ENERGY HUB MODELING FOR THE DESIGN OF SOLAR THERMAL ENERGY SYSTEMS WITH SHORT-TERM AND LONG-TERM STORAGE

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ABSTRACT

A mixed integer linear programming (MILP) energy hub model is developed to design a solar thermal district-heating network for a cluster of residential buildings in Rheinfelden, Switzerland. The model is employed to determine the area of roof-mounted solar thermal collectors that are required to meet the space heating and domestic hot water loads of the 11 buildings in the neighborhood. The installation and operation of electric heaters is permitted in order to supply back up heat during periods when the solar energy is not sufficient to meet thermal loads. The results of the energy hub model show that thermal energy storage (TES) is required in order to achieve solar fractions (i.e. the percentage of total energy demand that is met by solar energy) that are over 10%. Furthermore, the volume of required TES increases exponentially with the solar fraction. Due to the seasonality of space heating demand, the installation of short-term storage tanks alone is not sufficient for achieving solar fractions that are above 60%, and long-term TES units are also required. However, even when both short-term and long-term TES units are installed, 100% solar fraction is still not possible due to the loss of heat in the TES units over time. Finally, for the size and characteristics of the neighborhood analysed in this study, the decentralised storage configuration with both short-term and long-term storage units results in a cheaper energy system with a higher solar fraction, when compared with the centralised storage configurations.

Keywords: solar thermal, thermal energy storage, energy hub, optimisation, MILP

INTRODUCTION

Space heating accounts for around 70% of the final energy consumption in Swiss households. Therefore, as Switzerland looks towards its 2050 CO_2 emission targets which require an 80% reduction in per capita annual CO_2 emissions, there is a pressing need to increase the utilisation of energy efficient and renewable heating sources in the residential sector. Solar thermal collectors are an ideal candidate technology due to the abundance and sustainability of solar energy. However, in order to maximize the utilisation of solar energy, thermal energy storage (TES) is required as heating demand is typically not coincident with the availability of solar radiation. There are numerous decisions that must be made when designing these solar thermal + TES systems for residential quarters. These include determining the optimal solar thermal collector area, the required number and volume of TES units, and deciding whether the storage should be decentralised, with a TES unit located at each building, or centralised, with only a single TES unit that supplies all buildings through a district heating network. To facilitate this decision making, an energy hub model is developed in this paper to design a solar thermal district-heating network for a cluster of residential buildings. The energy hub concept, developed by [1] is a macro-level framework that is used to model the flow, conversion, and storage of multiple energy carriers within an energy system, in order to facilitate system design and unit scheduling. Energy hub models are typically developed using mixed integer linear programming (MILP) formulations composed of linear equations that describe the conversion of input energy streams (e.g. electricity, solar radiation) to output energy streams (e.g. electricity loads, space heating loads).

The model developed in this paper is used to determine the area of roof-mounted solar thermal collectors and the volume of short-term and long term thermal energy storage units that are required in order to meet the hourly space heating and domestic hot water loads of the buildings in the neighborhood over the course of a single year. In order to ensure that the simplified energy hub formulation is able to represent the typical performance of these systems, the energy hub model is first validated against dynamic simulation models developed in EnergyPlus of the solar thermal + TES systems that are optimised for each building. It is then employed to analyse the influence of the storage configurations by comparing the annual economic cost and renewable energy utilisation of the following system configurations, 1) no storage, 2) decentralised short-term storage only and no long-term storage, 3) decentralised short-term and decentralised long-term storage, and 4) decentralised short-term and centralised long-term storage.

METHODS

An 11 building neighborhood in Rheinfelden, Switzerland was used as a case study to analyse the influence that numerous factors have on the design of solar thermal + TES systems. Three building types, single-family house (SFH), attached single-family house (aSFH), and apartments, are present in the neighborhood. EnergyPlus was employed to simulate the heating demand by utilizing the building geometries and surfaces construction materials, in combination with local weather and internal gains to determine the additional energy required to maintain an indoor air temperature set point of 20°C. It was assumed that building renovation measures were implemented in compliance with SIA 380/1 [2], while mean air temperature was set to comply with Swiss standard indoor air temperature [3]. Internal gains from occupancy, electricity appliance usage, and lighting are accounted for with respect to activity schedules taken from Swiss standards [3]. Figure 1 depicts the layout of the neighborhood, while Table 1 summarises the pertinent information about each of the buildings in the neighborhood.

