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Provision of cooling in Oman - a linear optimisation problem with special consideration of different storage options

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***Abstract*— The work analyses thermal and electrical solar cooling systems regarding the influence of energy storages using the open source tool open energy modelling framework (*oemof*). The systems are optimised with respect to lowest cost, considering various storage configurations and boundary conditions such as a required solar fraction. The results illustrate the importance of the different storage options on the size of the system components and the solar fraction. Optimal solar electrical cooling achieves solar fractions above 65%, optimal solar thermal cooling solar fractions above 87%, with a clear economic advantage for solar electrical cooling. Electrical energy storage suffers from high investment cost (compared to other storage options) and is not part of the cost optimal solutions. A sensitivity analysis shows, that even 50% decreased storage costs and increased electricity prices don't allow a profitable use of large electrical storages. To increase the solar fraction of solar electrical cooling to more than 65 % it is mandatory to use electricity storage. For both concepts, higher than cost optimal solar fractions can be achieved by increasing the respective storage sizes. Solar fractions of up to 95% are still economically reasonable. However, solar fractions above 98% result in an extreme cost increase.**

Keywords — *energy system analysis, optimisation, open-source model, oemof, solar cooling, energy storage*

I. Introduction

Climate change as well as scarcity of fossil resources limit the use of fossil fuels. Substitution of fossil fuels by renewable energy carriers and efficient use of energy carriers are two means to tackle these problems. Hence, optimal energy system design as well as optimal energy system operation are preferred: over- or undersized systems and components not only waste resources, they might even fail to cover the demand. Modelling of energy systems allows to assess a variety of system components in different scenarios and setups and therefore facilitates fast and cost efficient system analysis, benchmarking and optimisation.

The following case study of a solar cooling system in Oman is a typical example of a complex energy system with more than one energy carrier as input and more than one product as output: The system is designed to provide cooling for an office building, using solar energy, natural gas and electricity as possible inputs and producing electricity as by-product. Technical options inside the system are PV, solar thermal collectors and a gas boiler to provide the required input for a compression or an absorption chiller, respectively. Energy can be stored as heat, cold, or electricity, to balance the difference between cooling demand and solar input.

Such systems offer a broad range of optimisation opportunities, allocated to both fields: energy system design and energy system operation. Extensive investigations and optimisations are carried out, as Huang [1] summarizes. Typically, these investigations focus on physical quality criteria such as primary energy efficiency or CO_2-savings compared to a reference case. Commonly used software tools are e.g. TRNSYS, INSEL or Polysun, for the solar thermal and PV based systems, respectively. These tools focus on the physical aspects of the problem and lack dedicated examination of economics or the possibility to use economics in objective functions. As a consequence, economic analyses as e.g. presented by [2] are done subsequent to the optimisation, rather than being an integral part of it.

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Solar cooling is attractive for hot climates with high insolation, also from an economic point of view [3]. It is even likely to be the most economical solution due to the dramatic price decline of photovoltaics in the last years. Optimisation during pre-planning of cooling systems for these regions should therefore include economic as well as energy aspects. Linear, open source optimisation tools such as the open energy framework *oemof* [4] allow fast and transparent assessment of complex energy systems, using total annual costs as objective function. The results include effects of technical parameters and of the economic framework on the respective optimum and display the interdependencies of the components.

We used *oemof* to find cost-optimal designs of a solar cooling system in Oman. The cooling task was first presented by Cordes et al. [5], using solar thermal cooling. We extended the concept by adding a compression cooler and PV as alternatives and considering a broad range of different storage options. The analysis was led by the following four research questions:

1. Do larger storage sizes allow to decrease the size of other components without loss of comfort?
2. Is it more advantageous to increase the solar (heat / electricity) storage or the cold storage?
3. Which concept achieves the higher solar fraction, considering reasonable sizing of the components?
4. At identical solar fraction, which concept is more advantageous regarding total cost and required space for the collectors / PV modules?

