12[th] IEA Heat Pump Conference 2017

Design Optimization of Hybrid heat Pumps for New and Existing Buildings in France

Michèle Mondot[a], Julien Caillet[b], Cathy Tang[c]

[a]CETIAT, 25 avenue des arts, Villeurbanne 69603 Cedex, France
[b]COSTIC, Domaine St. Paul, Saint-Rémy-lès-Chevreuse 78471 Cedex, France
[c]CARDONNEL Ingénierie, 5 rue de la Mare à Tissier, 91280 Saint Pierre du Perray, France

Abstract

Since several years (2011), the French heat pump market is the largest one in Europe reaching more than 150 000 air–to-water and water-to-water units for space heating and/or hot water production in 2015. Hybrid heat pumps, defined as a combination of a heat pump and a boiler with an optimized control strategy, still only represent 2 500 units on this market. However, hybrid systems can very much contribute to energy and CO_2 emissions reduction in both new and existing buildings.
The optimization of such a hybrid system is not only dependent on the optimized control of the two heat generators but may also depends on several design aspects such as: the type, size and location of the building, the temperature level of the heating system, the capacity and COP of the heat pump, etc.
A modeling and simulation study was carried out for AFPAC, French Heat Pump Association, to evaluate the impact of different design parameters: building, heating system, heat pump / boiler type and performance, hot water production, criteria for optimized control strategy on the sizing of the heat pump and the boiler.
From the analysis of the potential market in France and from the results of these simulations, of not less than 5000 case studies on a residential house, some recommendations have been identified for optimizing the implementation and use of hybrid heat pumps in France.

Keywords : heat pump ; hybrid ; boiler ; design ; building

1. Introduction

Heat pumping technology is now well known and applied for space heating/cooling and domestic hot water production in residential buildings. The benefits compared to other conventional heating systems are higher energy efficiency, reduced emissions of CO_2 and valuable use of renewable energy such as outdoor air, water or ground.

In the case of heat pumps using outdoor air as heat source, these benefits are somehow limited due to the reduced capacity and efficiency of the heat pump with the decreasing outdoor temperature. Considering the regulatory average climate [1], in the coldest days, the heat pump may not be able to provide the heat demand of the building and a back-up heater is necessary. The back-up system might be an electrical resistance or a fossil fuel boiler. The bivalent point is therefore defined as the temperature at which the heat pump is fulfilling 100% of the heat demand of the building and below which the back-up is operated in addition to the heat pump.

In view of optimizing the energy performance of heat pumps, hybrid heat pumps defined as the combination of a heat pump with a fossil fuel boiler, for which the bivalent point is not fixed but optimized according to energy or economic performance criteria, were more recently developed.

Hybrid heat pumps are gaining more and more interest in France ; not less than 2500 units were sold in 2015, on a market of 150 000 heat pumps. A significant growth of the share of hybrid heat pumps in the French market is foreseen for the coming years. Therefore AFPAC, the French association for heat pumps, decided to perform a study for establishing recommendations for the design of hybrid heat pumps in residential houses.

The study aimed at analyzing the design parameters of a hybrid heat pump providing both heating and domestic hot water, such as: heat pump / boiler type and performance, hot water production, criteria for optimized control strategy, heating emission temperature level and for different configurations of climate, building heat demand, energy prices, etc.

From the analysis of the potential market in France and from the results of these simulations, of not less than 5000 case studies, some recommendations have been identified and are reported.

2. Description and modeling of the building

2.1. Description of the buildings

Typical residential houses of about 80-100 m² were used having different construction materials and levels of insulation.

Two levels of insulation were chosen for representing the stock of existing houses, corresponding to the French building regulations from 1974 and 1988. Two levels of insulation were also identified for new built houses, according to the RT2012 building regulation and -20% improvement. The four levels of insulation are summarized in Table 1.