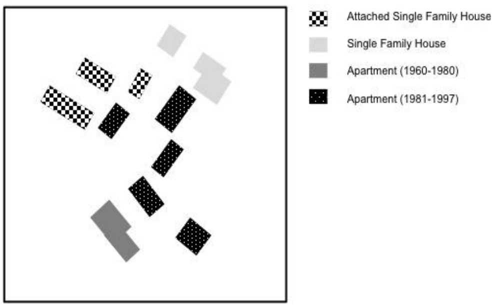

Figure 1: Layout of the 11 buildings in the quarter

Table 1: Summary of Building Information for Rheinfelden Neighborhood

		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	Total
Building Type		aSFH	SFH	SFH	Apartments						aSFH	aSFH	
Heated Area	**m^2**	286	842	407	1745	735	945	713	945	880	1100	902	*9500*
SH Demand	**MWh/yr**	8.1	23.1	7.7	25.7	8.9	13.2	10.3	13.5	16.2	21.6	11.9	*160.2*
DHW Demand	**MWh/yr**	2.6	7.5	3.6	17.6	7.4	9.5	7.2	9.5	8.9	9.8	8.1	*91.6*
Available Roof Area	**m^2**	115	211	102	218	92	189	143	252	176	183	150	*1831*

Figures 2(a-c) depict the energy hub structures for the four scenarios that were modeled. In the first scenario, No Storage (Figure 2a), there is no TES unit; therefore the solar thermal collector can only generate thermal energy when there is a demand for either space heating or domestic hot water. An electric heater, run on electricity that is purchased from the grid, is utilised during periods when there is not enough solar energy to meet demand. In the second scenario, Decentralised One Tank (Figure 2b), there is one short-term storage tank supplying heat for both space heating and domestic hot water, the electric heater is again present to supply the energy loads that cannot be met by the solar collector. The third and fourth scenarios, Decentralised and Centralised Two Tank, have the same energy hub structure (Figure 2c) in which both short-term and long-term storage tanks are charged by the heat transferred from the solar collectors, through a buffer tank. The heat stored in short-term tank is used to supply domestic hot water, while the heat stored in long-term tank is used to supply space heating. The first three scenarios are all decentralised scenarios, in which there is an energy hub at each of the 11 buildings with no energy distribution between buildings, while the fourth scenario is the centralised case, with a single energy hub at building 4 and distribution of energy to all buildings through a district-heating network.

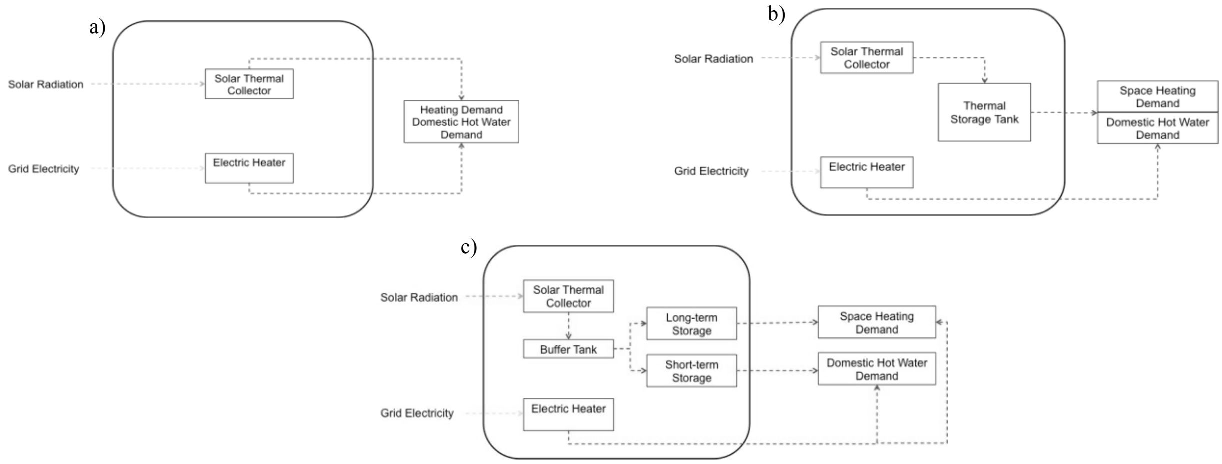

Figure 2: Energy hub structures for the four model scenarios, a) No Storage, b) Decentralised One Tank, c) Decentralised Two Tank and Centralised Two Tank.