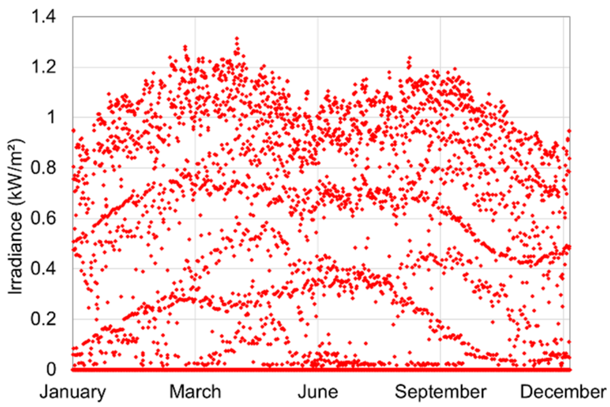

Fig. 1: Global irradiance, Muscat, Oman, Data [6]

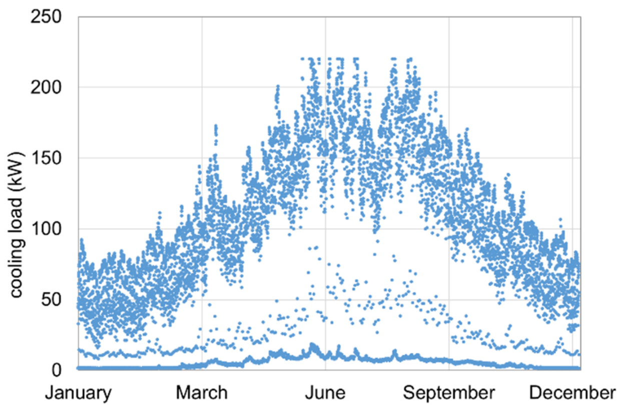

Fig. 2: Cooling load, Data [6]

II. SITE DATA AND DESIGN CONCEPTS

A. - Energy Supply and Cooling demand

The office building is located in Muscat, Oman. The cooling demand is elevated at day time and corresponds with the global irradiance.

Al Saadi et al. [6] calculated global irradiance in Muscat and the cooling load of the building with a temporal resolution of one hour (see Fig. 1and Fig. 2). These time series are used as input. The annual cooling demand is 721 GWh, the annual global irradiance 1970 kWh/m².

B. Solar Cooling Concepts

We assessed two solar cooling concepts, both summarized in Fig. 3.

Concept A, solar thermal cooling: Flat plate collectors and a gas boiler supply heat to an absorption chiller. Auxiliary electrical energy can be provided by PV panels or by the grid. Energy can be stored as heat and as cold in water tanks. This concept includes all items shown in Fig. 3 except the compression chiller.

Concept B, solar electrical cooling: PV panels and – if necessary – the grid provide electricity to power a compression chiller. Energy is stored as electricity in batteries and as cold in a water tank. This concept includes all blue and black components shown in Fig. 3.

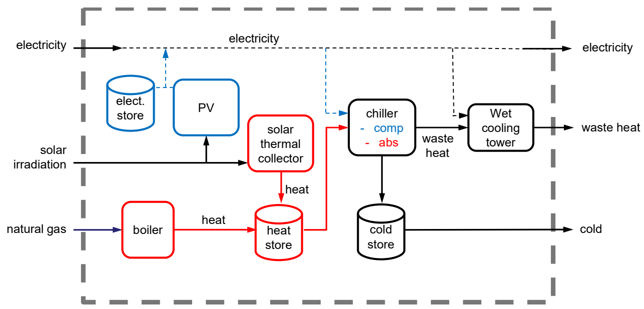

Fig. 3 System design

III. METHODOLOGY

The open source tool *oemof* (Open Energy Modelling Framework) is used for the optimisation. It allows to optimise energy systems with linear problems as well as with mixed-integer linear problems (MILP). The framework includes a variety of libraries to analyse diverse energy systems. At the current version, the tool set includes energy system components, optimisation libraries as well as tools to simulate feed-in from renewable energy sources or local heat demand for a specific region.

The optimisation aims at minimum total cost (initial investment and operational cost). The initial investment costs are distributed over the lifetime using the annuity method. Operational costs include the cost for electricity and gas as well as maintenance of the components.

