Vers une production d'eau chaude sanitaire à faible consommation d'énergie, à faible technicité et à faible coût pour les bâtiments

Towards low energy, low tech and low cost domestic hot water production for buildings

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Résumé - Avec l'amélioration de l'enveloppe des bâtiments et le recours à la récupération de chaleur sur l'air extrait, il s'avère que la production d'eau chaude sanitaire ECS devient un poste important dans le bilan énergétique des bâtiments. Cette étude vise à analyser l'intérêt que peut avoir la récupération de chaleur sur les eaux grises dans les bâtiments pour réduire les consommations liées à l'ECS. L'étude montre qu'un couplage de ce type de système avec une production thermodynamique et de petits panneaux solaires photovoltaïques peut réduire drastiquement ces consommations même en considérant l'impact de l'encrassement de l'échangeur et être compétitif avec des installations solaires thermiques souvent plus coûteuses et parfois difficiles à déployer notamment en rénovation et en milieu urbain.

Abstract - With improvements to the building envelope and the use of heat recovery from extracted air, DHW production is becoming a major item in the energy balance of buildings. The aim of this study is to analyze the potential benefits of grey water heat recovery in buildings to reduce DHW consumption. The study shows that combining this type of system with thermodynamic production and small photovoltaic solar panels can drastically reduce consumption, even taking into account the impact of heat exchanger fouling, and be competitive with solar thermal systems that are more expensive and sometimes difficult to install, particularly in renovation projects and urban environments.

Nomenclature

C_{dyn}	dynamic coefficient,-
COP	coefficient of performance, -
c_p	specific heat capacity, $J.kg^{-1}.K^{-1}$
E	electrical energy, J or kWh
E_{hx}	heat exchanger efficiency,-
k_f	fouling coefficient, $kJ.K^{-1}.m^{-2}.d^{-2}$
NTU	number of transfer units, -
Q	heat, J or kWh
q_v	volume flow rate, $m^3.h^{-1}$
R_f	fouling thermal resistance, $m^2.K.kW^{-1}$
$R_{f\infty}$	asymptotic fouling thermal resistance, $m^2.K.kW^{-1}$
US	thermal conductance, $W.K^{-1}$
T	temperature, °C or K

Index and exponent

0	nominal/initial
∞	stabilization phase
amb	ambient
C	*cold*
dhw	domestic hot water
el	electrical
f	fouling
grid	from grid
H	hot
hp	heat pump
hx	heat exchanger
loss	losses
p	peak
syst	system
th	thermal

