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Optimisation paramétrique de l'ECS solaire et de la repartition des panneaux thermiques et PV pour une maison à bilan énergie positif

Parametric Sensitivity Study and Optimization of the SDHW and PV Subsystems in an Energy Positive House

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RÉSUMÉ. Nous présentons une étude de sensibilité paramètrique sur la simulation numérique dynamique des systèmes d'ECS solaire (CESI) et PV dans une maison à bilan d'énergie positif. Les paramètres d'optimisation concernent les capteurs, le ballon de stockage et le circulateur. Grâce à cette étude, des gains important sont obtenus pour chacun des paramètres étudiés. Nous réduisons d'un facteur trois les besoins énergétiques annuels en appoint et circulation du système initial dans un scénario de charge correspondant à une famille moyenne de quatre personnes. Nous poursuivons l'étude avec le PV afin de déduire la répartition optimale de la surface du toit solaire entre les capteurs thermique et PV. Notre résultat permet de produire plus d'électricité pour la revente au réseau.

MOTS-CLÉS: Optimization d'un chauffe-eau solaire individuel (CESI), étude de sensibilité paramètrique utilisant TRNSYS, optimisation de la répartition de surface entre capteurs solaire thermique et PV

ABSTRACT. This study presents a parametric sensitivity analysis of the dynamic simulation of the Solar Domestic Hot Water (SDHW) and Photovoltaic (PV) solar systems in an energy positive house. The optimized parameters concern the solar collectors, the storage tank and the fluid circulator. Significant gains are obtained on most of the parameters which allows for a better solar fraction with the SDHW. The energy need for the DHW auxiliary and pump is divided by three with a load scenario corresponding to a family of four. Moreover, we extended the study to the PV system to provides the best repartition option between thermal and PV panels on the solar roof. This maximizes the opportunity of generating surplus electricity, sold back to the power grid.

KEYWORDS: Solar Domestic Hot Water (SDHW) optimization, sensitive parametric analysis using TRNSYS, thermal vs. PV panels surface performance crossover.

1. Introduction

Energy is a prime requirement of modern society. However, the use of energy from finite fossil fuels is recognized as changing the global climate through the excessive release of greenhouse gases. However there is a political realization of the consequences of the effects of climate change leading calls for a more sustainable way of living.

One particular sector where emissions of greenhouse gases is important is the built environment. In France, from (1), buildings consume 47% of the primary energy, while industry and agriculture account for 28% and transportation 25%. In buildings 2/3 of the energy need comes from dwellings and the remaining 1/3 comes from commercial activity. The energy efficiency of buildings in France has increased from 372 kWh/m^2/yr. in 1973 to 245 kWh/m^2/yr. Today, however, this is very far from other EU neighbors construction requirements where numerous examples are actually below 50 kWh/m^2/yr.

From these facts, the importance of setting energy efficient construction trends as well as methodologies to be able to model precisely building energy consumption is vital. In this work our aim was to use a dynamic numerical simulation software to reduce by design a house energy consumption. This is obtain by a sensitivity analysis on the solar domestic hot water (SDHW) of the so called Ener+ house. We thus carefully optimize the SDHW system parameters. With these settings, we deduce the best repartition between thermal and PV panels for the target house solar roof.

In the following, we present our operational hypothesis. Then, the sensitivity analysis of the SDHW subsystem is described. From that optimized design, called OptEner+, the PV production system is rationalized and an optimized repartition between thermal and PV collector areas is proposed.

2. RELATED WORK

Efficient energy housing Following the Swiss and German regulations, more than 20 efforts referenced in (2) propose normative projects or norms or guidelines. They are usually quantified by an energy consumption metric threshold in kWh/m^2/yr., see Table i, called Cep in France[1], beneath which a given label is accorded.

Table i : Tentative comparison of the labels for raw energy maximum consumption including heating, cooling, ventilation and DHW in buildings. As the parameters, the objectives and surfaces computations differ from country to country, these numbers should not be compared directly.