Table 1. Building characteristics

	Level	Building regulation	Heat loss coefficient (W/K)*
Existing house	1	1974	386
	2	1988	212
New built house	3	2012	149
	4	2012-20%	108

* rounded figures

Based on the physical description of the houses, i.e. surfaces, building materials (walls and windows), orientation, etc. the heat losses due to the envelop and the ventilation air were calculated following the French building code rules and the European standard EN 12831: "Heating systems in buildings - Method for calculation of the design heat load" with the following assumptions:

- No oversizing capacity coefficient
- Indoor temperature set point: 19°C
- Base design outdoor temperature as stated in Table 2.

Table 2. Base outdoor temperature for the three climatic zones

Climatic zone	H1b (Nancy)	H2b (La Rochelle)	H3 (Nice)
Base design temperature	(-15°C)	(-5°C)	(-6°C)

Using the heat loss coefficient values, the heat losses at base design temperature were calculated and are reported in Table 3.

Table 3. Heat losses at base design temperature

	Building regulation level	Heat losses at base design temperature (W)		
		H1b	H2b	H3
Existing house	Level 1 : 1974	13132	9270	9656
	Level 2 : 1988	7211	5090	5303
New built house	Level 3 : 2012	5084	3589	3739
	Level 4 : 2012-20%	3688	2603	2712

2.2. Scenario of occupancy

It has been considered that the houses were occupied according to the following scenario and assumptions:

- Identical scenario every day of the year
- Constant internal load due to equipment: 40W
- 4 persons corresponding to internal loads of 90W/each
- Ambient set temperature during occupation period: 21°C from 6 am to 10 pm
- Ambient set temperature during inoccupation period : 18°C from 11 pm to 5 am
- Occupation every day of the year
    - 1 occupant from 9 am to 6 pm, every day
    - 4 occupants during remaining time

Heating season is defined from mid-September to mid-April.

2.3. Modeling of the heating load

Calculations were made using a simplified RC model developed by CARDONNEL Ingénierie and run on an hourly-step basis. In order to compute temperature setback effect and resulting heating load, this model takes into account the thermal inertia of the building and the emitters. The hourly-based calculation over the 5112 hours of the heating season results in the required annual heating load.

2.4. Domestic hot water requirement

For domestic hot water demand, a load profile “L” according to Ecodesign regulation EU 813/2013 [1] was chosen. From the definition of the load profile, the hourly volume of hot water at 40°C is calculated considering a draw-off at a rate of 10 l/min. The heating need is expressed as the volume times the temperature difference between 40°C and the cold water temperature, which is varying according to climate data.

3. Description and modeling of the hybrid heat pump

3.1. Heating and domestic hot water production

The heating system is made of a heat pump and a boiler which capacities and energy performances may vary, associated to different water-based emission systems defined by the water temperature level.

The heat pump is either a low-temperature (LT) heat pump delivering water at 35°C or a medium temperature (MT) heat pump with 55°C water outlet temperature. The nominal COP is defined for an outdoor temperature of 7°C and is 4 and 2.5 respectively. The capacity of the heat pump is ranging from 2 to 15 kW and it is combined with a gas or fuel boiler of 15, 25 or 30 kW. All three condensing gas boilers have the same energy performance, i.e. 108% at nominal load (80/60°C) and 97% at 30% part load (30°C return temperature). Fuel boilers have an efficiency of 93% at nominal load and of 95% at 30% part load.

The domestic hot water production can be either instantaneous or with a storage tank of 200 liters. Preheating of the domestic hot water by the heat pump may be possible.

The emission system is a water-based system with three levels of inlet water temperature defined at base design temperature:

- For existing houses : 45°C, 55°C and 65°C, representing low (LT), medium (MT) and high temperature (HT) radiators respectively
- For new built houses : 35°C, 45°C and 55°C, representing heating floor, low and medium temperature radiators respectively

The water flow rate is constant in the emitters and inlet/outlet temperatures are varying according to the heat demand of the building at each hourly step of simulation.