Greek symbols

η_{ex}	exergetic efficiency, -
ρ	water density, $kg.m^{-3}$

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1. Introduction

Domestic hot water (DHW) is a major source of energy consumption in residential buildings (second behind heating), accounting for 16% in France [1, 2] in 2021 (15% in Europe in 2021 [3], 18% in the United States in 2023 [4]). This rate has risen steadily, doubling over the last 50 years in France [1,2], due to improvements in the thermal performance of buildings (increasingly stringent regulations (RT 2012 and RE2020)) and higher levels of comfort, particularly with more frequent showers. This rate will be even higher for high-performance buildings (new or renovated), reaching around 30% [5]. The energy consumed for DHW dedicated to showers in France will represent around 49 TWh in 2021 [1], of which 24 TWh [1] will be produced using electrical energy, mainly Joule-effect systems (around 11 million units) which operate mainly at night during off-peak hours. According to ADEME [6], the electrical energy consumed by the entire electrical water heater (Joule effect) EWH park represents 5.5% of national electricity consumption. This basic electricity consumption is mainly covered by nuclear power plants. This represents the electricity production of around 2 nuclear reactors (out of 57 in France in 2024). Among DHW consumption, shower consumption accounts for around 2/3 of the total. It also happens to be the easiest source of heat to recover ('lightly charged' grey water compared with 'heavily charged' grey water, i.e. oily water). In addition to the gains in terms of energy efficiency and greenhouse gas (GHG) emissions, recovering some of this energy offers the opportunity to free up electrical capacity in view of the growing use of electric mobility, which will require large quantities of energy during this same night-time period to recharge. Often, we work to improve DHW production (thermodynamic water heaters TWH, heat pumps, solar thermal panels, biomass, etc.) without bothering to recover the heat lost during the evacuation of grey water that is still hot. However, this is what is commonly done in a double flow ventilation system, for example. Furthermore, in energy terms, only 20% of the total heat produced is used (heat that is used/lost by convection with the skin and by evaporation between the shower head and the drain (see Fig.1)). 80% of the heat produced will be evacuated through the drain (powers of the order of 10 kW) with drain temperature between 33 and 37°C on average vs. DHW water at 40°C. Solar thermal panels can be installed in efficient buildings, often in new-build, with coverage rates ranging from 40 to 80% depending on the climatic zone (in France [7]), but they are often expensive and difficult to install in refurbishment or urban environments (collective housing). We can see on figure 1 a first example to compare a classical DHW production by electrical heater EWH (Joule effect) and a DHW production made by a drain shower water heat exchanger couple to an over insulated thermodynamic water heater TWH and photovoltaic (PV) panels. We see that we can in theory reduce DHW consumption by a factor 14 (between 10 and 15) while maintaining the same level of comfort (same volume of DHW at 40°C).

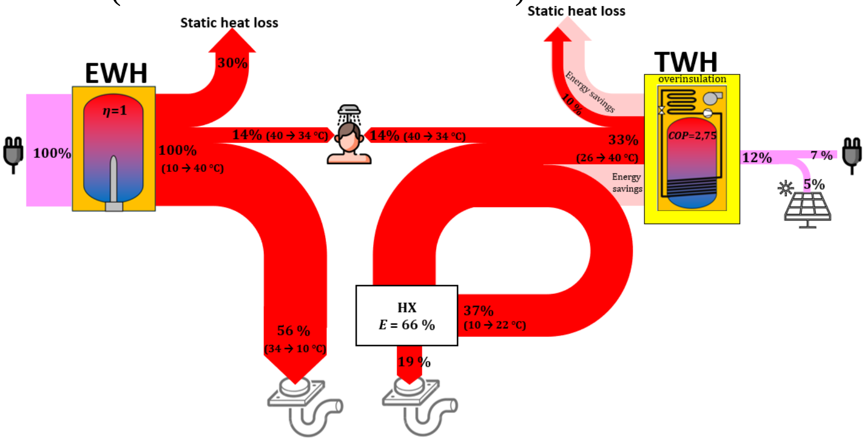

Figure 1: *Example of Sankey diagram about energy balance between classical EWH and TWH over insulated and coupled with drain water heat recovery heat exchanger and PV*

The first aim is to show that it is possible to significantly improve the performance of DHW production by using systems that are already widely used (thermodynamic water heater TWH) or low-tech systems (gravity plates drain water heat exchangers). Another aim of this study is to make an energy comparison between different DHW production strategies that include a drain water heat recovery strategy: electrical water heater + heat recovery unit + thermal over-insulation, thermodynamic water heater + heat recovery + thermal over-insulation unit and thermodynamic production using drain water as the cold source. These systems will also be coupled to photovoltaic panels to make comparison with thermal solar panels. This study will also take into account the development of biofilm in these exchangers, as well as dynamic effects (thermal inertia of the drain water heat exchanger).

2. Methodology

Previous works have modelled dynamic fouling by biofilm development and dynamic effects (exchanger inertia, successive withdrawals) [8-10]. A model has been developed in TRNSYS to simulate the energy performance of DHW production systems over a year, taking into account : DHW draw-off profiles, cold water temperature profile, a stratified DHW storage tanks, flow temperature control by thermostatic mixing valve and a heat pump model (see fig. 2).