Free parameters of the optimisation are either the size of components (investment / design optimisation) or the operation of components at given nominal size (dispatch optimisation). A combination of both, that is design optimisation for a number of components and dispatch optimisation of the remaining components, is possible as well. The simulation comprises one year, using a one hour time interval: the energy balance of all sources (electrical energy from the grid, solar irradiance, and gas) and sinks (surplus electrical energy to the grid, waste heat and cold) is calculated for every hour of the year. The storages are charged or discharge as needed.

A. Specifications and Modelling Assumptions

Table 1 and Table 2 summarise the technical and economic assumptions. The time series of the specific yield of the solar thermal collectors was pre-calculated by Cordes [7] and is directly used as input (in kWh/m²). The influence of the thermal storage size on the specific yield had to be neglected to comply with the linear modelling approach. The PV system is assumed as horizontally installed, its yield corresponds with the global irradiance.

TABLE 1: TECHNICAL ASSUMPTIONS

Heat and cold storage, losses	0,6%/h
Electrical storage, efficiency	85 %
Cooling tower, electrical demand	0,02 kWel / kWth
Absorption chiller, $COP_{thermal}$	0,65
Absorption Chiller, $COP_{electrical}$	44
Compression chiller, COP	3,5
Gas boiler, efficiency	95 %

In our study, we assess the influence of the different storage options and their sizes on the system, not the absolute cost of the system. Additional cost components such planning, piping or controls are neglected due to limited data availability; if needed they could be assumed as constant fraction of the total investment cost. This approach allows conclusions which set-up is more or less costly, but no precise cost estimate. It is sufficient to rate the systems and storage designs.

TABLE 2: ECONOMIC ASSUMPTIONS

Component	Specific investment cost	Life time (a)	Operational cost (% investment cost)
Solar thermal collector	130 €/ m²	20	2
Absorption chiller	300 €/kW	18	3
PV	1000 €/ kW_p	25	2
Compression chiller	350 €/kW	15	3,5
Gas boiler	100 €/kW	20	3
Cooling tower	30 €/kW	20	3,5
Heat storage	20 €/kWh	20	1
Cold storage	40 €/kWh	20	1
Electricity storage	400 €/kWh	20	1

Interest rate	6%
Price electricity	0,10 €/kWh
Electricity to grid	0 €/kWh
Price gas	0,04 €/kWh

B. Reference Scenario & Parameter Variations

The first step is a complete design optimisation for both concepts, resulting in two reference set-ups, each with the lowest total cost to supply the required cold demand with solar thermal or solar electric cooling, respectively. In this step, the rated power of the chiller, PV, cooling tower and boiler as well as the area of the solar collectors and the capacities of all storage options are free parameters; their values are determined through optimisation (all simultaneously).

Secondly, a set of variations of storage sizes is calculated, starting with these reference cases. The results are used to assess the influence of the storages on the system. Consequently, the size of the storages is fixed (operation optimisation), while the size of the remaining components is determined through optimisation (design optimisation). Table 3 summarises the bandwidths of these variations.

TABLE 3: VARIATION OF STORAGES

Cold storage [kWh]	200	300	500	750	1000	1250
	1500	2000				
Thermal storage [kWh]	500	750	1000	1250	1500	2000
	2500	3000	4000	5000	7500	
electric storage [kWh]	25	50	100	150	200	300
	400	500	750	1000		

The 3rd and 4th set of calculations cover fixed solar fractions and sensitivity analyses regarding energy prices (electricity and gas) and investment costs (electrical storage). The size of all components is determined through optimisation for a respective solar fraction (3rd set) and given investment cost and energy prices (4th set). The resulting sizes of the components represent the economical optimum considering these boundary condition. Since the high investment costs of the electrical storage are a barrier for its economic implementation, we assessed their influence by varying the investment cost of the electricity storage from 50% and 100% of the base costs given in Table 2. Moreover, the prices for electricity and gas are variated between 75% and 125% of the prices in the base case.

C. Optimisation Output & Assessment Criteria

Every single optimisation calculation delivers a cost optimal design of the components in design optimisation mode, the total annual costs and the annual energy balances. For the storage size variations, these results cover the rated power of the chiller, the boiler and the PV panels as well as the size of the solar thermal collectors.