Label	Cep ($kWh/m^2yr.$)
Average france	245
RT2005	130 (250 if all-electricity based)
Minergie `www.minergie.ch`	42 (80 for rebuild)
Effinergie `www.effinergie.org`	30-50 (depending on geo-localization)
PassivHaus `www.passiv.de`	15 (40 with DHW inclusion)

Simulation tools In energy simulation of buildings most of the physical processes are modeled with a set of algebraic equations, mostly non-linear, differential and integral (3). Several tools, referenced in (2), exist which solve these equations with different methods. The dynamic simulation systems are the more precise because they solve equations iteratively over time with a given time-step. Such a well-known system is TRNSYS[2] from University of Wisconsin or Comfie/Pleiade[3] from Ecole des Mines. For instance, a global model of a Zero Net Energy Home was design with TRNSYS in (4).

SDHW and PV system numerical simulation The basis of SDHW numerical simulation is described in (5; 6). In (7), TRNSYS is used to determine the impact on performance of orientation and inclination on PV panels for Ireland. (8) also describes TRNSYS simulation of SDHW systems for the tank sizing and panel positioning in order to get the best Return on Investment (RoI) depending on electricity tariff in Brazil. In (9; 10; 11), hybrid solar PV+thermal (PVT) collectors with thermal exchanger on their back are modeled numerically. This shows that the PV production is increased because of the lower collector temperature and thus solar fraction captured per m^2 is improved. In (12), a geothermal heat pump and solar thermal collectors coupling is simulated using TRNSYS. Thanks to the solar collectors, the system provides heating, cooling and DHW with only a very small thermal depletion of the soil around the bore-hole heat exchanger. Similarly to our work but with PVT, (13) study the combination of PVT panels with a ground coupled HVAC within a TRNSYS model. With $25m^3$ PVT roof, the system covers all the target Dutch house DWH needs and nearly all its electricity. This corroborates our results. In (14), the SDHW system is coupled with pellet heating systems in TRNSYS models to

[1] See French Reglementation Thermique (RT) established by CSTB `www.cstb.fr`
[2] Transient Systems Simulation Program: `sel.me.wisc.edu/trnsys`.
[3] `www.izuba.fr` from Bruno Peuportier's work.

investigate burners' parameters. In the context of ZNEH, (15) shows that the production of DHW with solar thermal collectors and an electric auxiliary backup, possibly from PV, is the best solution against three other alternatives. The results leads to zero net energy need from the grid with $4.5m^2$ of thermal and $2m^2$ of PV in the Los Angeles climate and $12+5.2m^2$ in Montreal. This system is similar to ours but at a different latitude, our results, in between, fits well with the analysis. For a SDHW system, the tank volume and stratification phenomena simulation was described in (16), (17). The tank influences the overall quality of a SDHW system because its storage effect absorbs variations and its stratification can help increase the efficiency of the thermal exchange with the solar source by providing relatively cold bottom temperature, while the top part still provide DHW at the required temperature. In a recent PhD (18), the optimization of heat exchanges in a stratified tank, is described with a fluid dynamic tool showing the water convection nodes for multiple inlets and different types of jet brakers. These brake the jets and help to keep the stratification of the tank while the inlet water temperature governs the best inlet level choice. Several studies about low-flow solar tanks (19; 16) and stratification fluid dynamics (18) also promote the usage of such stratification keepers like double skin, multiple inlet and jet-braker tanks. We followed these results by using a stratified tank model with 15 layers. The literature (18; 16; 19; 20) describe low flow studies in SDHW. This explains that even if the heat transport rate is lower, the heat exchange may be better due to better ΔT and less mixing in the tank. Optimally, the flow rate should be adjusted to the ΔT in order to choose high values when the ΔT is high and low value when it is low. We took these work into account in our model.

The Energy Positive House Ener+ The energy positive house Ener+ project[1] described technicaly in (21), aims to design a family size house, represented in Figure i, connected to the electricity grid that will produce enough energy to meet at least its own consumption[2]. A complete numeric model of the target house was set up in TRNSYS with 14 temperature zones in the Type56 description (22). Several scenario were ran for a location in Lyon-France where the climate is temperate and sunny[3]. The weather data input were from Typical Meteorological Year statistical hourly values.

Figure i : The Ener+ house small scale model.

The comfort temperature target was fixed at 19^oC with a maximum of 40 hours per year above 28^oC. This is obtained thanks to an efficient double-flows ventilation systems coupled to an underground pipe that damped the input air temperature, a greenhouse and a reversible heat pump[4]. The ventilation control allows for hyper ventilation and enables the air flow through the underground pipe and the greenhouse. The overall resulting building has a very small raw heating need of $13kWh/m^2$[5] per year which satisfy most of the existing energy labels.