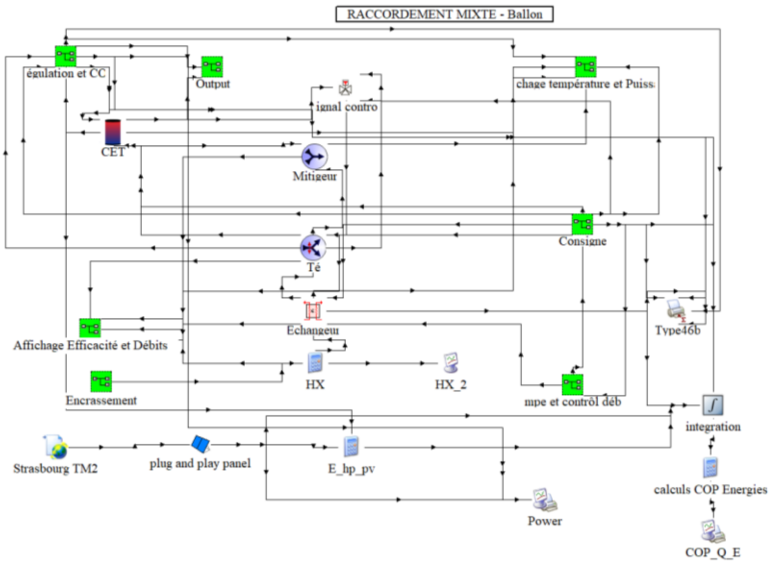

Figure 2: *TRNSYS interface*

2.1. Draw-off profile

A typical DHW withdrawal profile taken from standard NF EN 13203-2 with two showers a day, one in the morning and one in the evening, is considered. According to the standard, this profile represents a typical consumption profile for a French family. This profile results in a DHW energy need of 1671 kWh/year for each scenario.

2.2. Cold water temperature

Cold water temperatures were measured in Strasbourg in 2021 [9] to derive a sinusoidal pattern marked by an amplitude of 10 K and an average value of 15°C, which is higher than the regulatory value of 12.8°C. These temperatures are characteristic of an urban environment, where they will be higher than in rural areas in particular. This parameter is important here, as the system's performance (notably power and energy recovery) will vary significantly with the season, with a much greater quantity of heat recovered in winter (by a factor of around 2).

2.3. DHW tank

The DHW storage tank (electrical or thermodynamic) is modeled using TRNSYS Type n° 158 (stratified vertical liquid storage without exchanger with auxiliary heating). The tank is divided into temperature nodes (15 here) of constant volume (150 l of total volume) and are assumed to be isothermal and to interact thermally with neighboring nodes via several mechanisms: fluid conduction between nodes and fluid movement (either forced movement of inlet flows, natural de-stratification or mixing due to temperature inversions in the tank). The electrical resistance of the electrical water heater and the heat pump of the thermodynamic water heater are modeled as source terms on the 5 nodes at the bottom of the tank. For the electrical resistance, we consider a power of 2000 W and for the heat pump, the compressor power is assumed to be fixed at 300 W, so the source term will be equal to 300.*COP*(t). The tank has 2 ports: the injection port for cold or preheated water (node n°15) and a withdrawal port to supply the mixing valve (node n°1).

2.4. Heat Pump

The thermodynamic water heater is modeled using the performance map of a commercial device (refrigerant : R410a) supplied by the manufacturer. A linear regression was performed to simply characterize the instantaneous *COP* as a function of the difference between the temperatures of the hot and cold sources (water at the bottom of the tank and ambient air) (see Eq. 1 and Fig.2):