The solar fraction is defined as ratio of energy delivered by the solar component (Solar heat Q_{sol} for concept A, solar electricity $W_{el,PV}$ for concept B) and total heat / electricity input. The remaining fraction (1-SF) is provided as non-renewable energy: heat from the gas boiler or electricity from the grid, respectively.

$$SF_{C1} = \frac{Q_{sol}}{Q_{sol} + Q_{boiler}} \qquad eq\ (1)$$

$$SF_{C2} = \frac{W_{el,PV}}{W_{el,PV} + W_{el,grid}} \qquad eq(2)$$

As stated above, the calculated total annual costs are not representative due to missing cost components. We refrain from giving absolute cost figures but use the total annual cost C relative to the total annual cost of the reference scenario C_{ref}: as economic assessment criterion.

$$c = \frac{C}{C_{ref}} \qquad eq(3)$$

Derived assessment criteria such as collector area A_{coll} per chiller power $\dot{Q}_{chill}$ or storage size (volume) V_{st} per collector area, as proposed by Eicker et al. [8], are used to compare the technical results with literature.

$$a_{coll} = \frac{A_{coll}}{\dot{Q}_{chill}} \qquad eq(4)$$

$$v_{st} = \frac{V_{st}}{A_{coll}} \qquad eq(5)$$

Relative storage capacities q_{st} with reference to the chiller power and the collector area are used additionally (Q_{st}: storage capacity in kWh).

$$q_{st,ch} = \frac{Q_{st}}{\dot{Q}_{chill}} \qquad eq(6)$$

$$q_{st,col} = \frac{Q_{st}}{A_{coll}} \qquad eq(7)$$

IV. Results

A. *Reference Scenarios – Cost Optimal Solutions*

A reference scenario is the cost optimal solution of the respective problem. Accordingly, we determined two reference scenarios, one for each design concept (solar thermal and solar electrical cooling, respectively), summarised in Table 4. Both chillers have the same power of approximately 200 kW, which is 10% lower than the maximum load. This difference is facilitated by the cold storages each with a relative storage capacity of about 2kWh/kW$_{chill}$. Interestingly, the electrical storage is not included in either reference case due to its high cost. Solar thermal cooling achieves a more than 21%-points higher solar fraction than solar electrical cooling. It includes a thermal storage with a relative storage capacity of 1.3 kWh/m$^2_{koll}$.

Table 4: Reference scenarios

	Concept A – solar thermal cooling	Concept B – solar electrical cooling
Absorption chiller, power	197 kW	n.a.
Compression chiller, power	n.a.	196 kW
Gas boiler, power	156 kW	n.a.
Solar thermal collector, area	1148 m²	n.a.
PV, power	19 kWp	81 kWp
Cold storage, capacity	393 kWh	418 kWh
Electrical storage, capacity	0 kWh	0 kWh
Heat storage, capacity	1496 kWh	n.a.
Solar fraction	87.5 %	65.8 %
Fraction of electricity, which fed to the grid	6.3 %	6.3 %

B. *Interaction Storage Size – Cooling Power & Size of Solar Collectors - Do larger storage sizes allow to decrease the size of other components without loss of comfort?*

Fig. 4 and Fig. 5 show the dimensions of two main components of concept A, the chiller and the solar collector, for different storage capacities. Large thermal storages (size of reference scenario or larger) allow to decrease the chiller size with increasing cold storage. The lowest value is 150 kW, about ¾ of the size required in the reference scenario. This minimum size results from the demand, balanced by the respective cold storage.

For smaller thermal storages, the chiller capacity increases with increasing cold storage capacities, to use more thermal energy from the collectors directly and to avoid a high usage of gas. This reduces the load factor of the chiller, which impairs the operation of the chiller. Thus a minimum capacity of the thermal storage is strongly recommended.

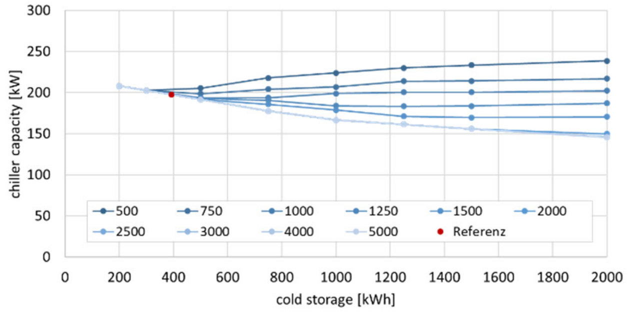

Fig. 4: Concept A: solar thermal cooling, chiller capacity depending on cold storage (abscissa) and heat storage (different lines). Reference: red dot.