[1]Between Centre de Genie Electrique de Lyon - Ampere (CEGELY), UMR 5005 and Centre de Thermique de Lyon (CETHIL), UMR 5008.
[2]The Ener+ house is a $191m^2$ affordable property suitable for four-five persons, compact, south facing with a greenhouse and adjustable external window blinds. The greenhouse is covered by PV and thermal solar collectors at the desired inclination. The external envelope insulation is 0.3m thick with $U = 0.13Wm^{-2}K^{-1}$.
[3]Average annual temperature around 11^oC with 2,000 hours of sunshine, 201m above sea level.
[4]The heat pump is geothermal water/water ground source with a 90 meter vertical bore-hole for a net efficiency of 320%. It is coupled to the low temperature floor exchanger through an heat storage tank.
[5]$5kWh/m^2$ consumption with the heat pump.

Table ii : Ener+ house yearly energy consumption repartition.

Category	Raw need kWh	%	Heat pump + SDHW kWh	%
Heating	2520	26	921	20
Venting	1239	13	1239	26
DHW	3665	38	663	14
Sp. elect.	2120	22	2120	40
Total	9544	-	4943	-
Per m^2	50	-	26	-

The energy needs of the Ener+ house are presented in Table ii. Within the model, the specific electricity needs, the heat contribution of the family scenario and appliances dissipations are also taken into account. Thanks to $52m^2$ of PV collectors producing 7099 kWh/year, the resulting Ener+ model showed a net production of 2156 kWh per year.

3. ENVIRONMENTAL AND OPERATIONAL CONDITIONS

TRNSYS was used to model the SDHW system with solar collector panels (Type 1b) and a stratified water tank (Type4c), see Figure ii which gives a schematic description of the main components involved. The time step of the simulation was set to 0.5 hours following the work of (21; 22) in the same context.

The daily DWH load follows the scheduled pattern averaging the EU behavior described in (21). This represents 200 liters consumption for a 4 person family is implemented thanks to a TRNSYS Type14 component.

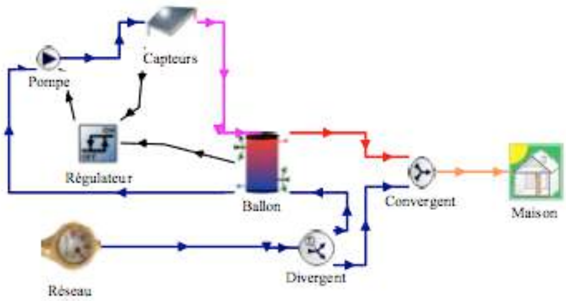

Figure ii : The main components involved in our SDHW model in the TRNSYS simulation software.

The consumption pattern consists of 2 peaks of approximately 100 liters each, one in the morning and one in the evening. The dish washer and washing machine are one of the main specific electricity need of a house, between 255 and 485 kWh/y for a 4 persons family (23), depending on the efficiency of the devices. Most of this power consists of water heating. This hot water consumption was added to the DHW load by adding 16 liters of hot water at the set-point 45^oC in the evenings. This covers the average hot water washing need[1] and enables a subtraction of 235 kWh on the specific electricity need of the house by adding the corresponding load on the SDHW.

4. SOLAR DHW OPTIMIZATION

This research tries to minimize the sum of the auxiliary water heating energy and the pump energy that circulates the water in the collectors : $f_{obj} = min(Q_{aux} + Q_{pump})$. For sake of clarity the parametric

[1] See www.eaudeparis.fr.

optimization is presented in Table iii as if parameters were optimized one after the others although the real scheduling of the parametric optimization is much more complex.

The experimental initial global approach on the whole model was using a software tool[1] in order to build an experience plan which reduces the parameters matrix and provides estimations of each parameter's influence.

With the reduced parameters set of our study and the already optimized initial solution we built our parameter surface study by hand, following Taguchi's method and taking into account the underlaying physics and the parameters' reasonable practical bounds for such an individual house. This results in a reduced experimental plan matrix where each parameters was varied first with large steps between its limits to try to avoid the local minima effects. On its variation ranges, all the parameters showed monotonous or parabolic-shaped responses. For the parabolic responses parameters, we then explored their coupling with others by varying them back and forth around the minimal value of the objective function. This was scheduled by decreasing order of their influence and from several initial solutions. As the solutions became better the influence order of the parameters became unclear since the variation scale was also adjusted to the precision reached. In the end, the finer grain matrix exploration was almost complete and the best values result in the Table iii solution. Notice that we did not succeed to get a better result with the TRNOpt sophisticated optimization tool.