$$COP = a(T_H - T_C) + b \tag{1}$$

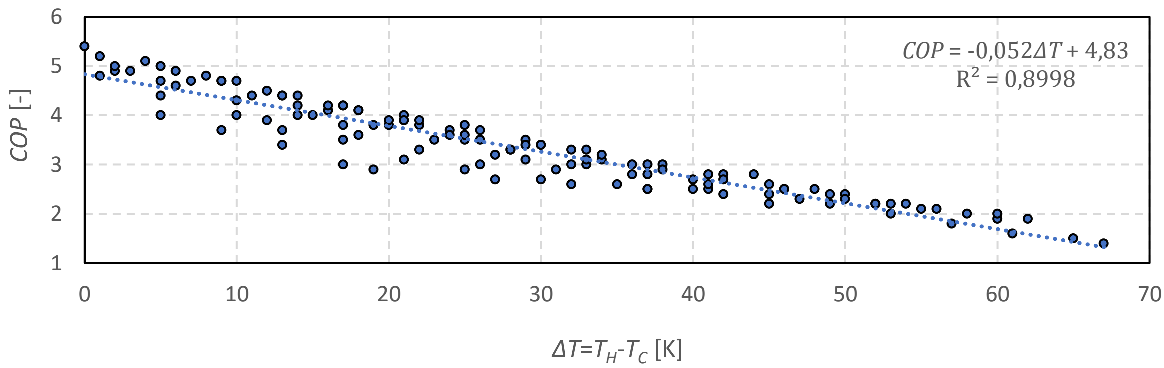

Figure 3: *TWH heat pump COP modeling*

This model takes into account the impact of heat recovery, which will heat up the hot source and therefore reduce the *COP*. The tank is modeled with 15 horizontal nodes, and the condenser is assumed to be located on the first 1/3 of the tank. The hot source temperature T_H is therefore calculated on the average of these first 5 nodes (n° 11 to 15). For the purposes of this study, we assume an air temperature (cold source T_C) of 10°C (ambient air in a cellar or garage). For the last scenario tested, we consider a heat pump that heats DHW instantaneously from the temperature of the preheated water leaving the grey water heat recovery unit (34°C) to 40°C (T_H here), the cold source always being the ambient air at T_C. We use the following equation, assuming an exergy efficiency of 0.35:

$$COP = \eta_{ex} \frac{T_H}{T_H - T_C} \quad \text{with} \quad \eta_{ex} = 0{,}35 \text{ and } T \text{ in } K \tag{2}$$

2.5. Control strategy

The control strategy of the DHW systems consists of an ideal thermostatic mixing valve on the draw-off side, which continuously adjusts the hot water mass flow rate from the storage tank according to the temperature of the cold water preheated by the recovery heat exchanger to obtain 40 °C at the shower head. The water tank temperature set point is set to 55°C at the top of the DHW tank. The ambient air temperature around the storage tank is assumed to be 10°C all year round (garage or cellar). A 20°C variant will be proposed. The electric resistance of the electrical water heater is switched on during off-peak hours between 11pm and 7am. The heat pump is programmed to produce when the solar PV panels are most likely to produce around 1pm (between 11am and 5pm). This regulation is deliberately simple, in keeping with the "low tech" philosophy of this system, which is based on widespread, cheap commercial systems. Finally, the default insulation thickness is 3 cm (current values), and a variant with thermal over-insulation will be considered with 10 cm of insulation to reduce heat losses which can have a significant influence in the DHW system energy balance.

2.6. Shower drain water heat recovery exchanger

The heat exchanger is simply modeled using the *NTU* method (see Eq. 3 and 4), considering a thermal conductance US_f integrating a fouling resistance R_f obeying Nebot's model [11] (see Eq. 5 and 6). The parameterization of this model was carried out thanks to the identification made on in situ experimental data in previous works [9]. Here, we assume that the system is cleaned once a month. A grey water temperature of 34°C (at drain level) is assumed, again based on experimental data [9]. The shower flow rate is fixed at 8 $\mathrm{l.min^{-1}}$. Finally, dynamic phenomena (exchanger inertia, successive showers) are taken into account by means of a C_{dyn} parameter, determined using experimental data and set at 0.97. We define the fouling thermal resistance R_f such as:

$$NTU = \frac{US_f}{\rho c_p q_v} \quad \text{with } q_v = 8\,\mathrm{l.min^{-1}} \tag{3}$$

$$E_{HX} = C_{dyn}\frac{NTU}{1+NTU} \tag{4}$$

$$R_f = \frac{1}{US_f} - \frac{1}{US_0} \quad \text{with } US_0 = \rho c q_v \frac{E_{HX\_0}}{1-E_{HX\_0}} = 1365\ \mathrm{W.K^{-1}} \tag{5}$$

$$\text{With } \begin{cases} \frac{dR_f}{dt} = k_f\left(R_{f\infty} - R_f\right)R_f & \text{(Nebot model)} \\ R_f(0) = R_{f0} \neq 0 \end{cases} \tag{6}$$

A specific model for calculating fouling has been created in TRNSYS to feed the heat exchanger efficiency calculation. The TRNYSY 91b type was then used to model the heat exchanger (see Fig. 2).

2.7. Photovoltaic panel

A PV solar panel is considered for the scenario in which a thermodynamic water heater is operated during the day, in order to make maximum use of solar energy for self-consumption by the heat pump. We assume a "plug and play" solar panel (which are now widespread) of 400 W_p (2 m²) corresponding to commercial products and to the nominal power of the compressor (300 W). A 60° inclination is assumed to maximize production in winter. This panel is modeled by TRNSYS type 103. The model can apply the MPPT (maximum power point tracking) mode. The parameters of the model are given on table 1 and are derived from an available device on the market (Sunology®). Two weather stations are used: Strasbourg and Nice (2020 TM2 meteorological data files).

Module short-circuit current at reference conditions	10,97	A
Module current at max power point and reference conditions	10,36	A
Module open-circuit voltage at reference conditions	46,4	V
Module voltage at max power point and reference conditions	38,6	V
Temperature coefficient of I_{sc} (reference conditions)	0,004388	A/K
Temperature coefficient of V_{oc} (reference conditions)	-0,1253	V/K
Number of cells wired in series	108	-
Module temperature at NOCT	43,2	°C
Module area	1,96	m²
Reference cell temperature	25	°C
Reference insolation	1000	W.m^{-2}

Table 1: *PV panel type 103 parameters in TRNSYS from Sunology® company*

3. Results

We simulated different configurations under common assumptions (T_{amb}=10°C) using the Strasbourg meteo file. The different configurations tested are as follows:

- electrical water heater during off-peak hours (EWH)
- electrical water heater with thermal over-insulation (EWH+TI)
- electrical water heater with drain water recovery heat exchanger (EWH+HX)
- electrical water heater with thermal over-insulation and drain water recovery heat exchanger (EWH+TI+HX)
- thermodynamic water heater during off-peak hours (TWH)
- thermodynamic water heater with thermal over-insulation (TWH+TI)
- thermodynamic water heater with drain water recovery heat exchanger (TWH+HX)
- thermodynamic water heater with thermal over-insulation and drain water recovery heat exchanger (TWH + TI + HX)
- thermodynamic water heater during solar hours with thermal over-insulation and drain water recovery heat exchanger and PV panel (TWH + TI + HX + PV)

We also tested systems for instantaneous DHW heating coupled to drain water recovery HX via an electric resistance (Elec instant. + HX) or via a *air/drain water* heat pump (HP instant. + HX), thus avoiding static losses. In this case, heat recovery limits the electrical power demand to around 4 kW for the resistance or 1 kW for the heat pump, making these systems compatible with standard domestic electrical installations. We also define the DHW heat requirements Q_{dhw}, the tank static heat losses Q_{loss}, the drain water heat recovery Q_{hx} and the total heat produced by the electrical resistance or the heat pump in the tank Q_{th}. In each case, the following conservation heat balance can be applied to verify the calculations:

$$Q_{dhw} + Q_{loss} = Q_{hx} + Q_{th} \tag{7}$$

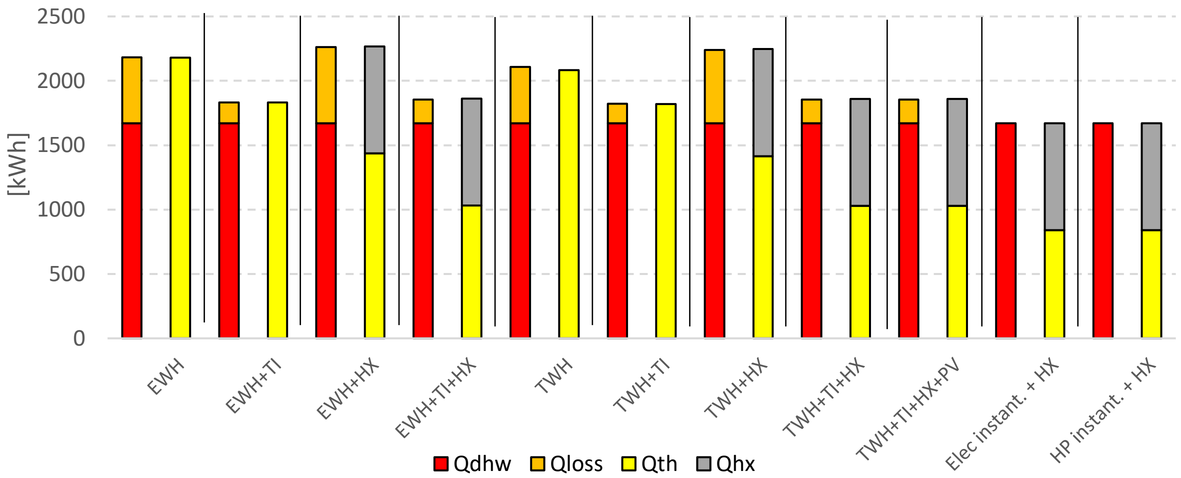

Figure 4: *Thermal balance of each configuration*

We can see on figure 4 the benefits of each configuration, and in particular the significant reduction in the amount of heat Q_{th} required to produce the same amount of DHW. On this criterion alone, configurations using a thermodynamic water heater combined with thermal over-insulation and heat recovery, as well as instantaneous production, offer a saving by a factor 2 to 3 on the amount of heat to be produced. We now define the energy performance indicators that will enable us to compare the systems from a global point of view, by defining water heater coefficient of performance *COP* (equal to 1 for electrical resistance and >1 for heat pumps) and the system performance coefficient COP_{syst} based on the amount of electrical energy from the grid E_{grid} required to produce the same amount of DHW (1671 kWh/year) (see Eq. 8 and 9).

$$COP_{syst} = \frac{Q_{dhw}}{E_{grid}} \tag{8}$$

$$COP = \frac{Q_{th}}{E_{el}} \tag{9}$$

For the last case, the photovoltaic production consumed by the TWH is subtracted from the system's overall consumption.

