Modelling and design of a hybrid solar + micro-cogeneration system for water heating

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SUMMARY

This work compares three alternatives to produce domestic hot water (DHW) in a building with 140 dwellings: individual butane heater in each dwelling, centralized solar system, and centralized hybrid solar+micro-cogeneration system.

In Spain, solar DHW systems are mandatory for new buildings and major refurbishments. In this paper, we explore a new idea that combines a centralized solar system with a small reciprocating gas engine that produces electricity and heat.

The performance of the proposed system is tested in a project that is part of the European MED program. In this paper, we present the results of several TRNSYS simulations. The simulations show that the best solution in terms of CO_2 emissions and primary energy consumption is the hybrid system. For this alternative, the effect of the solar collector surface and the set point temperature of the auxiliary system are analyzed.

INTRODUCTION

The construction of residential buildings began intensively in Spain in the 1950's, with the number of new buildings roughly doubling each decade. This trend reversed with the 2007 crash, leaving the market for new buildings deeply depressed. Building engineering companies, as well as many national and European regulations, are now turning attention towards the refurbishment market. In this context, the European Union has funded the project ELIH-MED (Energy Efficiency in Low Income Housing in the Mediterranean) [1]. The general purpose of this project is to analyze the technical, social and financial aspects of refurbishment projects in buildings occupied by low income people. The authors of this paper participate in this project as contractors of the Urban Environment Monitoring Center, an agency of the City Council.

The work described here is part of a specific refurbishment action that is being developed in a multi-family building owned by the Municipal Housing Institute and rented to low-income families. The purpose of this action is to reduce the energy budget of the building while improving the indoor environment. The building has no mechanical systems for space conditioning because the climate at the location is mild, and passive systems are enough to provide fair conditions inside. With this in mind, hot water heating turns out to be one of the largest contributors to the energy budget of the residents. Currently, these needs are met by gas heaters installed on each dwelling.

The Spanish building regulations of 2006 mandate solar thermal systems for DHW production in new buildings and major refurbishments of existing buildings. The minimum solar fraction required by law depends on the annual average solar radiation and the hot water consumption. The common choice to meet this requirement is to install a centralized solar system, in which users share the solar field and, possibly, other components such as the storage tank and the backup heater.

In this paper, we explore a new idea, which combines a centralized solar system with a small reciprocating gas engine that produces electricity and heat. Water is preheated by the central solar system, while the heat recovered from the gas engine is used for auxiliary heating when needed. It is interesting to note that both products of the engine, electricity and heat, have to be consumed in the building. In the past, it was highly profitable to sell the produced electricity to the utility company, because distributed generation (solar, wind, cogeneration, etc.) was heavily subsidized by the government. These subsidies were frozen by January 2012 and no new installation is allowed to enter into the system. This situation represents a challenge, further complicated by the fact that the thermal demand of the building is rarely synchronized with the electric demand.

Sizing the proposed system is not an obvious task. The area of the solar field, the volume of the storage, and the nominal power of the gas engine are interdependent variables. The optimal design also depends on the control strategy and the demand and weather profiles. A dynamic simulation model implemented in TRNSYS will be used to analyze the problem.

CASE STUDY

The building being refurbish is located north of Malaga, a coastal city in south Spain (N 36° 40', W 4° 29'; 3026 annual cooling degree-days and 14 annual heating degree-days, both at 10°C baseline; 4.83 kWh/m^2 yearly average horizontal global solar radiation). The building has 6 floors (5+basement), 140 dwellings, and a gross built area of 14,547 m^2. It is divided into four blocks connected each other forming a central atrium. The roof is flat, with a free surface of about 1000 m^2, where solar collectors can be installed without shadowing problems. Below the basement, under the slab, there is an empty space 2 m high that can accommodate the mechanical room.

Figure 1. General view of the building.

Water heating system

In the existing building, hot water is prepared on each dwelling using gas heaters. We will consider two alternatives to this system.