3.2. Control strategies

Two control strategies for optimizing the operation of both the heat pump and the boiler were considered:

- Energy ratio: at each hourly-step, the energy performance of the boiler and of the heat pump are compared in primary energy, using a conversion coefficient for electricity of 2.58 for France.
- Price ratio: energy prices - fuel, gas and electricity - are varying or may vary in the future depending on the "grid content /consumption". At each hourly-step, the energy costs for running the boiler and the heat pump can be compared to achieve an economic optimization of the operation of the hybrid heat pump.

The operation of the heat pump is not limited with the outdoor temperature and a simultaneous operation of both the heat pump and the fossil fuel boiler is allowed.

3.3. Modeling of the hybrid heat pump

The modeling was developed for two configurations of the hybrid system:

- With instantaneous production of domestic hot water, as shown in Figure 1. The heat pump does not contribute to the hot water production. The heat pump and the boiler can operate simultaneously for providing both space heating and domestic hot water.
- With a storage tank as shown in Figure 2. The heat pump may contribute to (pre)heat the hot water in the storage tank. Both the heat pump and the boiler operate alternatively for either space heating or domestic hot water production.

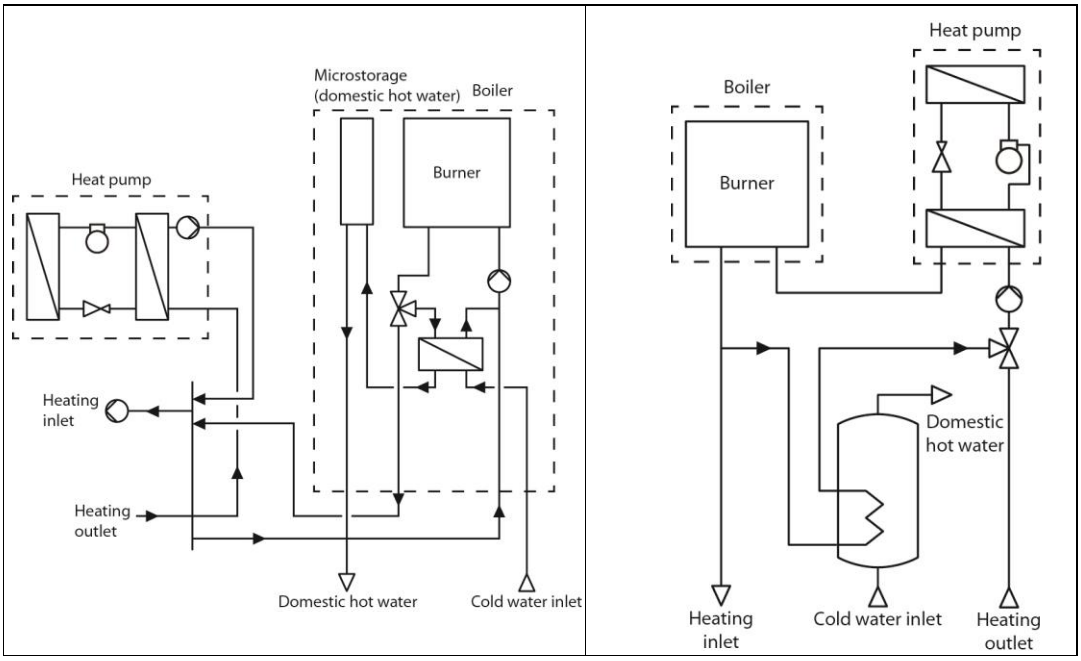

Fig 1. Hybrid heat pump with instantaneous hot water production

Fig 2. Hybrid heat pump with storage tank

The model uses the heat demand for space heating and domestic water and the water return temperature from the emission system calculated by the building model. The calculation is performed on an hourly-basis and the indicators are finally calculated on an annual basis.