The collector area depends mainly on the size of the thermal storage (see Fig. 5): It increases with increasing storage capacities up to a saturation. The cold storage capacity has an influence for small thermal storages only, increasing the collector area with increasing cold storage capacity.

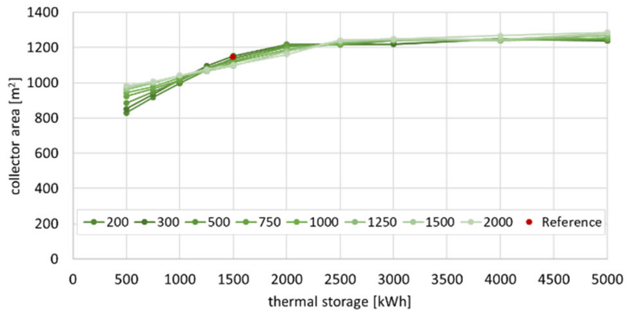

Fig. 5: Concept A: solar thermal cooling, collector area depending on thermal storage (abscissa) and cold storage (different lines). Reference: red dot.

Fig. 6 and Fig. 7 show the dimensions of two main components of concept B, the chiller and the PV system, for different storage capacities.

The size of the compression chiller depends solely on the cold storage capacity: It decreases with increasing storage capacities (Fig. 6), reaching a minimum value of less than 150 kW for a cold storage which is about 5 times larger than the one in the reference scenario.

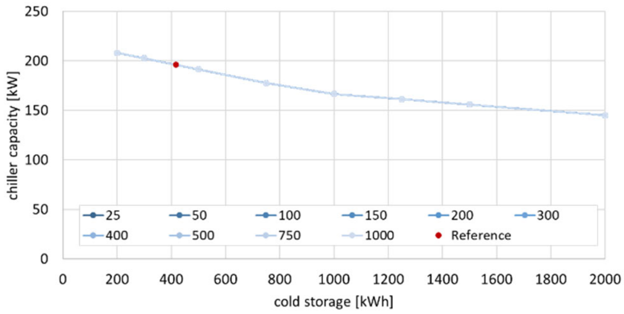

Fig. 6: Concept B: solar electrical cooling, chiller capacity depending on cold storage (abscissa) and electrical storage (no influence, all lines are identical). Reference: red dot.

The PV capacity increases with increasing electrical storage capacity (see Fig. 7).

It features a clear maximum for medium sized cold storages (300 – 500 kWh) and electrical storage capacity below 200 kWh. The maximum can be explained as follows: A small cold storage (<200kWh) is loaded fast; and surplus solar energy from a large PV installation would have to be dumped due to insufficient electrical storage capacity. Thus, large PV installations together with small cold storages are economically not viable. Increasing the cold storage size allows to increase the PV installation, since more energy can be stored. However, large cold storages lead to smaller chiller capacities (see Fig. 7). If a large PV installation feeds such a small electrical chiller, it is oversized and again a fraction of the solar energy would have to be dumped. Consequently, the PV capacity decreases when the cold storage capacity exceeds the optimal size. The optimal cold storage capacity depends on the capacity of the electrical storage: The maximum moves to lower cold storage capacities and larger PV installations with increasing electrical storage capacity. The reference case is located outside of the storage size variations, since it resulted in zero electrical energy storage.

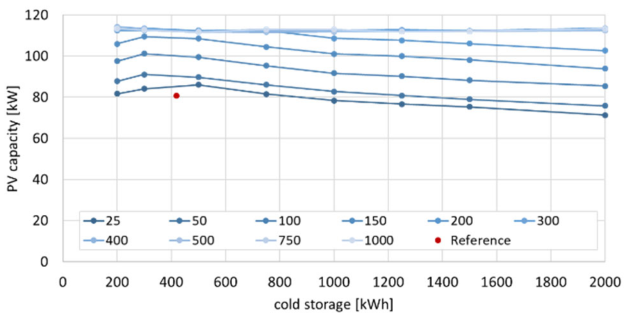

Fig. 7: Concept B: solar electrical cooling, PV capacity depending on cold storage (abscissa) and electrical storage (different lines). Reference: red dot.