The first option is a central collector field with a central buffer storage tank. This tank does not contain drinking water. Instead, hot water from the tank is circulated through the building in a closed loop (*solar circulation loop*). Each dwelling is equipped with a fresh water station that consists of a plate heat exchanger along with some hydraulic accessories. The hot side of these heat exchangers is connected to the solar circulation loop. Drinking water is heated by circulating it through the cold side. A backup system, in this case a gas heater, is installed in series after each heat exchanger. This configuration was chosen because it avoids community bills other than equipment maintenance; i.e. each resident pays its own bills for water and gas.

The second option is the hybrid solar + micro-cogeneration system depicted in Fig. 2. A central collector field, which is smaller than in the previous system, is used to preheat the water of the solar circulation loop. The heat recovered from a small gas engine provides additional heating if required. The rest of the installation does not change: one fresh water stations and one auxiliary system per dwelling.

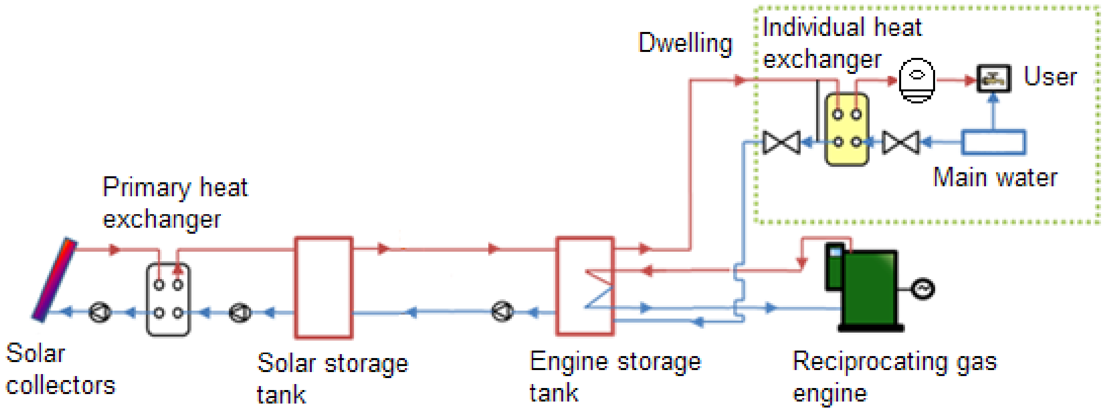

Figure 2. Basic schematics of the proposed system

MODEL OF THE SYSTEM

The performance of the proposed systems (solar only and hybrid) was investigated using TRNSYS [3] simulations. This software is a flexible simulation environment that lets users to create new component's models (called "types" in the TRNSYS terminology). In our case, three new components had to be developed: (1) domestic fresh water station, (2) reciprocating gas engine, and (3) controller.

Solar collector, heat storage tanks and primary heat exchanger

Standard TRNSYS types were used to model the solar collectors, heat storage tanks and primary heat exchanger.

The solar collector model is based on the well-known Hottel-Whillier model [4], which fits the collector efficiency to a quadratic curve in the inlet water temperature:

$$\eta = F_R\left(\tau\alpha\right)_n - F_R U_L \frac{\left(T_i - T_a\right)}{I_T} - F_R U_{L/T} \frac{\left(T_i - T_a\right)^2}{I_T} \quad (1)$$

Where:

η	Collector efficiency
$F_R(\tau\alpha)_n$	Optical loss coefficient at normal incidence
F_RU_L	Transmission loss coefficient (W/m^{2}K)
$F_RU_{L/T}$	Quadratic transmission loss coefficient (W/m^{2}K^2)
I_T	Solar radiation incident on the collector surface (W/m^2)
T_a	Ambient temperature (ºC)
T_i	Inlet water temperature (ºC)

Temperature stratification in the solar tank is modeled using five nodes; more details about the multimode tank model can be found in Ref. [4]. The solar field heat exchanger is modeled using a constant effectiveness approach, which is a good hypothesis case because the mass flow rates at both sides of the exchanger are constant.