Table iii : Gains for each parameters optimization.

Parameter	Variation	Q_{aux} kWh	Q_{pump} kWh
	Ener+ → OptEner+	652	59
Temp. set point	$60 \rightarrow 46^oC$	536	60
Collector area	$7.5 \rightarrow 10\ m^2$	369	55
Tank volume	$0.45 \rightarrow 1.1m^3$	292	60
Pump low Flow	$40 \rightarrow 7\ \frac{kg}{m^2h}$	221	74
Pump power	$240 \rightarrow 60W$	221	18
Tank's height	$1.5 \rightarrow 1.2m$	220	19
Control dead band	$2..10 \rightarrow 2..7^oC$	219	19
Collector slope	$45 \rightarrow 56^o$	199	19

Set point temperature The temperature 45^oC determines the set-point parameter of the DHW tank [2] In order to have a "stationary regime" simulation the tank is initially set at $T^{tank}_{set-point}$ for its upper half and 15^oC for its lower half. Clearly, this parameter has a major impact because it dictates the quantity of energy stored in the system. Our attention was to keep the DHW T^{tank}_{outlet} above 45^oC most of the time, as this was controlled during the tests. Due to the dead-band, during the winter, a few half an hour measurements on the water-out temperature went down to 43^oC in the simulations, but this is rare and thus acceptable.

Collector area In the Ener+ model, the collectors are provided by slices of $2.5m^2$ because of the targeted solar product.

In this system, the first 2 slices $5.0m^2$ provide approximately $1MWh$ of the energy each. Then the gain per slice decreases roughly by a factor 2 for each new slice, see Tabletotalthermal. The asymptote is almost reached by $20m^2$. After $10m^2$, the efficiency of the added slice is less than 4%, we therefore ran the model only up to $\mathbf{10m^2}$ collectors.

[1]NemrodW from LPRAI Inc. `www.nemrodw.com`.

[2]For sanitary reasons, periods with water above 65^oC are recommended and we assume that micro-filtering or UV-light systems are used during the winter time period as proposed in (18). Moreover, a high temperature set point increases the precipitation of dissolved minerals.

Table iv : Total auxiliary energy with the different DWH systems (washers need $235kWh$).

Model	Area m^2	Q_{aux} kWh	Q_{pump} kWh	Solar frac.
No solar	0	3240+235	0	-
Ener+	7.5	$606+235$	57	74
OptEner+	5	605	26	82
OptEner+	7.5	341	21	90
OptEner+	10	199	19	94

Tank volume The best tank volume is linked to the collector area and load because stratification increases the thermal exchange efficiency and decreases the overall energy needed to serve the load from the upper tank. Furthermore the volume also dictates the amount of energy needed to raise the tank to service temperature. We saw that the best volume increases with the collector area, the optimization of the other parameters and the decrease of $T^{tank}_{set-point}$.

Pump low flow The literature proposes values about $10kg/hm^2$ for low flow while usual flow rates can be practically set to more than $40kg/hm^2$. Our best simulated value is even smaller at $7kg/hm^2$. Due to the slower heat transfer, the pump runs on longer periods and this slightly increases Q_{aux}. However, the gain fully justifies the usage of low flow circulation pumps associated with anti-mixing systems in stratified tanks.

Pump power At low flow rates, the pump power can be decreased. In our model, the pump power is linearly liked to its consumption and the heat transfer coefficient to the fluid is very small at 0.05. Thus choosing a pump power adjusted to the flow rate lead to significant improvement. The initial Ener+ 240W pump was able to sustain $300kg/h$ while in OptEner+ the best low flow need is only $70kg/h$. As the pump consumption represents $1/3$ of the optimized auxiliary energy, the gain with an adjusted 60W circulator is 19 % against the initial one[1].

