditions in Germany it is possible to obtain combinations for the solar-assisted trigeneration, where the cost performance is equal to that of the conventional system. Compared to the conventional system, the solar-assisted trigeneration reached a primary energy reduction of 52% for Kempten, 51% for Berlin and 42% for Milan with simultaneous consideration of equal overall costs.

**Acknowledgement**

The authors acknowledge the financial support of the Bavarian State Ministry of Sciences, Research and the Arts. The results of this publication base on the work of the research project "InnoKKK – Renewable driven, innovative trigeneration", which was part of the Bavarian research cooperation „Energy efficient technologies and applications“ (FORETA).

**References**