Reciprocating gas engine

A new TRNSYS model was implemented to simulate the gas engine. This model follows a table lookup approach based on catalog data. Manufacturers of gas engines report detailed energy balances of the engine for different load regimes. The variables relevant to our analysis are the mechanical and electrical efficiencies, and the recoverable heat from the jacket and the exhaust gas. At each time step, the *part load ratio* is calculated by dividing the electric demand ($P_{e,required}$) by the nominal electric power of the engine ($P_{e,nominal}$):

$$PLR = \frac{P_{e,required}}{P_{e,nominal}} \tag{2}$$

In our system, the nominal electric power of the engine will be chosen much lower than the electric demand of the building, so that for most of the time PLR will be equal or close to 1. The electrical and mechanical efficiencies and the amount of recoverable heat are interpolated from the catalog table, using PLR as independent variable. The mechanical shaft power (P_{mec}), the gas consumption (Q_{comb}), and the heat recoverable from the jackets ($Q_{jackets}$) are calculated as:

$$P_{mec} = \frac{P_{e,requiered}}{\varepsilon_{elec}(PLR)} \tag{3}$$

$$Q_{comb} = \frac{P_{mec}}{\varepsilon_{mec}(PLR)} \tag{4}$$

$$Q_{jackets} = F_{jackets}\left(Q_{comb} - P_{mec}\right) \tag{5}$$

Instantaneous fresh water station

A fresh water station utilizes heat from the solar circulation loop to produce hot water. A typical fresh water station comprises four basic elements: plate heat exchanger, hydraulic valve, cold-side outlet temperature limitation and bypass conduit. A new TRNSYS type was developed to model fresh water stations, which includes the four elements cited above. An important consideration in developing this model was the temporal distribution of the hot water draw-offs [2]. While solar systems are typically simulated using hourly time-steps, the hot water demand is distributed in short pulses of variable intensity and duration. Typical draw-offs involve flow-rates from 1 to 15 liters/min over periods ranging from 1 to 10 minutes. This fact is important because the effectiveness of the heat exchanger varies for varying flow-rates. Our fresh water station model calculates the average effectiveness of the heat exchanger at each simulation time-step (1 hour) in the following way:

1. The average mass flow during the hour is split into a stochastic sequence of pulses. These pulses are one minute long and their intensity is randomly generated. The result of this step is a stochastic demand profile
2. For each pulse, a UA value is calculated by correcting the nominal UA value of the heat exchanger with the pulse mass flow rate. This step considers the dependence of the heat transfer coefficients with the mass flow
3. The hourly average effectiveness is calculated by weighting the effectiveness of the different pulses.

Control

The control strategy determines the priority and the sequence of operation for the solar collector field, the gas engine and the auxiliary system. The performance of the system depends strongly on the temperature set-points and the operating conditions of each subsystem:

a) *Solar collector field pump*. An on/off controller with hysteresis is used. The primary and secondary pumps operate when the collector outlet temperature is at least 2ºC higher than the temperature at the bottom of the solar storage tank. When the pumps are off, they begin to operate when a temperature difference of 7ºC is reached. To avoid lime deposition, pumps are switched off when the temperature at the top of the solar tank reaches 60ºC
b) *Pump between solar tank and engine tank*. An on/off controller with hysteresis is also used in this case. If the temperature of the solar tank is 4ºC higher than the temperature at the lower section of the engine tank, the pump between both storages is switched on (see Fig. 2). The pump stops when the temperature difference falls below 2ºC
c) *Heat exchange with the engine jacket.* The manufacturer of the engine states that (1) the inlet water temperature to the engine must be lower than 70 ºC and (2) the outlet water temperature will be lower than 83 ºC. The design of the heat exchanger in the engine tank guarantees that when the water temperature in the tank is 60 ºC, and the temperature difference is 9 ºC between inlet and outlet, the restrictions for the water temperatures in the engine are met. Sometimes, when the hot water demand is low, the engine stops because the temperatures of the refrigeration water are out of range.
d) *Individual heat exchanger.* The minimum mass flow rate in the solar distribution circuit is set at 5% of the nominal flow. A two-way valve in the hot-side side of the heat exchanger regulates the mass flow to maintain the outlet water temperature in the cold side below 55ºC. The purpose is to avoid scalds and lime deposition.