Tank's node height Our tank model is a vertical cylinder divided in 15 horizontal slices of equal height, each being simulated as a homogenous temperature convection zone in a multi-layer approach. The tank has one inlet per zone in order to provide less mixing while entering water in the zone closest in temperature. For a given volume, the zone's height parameter governs the height and diameter of the tank and this influences the heat exchanges. The yearly gain of a 15 zones stratified tank was 75% over a fully mixed (1 zone) tank and 40% over a partially mixed (3 zones) tank. The optimization gave practical dimensions with $H = 1.2m$ and $D = 1.08m$ for the $1.1m^3$ tank.

Pump Dead Band The pump dead-band value decides when the ΔT is enough to start circulating the fluid and also when it stops. As there is no loss in the circuit pipes with the model, it is not surprising to find the best low value at 0 for the best Q_{aux}. But running the heat transfer with a small ΔT leads to a lot of circulation of water and thus over values Q_{pump}. The best start up value is dictated by the heat exchange efficiency and the amount of energy that will be spent in the circulating pump. The best up value is smaller than the original one in order to fit with the low flow optimization. The gain against the initial value is small but reaches 7% when applied on less optimized values and such an optimization can be applied to any system.

Collector slope Due to the integration of the solar irradiation, with azimuth zero, the slope that provides the most irradiation per year is roughly equal to the latitude hence 45 degrees. But with large

[1]For instance a Grunfos^{tm} circulation pumps with electronic adjustment from 25 to 60W, giving up to 350 kg/h.

collectors, regarding the DHW coverage aim, the summer sun will provide too much energy while winter will need more auxiliary. Thus, steeper slope should be better, the optimal being roughly latitude plus 10 degrees. We obtained the best performances for 56 degrees with the range [55 – 64] degrees staying within 0.5% of this optimal slope.

Control Trying to turn off the auxiliary heater may be of importance on non optimized systems, especially when the tank dead-band is narrow and the set point temperature higher than the DHW service temperature. As the system is being kept close to the DHW service temperature, it cannot tolerate to be switched off. For instance, with 3 hours off during the night, several measurements present a small amount of time where T_{tank}^{outlet} is below 40^oC which is unacceptable compared to the comfort level we sustained until now on the DHW. Thus, this optimization can not be used because it does not guarantee the targeted comfort.

5. BEST THERMAL VS. PV AREA

We assume the inverter is tracking the maximum power point in any situation. The parametric study shows that the best slope for a PV collector at our location is 33 degrees. With the optimal slope, the gain against Ener+ model is up to 30% with monocristalline Si, see Table v.

Table v : Total PV systems production for the solar roof.

Model	Area $m^2(slope^o)$	Product. kWh	Net elec. for grid
Ener+	51.5(45)	7099	2156
OptEner+p	54(33)	7553	2877
OptEner+m	54(33)	**9285**	**4609**

With thermal collectors, the impact of the first m^2 is huge but then the contribution decreases rapidly as described in section 4. On the contrary, each PV m^2 always brings the same amount of energy. Hence, the cross-point, when an added thermal surface provides less energy than the similar added PV surface, appears to be at $5m^2$.

6. CONCLUSION

The optimisation of the SDHW and PV subsystems in the Ener+ house with this sensitivity analysis tracked auxiliary energy reduction. Even if the project is based on a specific building, location and energy performance parameters, potentially this study has a larger scope. The dynamic models used in this study have the ability to be applied to other locations and other scenarios. Building parameters such as U-values, solar gain, orientation and size can be adjusted. Energy load and thermal comfort, along with auxiliary system component energy use can be modified. Therefore, it is fully feasible to adapt this sensitivity analysis to other target building data.

Moreover, this simulation work shows that the parametric optimization of energy in buildings can lead to large improvements on the energy consumption and production for given architectural characteristics. For instance, with $10m^2$ of thermal collectors in the OptEner+ design, the total auxiliary energy for DHW is less than 218kWh per year, i.e. less than the production of $2m^2$ of PV panels.

Our overall best OptEner+ design has $5m^2$ of thermal collectors and needs less auxiliary energy input for DHW than the Ener+ initial model with $7.5m^2$, and this, with the washers hot water needs fulfilled by the DHW system. This allows for a greater PV surface and a larger positive annual production of energy especially with monocristalline PV at optimal slope. With that OptEner+m the PV electricity production is more than doubled with up to $4609kWh$ potentially sold to the grid after deduction of all the electrical consumptions. Associated with the financial levy of PV electricity production, such efficient SDHW and PV optimizations also reduce the return on investment in the renewable energy systems.

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