The energy hub model contains both integer and continuous decision variables that are indexed over 5 sets, b, b', h, i, and k. b denotes the buildings in the quarter that generate energy, b' denotes the buildings that consume energy, h denotes the 8760 hourly time intervals that make up the 1 year analysis period, i denotes the technologies that can be included in the energy system (i.e. solar thermal collectors (ST) and electric heaters (EH)), and k denotes the types of storage (i.e. short-term (Short) or long-term (Long)). The model contains two integer decision variables, the number of units of technology i purchased at building b ($U_{i,b}$) and the active/inactive status of the district heating network connection between buildings b and b' ($L_{b,b'}$). The continuous variables in the model are the amount of heat generated by technology i at building b during hour h ($G_{i,h,b}$), the quantity of heat distributed from building b to building b' during hour h ($D_{h,b,b'}$), the electricity that each building b' purchases during each hour h ($EP_{h,b'}$), the amount of energy stored in storage k at building b during hour h ($Q^{stored}_{h,b,k}$), the amount of energy charged into storage k at building b during hour h ($Q^{ch}_{h,b,k}$), the amount of energy discharged from storage k at building b during hour h ($Q^{dish}_{h,b,k}$), and the quantity of heat lost from storage k at building b during hour h ($Q^{storeloss}_{h,b,k}$). The objective function (Eqn. 1) is to minimise annual economic cost of the energy system, which is the sum of the electricity and fuel costs (C_{elec} and C_{fuel}), operational and maintenance costs (C_{om}), amortised technological capital and installation costs ($C_{capital}$), amortised network cost ($C_{network}$), and the amortised storage cost (C_{store}).

$$\mathbf{min}\ C_{fuel} + C_{elec} + C_{om} + C_{capital} + C_{network} + C_{store} \tag{1}$$

The objective function is minimised subject to the following constraints. Firstly, the generation of thermal energy by each technology i is bounded by the maximum capacity of the technology ($MaxCap_i$) multiplied by the number of units of the technology that have been purchased at each building (Eqn. 2).

$$G_{i,b,h} \leq MaxCap_i \cdot U_{i,b} \qquad \forall i, h, b \quad (2)$$

Additionally, the space heating demand ($Heating_{b',h}$) at each building b' during every hour h must be equal to the amount of energy distributed to the building from all buildings b during hour h (Eqn. 3). The amount of energy distributed from each building b to all buildings b' is equal to the amount of energy discharged from the TES units at building b plus any additional energy generated by the auxiliary electric heaters (Eqn. 4). Distribution heat losses are not explicitly modeled in this energy hub formulation. Instead a fixed heat loss value of ($Q^{distloss} = 4.3\%/\text{km}$) [4] is employed to take into account the losses that occur within the district heating network pipes.

$$Heating_{b',h} = \sum_b D_{h,b,b'} \qquad \forall h, b' \quad (3)$$
$$\sum_{b'} \left(D_{h,b,b'} / \left(1 - Distance_{b,b'} \cdot Q^{distloss}\right)\right) = Q^{disch}_{h,b,k} + \sum_i G_{i,b,h} \qquad \forall h, b, k, i = EH \quad (4)$$

Similarly, the domestic how water demand ($DHW_{b',h}$) at each building b' must be equal to the energy discharged from the storage k plus any energy generated by the electric heater (Eqn. 5). For the one tank scenario both space heating and domestic hot water loads can be met by the energy discharged from the single tank, and there is only one type of auxiliary electric heater installed. However, for the two tank scenarios, the short-term storage tank can only be used to supply domestic hot water loads, and the long-term storage tank can only be used to supply space-heating loads. Furthermore, a differentiation is made between the auxiliary electric heaters that are used to supply the space heating loads, and those that are used to supply the domestic hot water loads.