RESULTS

Definition of the comparison parameters

The following parameters have been selected to compare the different designs: solar and engine contributions to the DHW energy needs, CO_2 emissions, and primary energy consumption. The CO_2 emissions are estimated from the final energy consumption using specific coefficients for each energy source. The auxiliary system in the dwellings consumes butane, while the engine burns natural gas. The emissions due to electric consumption of the pumps are also considered. The formula is:

$$E_{CO_2} = C_{aux} \cdot C_{emis,butane} + C_{engine} \cdot C_{emis,natural\ gas} + C_{elec} \cdot C_{emis,elec} \quad (6)$$

The numerical values of the coefficients in Equation (6) can be found in Table 1.

Table 1. Coefficients to calculate the CO_2 emissions.

	Emissions
Natural gas	0.204 kg CO_2/kWh_t
Butane gas	0.243 kg CO_2/kWh_t
Electricity	0.649 kg CO_2/kWh_e

In the case of the micro-cogeneration engine, the electricity produced by the engine reduces the CO_2 emissions of the central (national) electric system, as well as the primary energy consumption. To convert electricity into primary energy, we used this equivalence: 2,603 kWh_t/kWh_e

Base case

The main design parameters of the base case are given in Table 2. The two aforementioned systems are considered: (1) central solar system, and (2) hybrid central solar + micro-cogeneration system. Both systems are compared with the existing situation in which DHW needs are satisfied using individual butane heaters.

Table 2. Design parameters of the base case.

Subsystem	Size	Thermal parameters
Solar collector area	250 m^2	$FR(\tau\alpha)_n$=0,8; F_RU_L=3,5 W/m^2K
Solar storage tank volume	18000 L	4 tanks; H=2,65 m; U=0,83 W/m^2K
Engine storage tank volume	2000 L	H=2,28 m; U=0,64 W/m^2K
Gas engine (Dachs HKA G5)	5,5 kW_e	14,5 kWt; ε_{elec}=0,27; $\varepsilon_{térmico}$=0,72
Individual heat exchangers	28 kW	UA=1720 W/K

Simulations show that the central solar system will achieve a solar contribution of 77% of the total thermal demand. The remaining 23% is delivered by the auxiliary systems in the dwellings. In the case of the hybrid system, the solar plant satisfies 72% of the thermal demand, the gas engine the 21%, and the auxiliary systems the remaining 7%.

For the hybrid system, the Equivalent Electric Efficiency (*REE*) is 63.4 %, and the reduction of primary energy consumption (*PES*) is 7 %. These parameters are defined in Spanish co-generation regulations [6]. The solar circuit operates for 2,707 hours/year, and the engine for 5,051 hours/year.

Table 3 summarizes the monthly CO_2 emissions and the consumption of primary energy for each case. The hybrid system reduces the CO_2 emissions by 82.1 % compared with the current system. The largest contributor is the solar plant (77%). If we compare the hybrid system with the solar only system, the addition of the engine reduces CO_2 emissions by 22.4 % and the primary energy consumption by 6 %.

Table 3. CO_2 emissions and primary energy consumption in the base case.