C. Assessment of Storage Options

Fig. 8 shows the solar fraction achieved with concept A for variable heat and cold storage sizes. The solar fraction increases with both, increasing heat and cold storage. However, the sensitivity towards the heat storages is higher, and the influence of the cold storage even disappears for large heat storages.

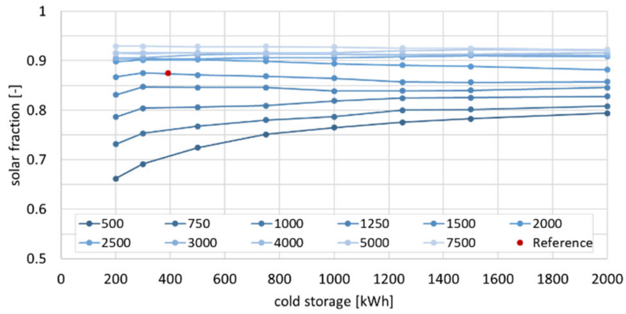

Fig. 8: Concept A: solar thermal cooling, solar fraction depending on cold storage (abscissa) and heat storage (different lines). Reference: red dot.

Fig. 9 displays the corresponding costs, relative to the reference scenario. As expected, the costs increase for storages sizes other than in the reference scenario: smaller as well as larger storages size lead to higher total costs. However, the sensitivity is higher towards heat storage capacity, and especially too large heat storages increase the total cost. Doubling the sizes of the storages compared to the reference case increases the total cost by 5% (thermal storage) and 2% (cold storage). A reduction of the storage sizes by 50% increases the costs by 4% (heat storage) and less than 1% (cold storage), respectively.

Consequently, the size of the thermal storage should be determined with great care. Too small thermal storages do not only increase the total cost, but also decrease the solar fraction. The size of the thermal storage in the reference case corresponds to a relative storage size of 12 kWh_{th}/kW_{cool}. Relative storage sizes in the range of 6 – 12 kWh_{th}/kW_{cool} and 1.3 – 1.7 kWh_{th}/m^2 collector lead to reasonable costs and solar fractions.

The cold storage has little influence on the solar fraction, however, too small cold storages increase the total costs. An adequate cold storage capacity is in the range of 400 – 500 kWh.

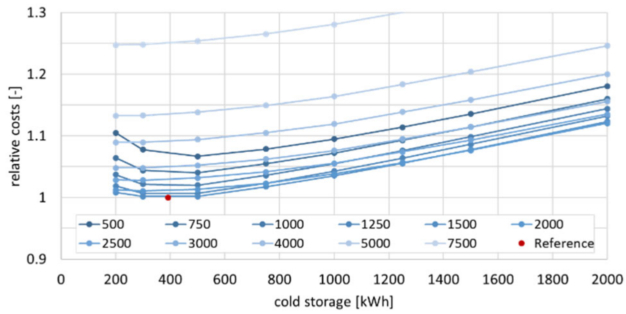

Fig. 9: Concept A: solar thermal cooling, relative costs depending on cold storage (abscissa) and heat storage (different lines). Reference: red dot.

Fig. 10 confirms the findings of concept A for concept B: an increase of solar storage capacity (here: electrical storage) leads to increasing solar (here: PV) systems (see Fig. 7) and increasing solar fractions.

Again, an optimal cold storage capacity with maximum solar fraction is identified, but only for small electrical storages. This maximum moves from 500 kWh to smaller values for increasing electrical storage capacities and disappears for large electrical storage capacity.

Fig. 11 confirms that cold storage capacities of 300 – 500 kWh also lead to cost minima for the respective electrical storage.