$$DHW_{b',h} = Q^{disch}_{h,b,k} + \sum_i G_{i,h,b} \qquad \forall h, b', i = EH \quad (5)$$

Finally, the energy that is used to charge the storage tanks at each building b in every hour h is equal to the amount of energy generated by the solar thermal collectors at building b in hour h (Eqn. 6). The upper bound on this solar energy generation is calculated by multiplying the number of solar thermal collector units that are installed at each building ($U_{i,b}$) by the area of each collector ($Area_i$), the efficiency of each collector (η_i), and the amount of incident solar radiation ($Solar_h$) (Eqn. 7).

$$G_{i,b,h} = \sum_k Q^{ch}_{h,b,k} \qquad \forall h, b, i = ST \quad (6)$$
$$G_{i,b,h} \leq U_{i,b} \cdot Area_i \cdot \eta_i \cdot Solar_h \qquad \forall h, b, i = ST \quad (7)$$

Although the optimisation is a cost minimisation, the emissions are controlled using the ϵ constraint method in which a constraint is used to set an upper bound on the allowable system emissions based on the maximum CO_2 emissions that the system can produce ($MaxCO2_{b'}$) (Eqn. 8). The value of ϵ can then be reduced from 1 to 0 in order to find least cost solutions that lead to increasingly smaller CO_2 emissions.

$$\sum_h GridCO2EmissionFactor \cdot EP_{h,b'} \leq \epsilon \cdot MaxCO2_{b'} \qquad \forall b' \quad (8)$$

The thermal energy storage model employed is adapted from [5] in which the amount of energy stored in each hour h is a function of the amount of energy stored in the previous hour ($Q^{stored}_{h,b,k}$), plus any energy charged into the storage ($Q^{ch}_{h,b,k}$), minus any energy discharged from the tank ($Q^{dish}_{h,b,k}$), minus storage losses ($Q^{storeloss}_{h,b,k}$) (Eq. 9). Both the charging and discharging efficiencies (η^{ch}_k and η^{disch}_k) are assumed to be 90%.

$$Q_{h,b,k}^{stored} = Q_{h-1,b,k}^{stored} + \eta_k^{ch} \cdot Q_{h,b,k}^{ch} - \frac{Q_{h,b,k}^{dish}}{\eta_k^{disch}} - Q_{h,b,k}^{storeloss} \qquad \forall h,b,k \quad (9)$$

Storage losses are calculated using the two parameter heat loss expression developed by [5] in which the hourly heat losses are a function of the amount of energy stored in the previous hour as well as static losses from the unusable energy in the tank (Eqn. 10).

$$Q_{h,b,k}^{storeloss} = Q_{h-1,b,k}^{stored} \cdot \theta_k^{store} + Q_{b,k}^{capacity} \cdot \left(\frac{T_k^{min} - T_k^{amb}}{T_k^{max} - T_k^{min}}\right) \cdot \theta_k^{static} \qquad \forall h,b,k \quad (10)$$

The MILP model is solved using the AIMMS Software program, which is an optimisation software program that uses the CPLEX solver. CPLEX employs a branch and bound algorithm to solve the MILP.

RESULTS AND DISCUSSION

In order to first validate the energy hub model, the solar thermal collector area was fixed at the maximum available roof area for each building and the resulting short-term and long-term storage volume sizes were determined. These design specification were then used to create dynamic simulation models for each building in EnergyPlus [6]. The system performance of the energy hub models and the corresponding EnergyPlus models were then compared in order to determine if the simplifications that are made in the linear energy hub model have a significant impact on the performance of the energy system. Solar fraction (SF) was chosen as the metric of comparison. Solar fraction, defined as the percentage of the total annual energy demand that is satisfied by solar energy, is calculated as SF = 1 – ($Generation_{ElecticHeater}$/Total Energy Demand). Figure 3 shows the solar fraction comparison of the energy hub and EnergyPlus models for the individual buildings in the three decentralised scenarios. The comparison shows that although the energy hub model is not always able to achieve solar fractions that are equal to the results of the more detailed EnergyPlus model, it typically leads to results that are within 10% of the EnergyPlus output. Additionally models show a similar trend of increasing solar fractions when going from no storage to only a short-term storage tank to both short-term and long-term storage tanks for most of the buildings.