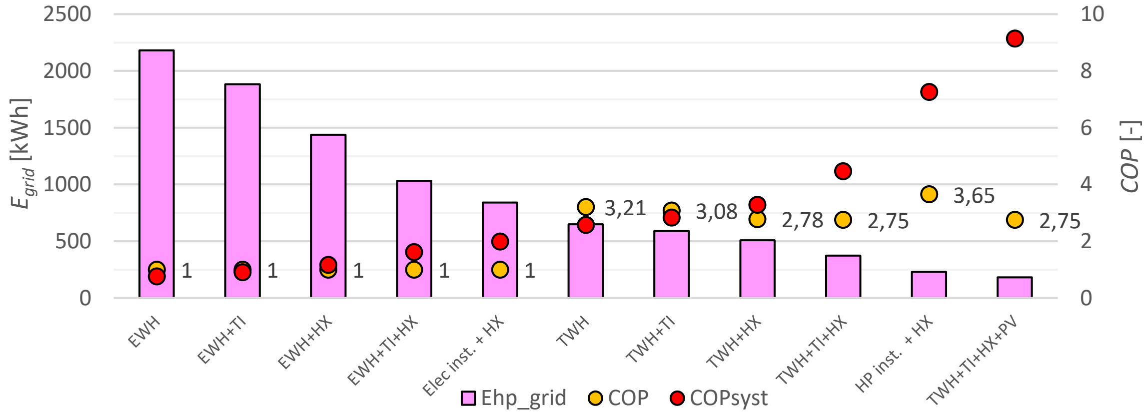

Figure 5: *Electrical consumption from grid and COP calculations*

Configurations are ranked in figure 5 in order of performance on 2 indicators: the electrical energy drawn from the grid to produce the same quantity of DHW, and the system's overall *COP*, which gives the quantity of DHW that can be produced with 1 kWh of electricity input to the system. The system's overall *COP* therefore varies from 0.77 for the reference case to around 9 for the best case, representing a 12-fold reduction in electricity consumption. These results show the significant role that static losses can play in such systems, as well as the significant impact that over-insulation, heat recovery and the use of a heat pump can have on the energy efficiency of DHW production.

4. Discussions

We have therefore studied different DHW production strategies, starting from a reference case based on a EWH (Joule effect). These different strategies are based on mass-market, relatively affordable systems (thermodynamic water heater TWH, gravity drain water heat recovery systems and insulating shells or panels) enabling “low-tech” DHW production and applicable to all types of building. The overall extra cost of such an installation (TWH+HX+PV) is around €3,000, compared with a solar installation costing at least €6,000 to €8,000 (between €1,000 and €2,000/m^2 thermal solar collector at a rate of 2 to 4 m^2 depending on the climatic zone) [12]. The coverage rate obtained by the best configuration (TWH+PV) allows very high coverage rates (89% in Strasbourg if T_{amb}=10°C, 91% if T_{amb}=20°C and 94% for Nice case), which are much higher than a solar thermal installation (between 50 and 80% according to ADEME [12]). Heat recovery, even taking fouling into account, drastically reduces electricity consumption, even though it significantly increases static losses by around 15 to 20%, due to the fact that the water in the storage tank is on average hotter. Preheating the cold water from city network and over-insulating also degrades the heat pump's *COP*, as shown in figure 5 (by around 15%), an impact that has already been studied in previous work [10]. However, the overall gain remains significant thanks to the reduction in static losses and heat recovery, enabling the heat pump to run for shorter periods. Finally, we can see that a single 400 W_p solar PV panel with very simple regulation can cover around half the heat pump's needs, doubling the *COP* of the overall system. Finally, we can compare these results with another approach proposed by the Solaronics company (PAC facteur 7 ®), which offers a heat pump that recovers grey water, this time used as a cold source to produce DHW up to 55°C. Considering grey water at 31°C, they report a *COP* of 7.34, equivalent to our configuration: instantaneous HP (air/water) + heat recovery unit, demonstrating the relevance of this simpler-to-implement combination for residential buildings.

5. Conclusion

In conclusion, we have proposed an original study which has shown that a combination of common energy systems (thermodynamic water heater, gravity heat exchanger and little “plug and play” PV panels) can achieve very high performance in DHW production in buildings. This combination is particularly cost-effective when compared with solar thermal systems, which are often more expensive and more difficult to install, especially in urban environments or during renovation work. Regardless of the climatic zone, these systems can easily achieve coverage rates of around 90%, and reduce electricity consumption by a factor of around 10 compared with a conventional electrical water heater. Figure 1 used the best configuration results to represent the Sankey diagram between the reference case (EWH) and the best case (TWH+TI+HX+PV). Payback times are relatively short, about 5 to 8 years based on the assumptions made. These systems could significantly reduce the energy consumption of buildings, and potentially free up centralized production capacity for electric mobility.

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