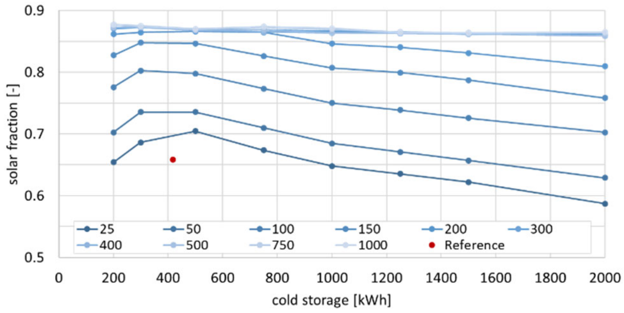

Fig. 10: Concept B: solar electrical cooling, solar fraction depending on cold storage (abscissa) and electrical storage (different lines). Reference: red dot.

Solar fractions above 70% require electrical storage, although the use of electrical storage is in no case the most economical solution, as Fig. 10 and Fig. 11 show. A reasonable trade-off is an electrical storage capacity of about 200 kWh, which increases the total costs only ca. 10 % and allows a solar fraction of 80%.

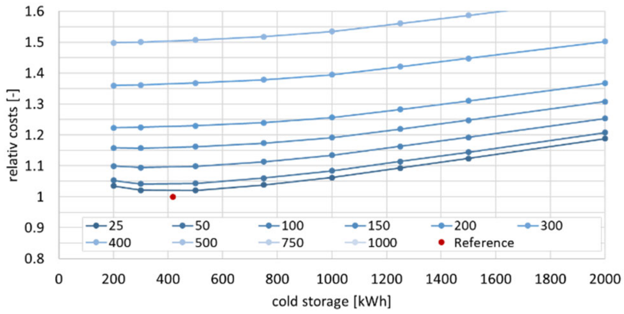

Fig. 11: Concept B: solar electrical cooling, relative costs depending on cold storage (abscissa) and electrical storage (different lines). Reference: red dot.

The considerations of the preceding paragraphs result in the following reasonable storage designs for the two concepts: Solar thermal cooling with 1500 kWh heat and 500 kWh cold storage capacity achieves a solar fraction of 87%. This design corresponds to the reference case and represents the most economical solution for this concept.

Solar electrical cooling with 200 kWh electrical and 500 kWh cold storage also achieves a solar fraction of 87%. Although this is not the most economical solution for this concept, the increase in solar fraction justifies the (moderate) additional costs. Larger electrical storage capacity can not be justified with corresponding increases in solar fraction, while the total costs escalate.

D. Assessment of Solar Cooling Options

We used three criteria to assess the two solar cooling concepts: solar fraction, total costs and area needed for the solar collectors and the PV, respectively. Fig. 12 shows total costs relative to a reference, solar thermal cooling with a solar fraction of 100%. Each dot in the graph represents the cost optimal designed system which achieves the required solar fraction. The figure includes the reference scenarios for solar thermal cooling (solar fraction 87.5%) and for solar electrical cooling (solar fraction 65.8%).

Both concepts are able to deliver high solar fractions up to 100 % (see Fig. 12). The total costs increase up to a solar fraction of 99% almost linearly, higher solar fractions lead to a steep increase of costs. This steepness is more pronounced for solar thermal cooling, while the linear increase shows a higher gradient for solar electrical cooling.

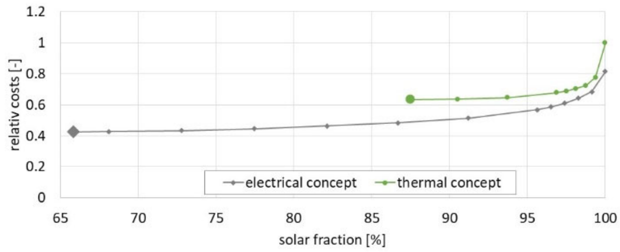

Fig. 12: Concept comparison. Relative cost of both concepts for different solar fractions. Cost reference: solar fraction 100%, solar thermal cooling. Enlarged symbols: reference scenarios.

The concepts differ only slightly regarding area needed to harvest solar energy. Reasonable dimensions are a collector area of 5-8 m^2/kW_{cool} (reaches solar fractions of 85 – 95%) and specific PV power of 0,4-0,8 kW_p/kW_{cool} (reaches solar fractions of 65 – 95%).