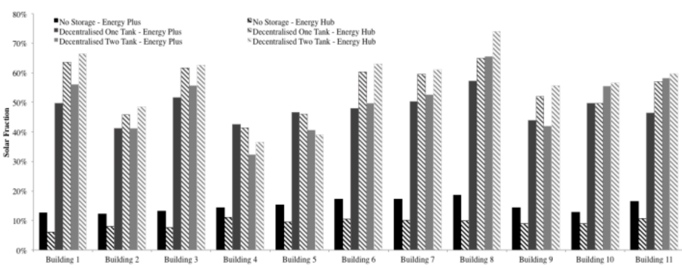

Figure 3: Comparison of solar fraction results for energy hub and EnergyPlus models for the three decentralised scenarios

In Figure 4a the aggregated optimal solar thermal collector area and required short-term and long-term storage volumes for the whole Rheinfelden neighborhood are plotted with the resulting solar fraction for the different energy hub scenarios at multiple ϵ constraint values. An increase in the solar thermal collector area and short-term and long-storage volumes leads to an increase in the solar fraction. Figure 4b shows a graph of the aggregated solar fraction and resulting total annual cost of the optimal energy systems for the entire neighborhood in all four scenarios at multiple ϵ constraint values. In the No Storage scenarios, the solar fraction does not increase beyond 10%, however, the addition of a short-term storage tank can result in solar fractions of up to 60%. When long-term storage is also available, the solar fraction can reach 90%. Increasing storage volume results in the longer storage of solar energy, which facilitates the increased utilisation of solar and thus higher solar fractions. For this quarter, the results in Figure 4b also indicate that centralisation of storage does not result in the energy system with the highest solar fraction. This is likely due to high heat losses, both in the large centralised long-term storage tank, but also due to additional heat losses in the district heating network pipes.

a) b)

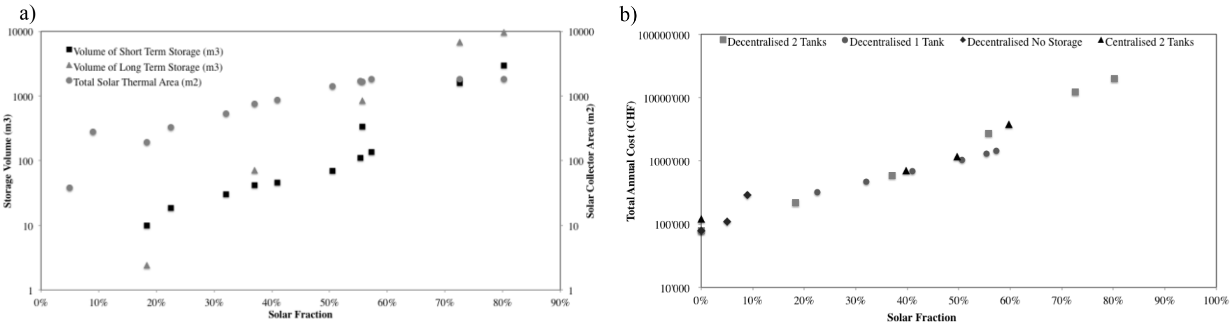

Figure 3: a) Solar thermal collector area, short-term storage volume, and long-term storage volume corresponding to the different solar fractions, b) Solar fraction and resulting annual cost of different scenarios

CONCLUSION

In this study, an energy hub model was developed in order to design the solar thermal energy system for a neighborhood in Rheinfelden, Switzerland. While dynamic simulation models are useful for accurately modeling the temperature dependent system performances, linear energy hub models were found to be an adequate simplification that facilitates optimal sizing of the system components. The temporal mismatch between thermal energy demands and solar energy availability necessitates the adoption of both short and long-term thermal energy storage units. However, even when storage is installed, 100% solar fraction is not attainable due to the characteristics of the thermal loads and the thermal losses in the TES units and district-heating network. Furthermore, as solar thermal collector area and solar fraction increase, the required storage volume increases to potentially impractical levels. Therefore it may be worth investigating other types of storage system, such as sorption storage. While these systems may have lower charging efficiencies, they also have higher storage densities and no time dependent heat losses which might make it possible to achieve solar fractions that are close 100%.

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