Month	Current		Solar+Auxiliary		Solar+Engine+Auxiliary	
	CO_2 emissions (kg)	Primary energy (kgoe)	CO_2 emissions (kg)	Primary energy (kgoe)	CO_2 emissions (kg)	Primary energy (kgoe)
Annual	81181	334	18722	83	14531	78
January	8221	34	3607	15	2373	12
February	7225	30	2804	12	1872	10
March	7470	31	1883	8	1303	7
April	7418	31	1570	7	1152	6
May	6993	29	700	3	804	4
June	6397	26	332	2	564	3
July	5555	23	25	1	400	1
August	4877	20	4	0	382	1
September	5572	23	151	1	481	2
October	6383	26	1062	5	917	5
November	7144	29	2625	11	1626	9
December	7926	33	3959	17	2651	13

Effect of the set point temperature of the auxiliary system

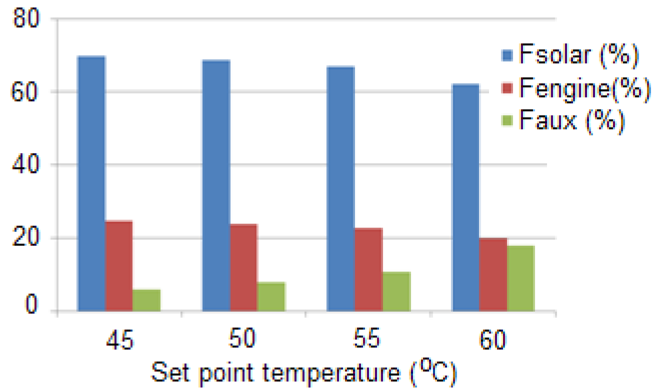

Figure 3. Influence of the set point temperature of the auxiliary system.

If the set point temperature of the auxiliary system increases, the solar contribution decreases. This is because the collector inlet water temperature and the storage temperature increase, and consequently the collector efficiency decreases. Fig. 3 shows how the solar contribution changes when the DHW set point temperature varies between 45ºC and 60ºC. The lower limit is set at 45ºC, a reasonably low yet useful temperature level. The upper limit is set at 60ºC to avoid scalds and lime deposition. The results show that the auxiliary system increases its contribution from 7% to 18%, decreasing the yields from the solar system and the engine.

Effect of the collector surface

Fig. 4 shows the energy output from each subsystem when the solar collector surface increases from 150 m^2 to 450 m^2. The total heating demand is 233.85 MWh for all cases.

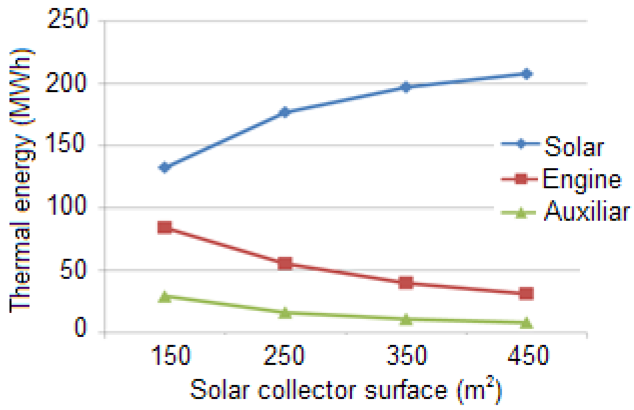

Figure 4: Influence of solar collector surface.

SUMMARY AND CONCLUSIONS

This paper uses TRNSYS simulations to design and optimize a solar + micro-cogeneration hybrid system. This system produces hot water for a building with 140 dwellings. We analyze three alternatives: the current situation with individual butane heaters, a standard central solar system, and a hybrid solar + small reciprocating gas engine. The electricity produced by the engine is consumed in the building, and the recovered thermal energy supplements the solar energy production.

The simulations show that the hybrid installation reduces the operating CO_2 emissions by 82% compared with the current system. Most of this reduction is due to the solar system (77 %). The use of the gas engine contributes to the reduction of CO_2 emissions about 22.4 % additionally to the solar field and the primary energy consumption is 6 % lower. To calculate these figures, we took into account the electricity produced by the gas engine.

ACKNOWLEDGEMENT

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