E. Cost Sensitivity Analysis

Cost assumptions affect the results of the optimisation. For instance, electrical storage was not present in any reference case due to its high initial investment costs. We investigated the influence of two cost assumptions: the gas price for concept A and the investment costs for electrical storage (concept B). All components were in design optimisation mode, so their optimal size was determined for the respective economic environments.

For solar thermal cooling, the optimal solar fraction increases with increasing gas price (see Fig. 13). A 25% higher gas price yields 3% (percentage points) higher optimal solar fraction; a 25% lower gas price lowers the optimal solar fraction by 4% (percentage points).

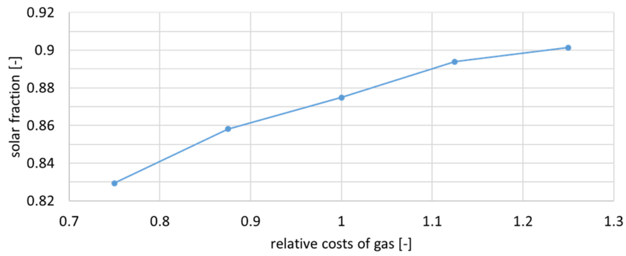

Fig. 13: solar fraction of concept A for different gas prices

Fig. 14 shows the optimal electrical storage capacity for variable energy prices and sinking storage costs. It allows to determine the required drop of investment cost of electrical storage to make it economically viable. We determined this limit for different energy prices, ranging up to 125% of the initial energy price assumption.

The maximum electrical energy storage capacity is about 50 kWh, which still only ¼ of the storage capacity needed to reach high solar fractions. It requires 25% increase of energy prices and a simultaneous cost drop of 50% for electrical energy storage.

With current energy prices, electrical energy storage is no fast-selling item: Its costs need to decrease at least 40% to become economically viable, a future energy price scenario still requires a minimum 10% decrease. By reaching these cost limits, the optimal electrical storage size increases only gradually, not abruptly.

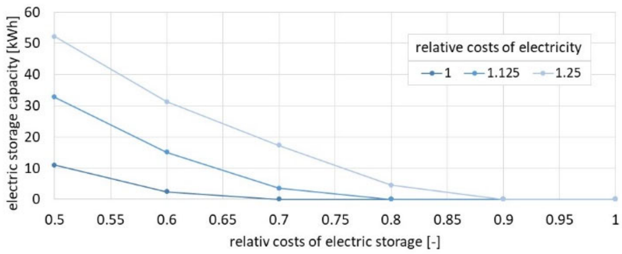

Fig. 14: Concept B: solar electrical cooling: electric storage capacity depending on relative costs of electrical storage (abscissa) and relative energy prices (different lines).

V. Conclusions & Summary

The storage size has significant influence on the size of the remaining components, e.g. the optimal chiller size shrinks by 25%, when the cold storage capacity quadruples. The proportion of the storage types does not solely depend on the ratio of the respective investment cost; demonstrated by the almost identical optimal cold storage capacity in both concepts. The reference cases result in solar fractions of 87% (solar thermal) and 66 % (solar electrical). The total annual costs in these reference cases are significantly lower for solar electrical cooling than for solar thermal cooling

High solar fractions (>70%) require storage of solar energy. This is already economically viable for solar thermal cooling, storage of thermal energy is reasonably priced. Solar electrical cooling has to deviate from its economic optimum to reach high solar fractions due to the costly electrical energy storage.

Hence, higher than cost optimal solar fractions call for a trade-off with economics – reasonable solutions can be determined by using a tool such as *oemof*, which considers both, energy and cost flows.

Still, solar electrical cooling is superior to solar thermal cooling considering the total annual cost, even for identical solar fractions. This cost gap shrinks with increasing solar fraction.

The cost sensitivity analyses confirmed the influence of cost assumptions on the optimal design. As expected, optimal solar fractions rise with increasing energy prices. The most surprising result is the optimal size of the electrical storage, which is zero for the considered economic framework. The cost of electrical energy storage would need to drop almost by 50% to make it economically attractive. However, this result has to be treated with care. It is only valid for the assessed cost assumption, further research is needed for validation. Again, these validations will have to consider both, cost and energy flows, simultaneously.

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