The heat pump model is based on a matrix of performance representing the heating capacity and COP for a range of heat source and heat sink temperatures. In addition, the variable capacity behavior through inverter control is taken into account for part load operation as well as a standby power input when there is no heat demand. Table 4 shows an example of a matrix of performance for the low temperature heat pump.

The fossil fuel boiler is characterized by its performance, i.e. capacity and efficiency with water temperature at nominal load and at 30% part load, standby losses and auxiliary power input.

The storage tank is described as a 4-layer volume with stratification.

Table 4. Matrix of performance of the 8kW low temperature heat pump

COP		Outdoor air temperature (°C) -15	-7	2	7	20
Outlet water temperature (°C)	25	1.76	2.20	3.52	4.40	5.50
	35	1.60	2.00	3.20	4.00	5.00
	45	1.28	1.60	2.56	3.20	4.00
	55	1.02	1.28	2.05	2.56	3.20
	65	0.82	1.02	1.64	2.05	2.56

Capacity (kW)		Outdoor air temperature (°C) -15	-7	2	7	20
Outlet water temperature (°C)	25	3.04	4.12	7.29	9.59	13.55
	35	2.53	3.44	6.08	8.00	11.30
	45	1.82	2.48	4.38	5.76	8.14
	55	1.33	1.81	3.20	4.22	5.96
	65	0.97	1.32	2.33	3.07	4.34

For the control strategy, the COP of the heat pump is calculated at each hour step. It is compared to:

- The efficiency of the boiler muliplied by the elecricty conversion coefficient, for the strategy based on energy performance.
- The ratio of the electricty and gas/fuel prices, for the strategy based on economy.

4. Simulation results

4.1. Performance indicators

The selected performance indicators were chosen for evaluating the design of the hybrid heat pump on both environmental and economic criteria:

- Renewable energy share (RES): This criterion may be sensitive for new built houses for which the low energy consumption is already a requirement to fulfill according to the building code regulation. The customer may want to have a "green house".
- Share of the heat pump: This criterion indicates the contribution of the heat pump to the global demand of the building, for both space heating and domestic hot water demand.
- Primary energy efficiency: On an environmental point of view, it is essential to assess the overall energy efficiency to determine the best hybrid heat pump combination for a given set of parameters. It is expressed in % of primary energy.
- Annual operation cost and overall cost: The annual operation cost is based on the energy consumption and energy prices in €/kWh. The overall cost is estimated over a life time of 15 years including operating and investment costs. Maintenance is not taken into account as it is assumed to be independent on the hybrid combination.

4.2. Calculations

Considering the different parameters of the study:

- Climatic zone, building characteristics
- Size and performance of the heat pump
- Size of the boiler and energy used
- Domestic hot production, emission systems
- Control strategy

and their possible combinations, not less than 5000 case studies were simulated, corresponding to three major configurations:

- Existing house (combined Levels 1 and 2) with fuel boiler
- Existing house (combined Levels 1 and 2) with gas boiler
- New built house (combined Levels 3 and 4) with gas boiler

These configurations were identified from the potential market penetration of hybrid heat pumps in France. The results and recommendations for the first configuration are detailed while main results will be given for the two other configurations.

4.3. Existing house with fuel boiler

In this configuration, instantaneous domestic hot water production is not considered.

The detailed analysis of the boiler sizing showed poor indicator results when the heat pump is associated with a 30 kW boiler. This is due to the assumption of not allowing preheating of the hot water by the heat pump. For the combination with either a 15 kW or 25 kW boiler, results are quite similar.

It is to be noted as well that the control strategy, energy price or energy efficiency, was not a crucial parameter on the studied indicators.

In the following analysis, the two most influencing parameters have been identified for each performance indicator and are used to plot the behavior of this performance indicator, independently of all other parameters of the configuration.

4.3.1. Environmental indicators

The capacity of the heat pump and the outlet water temperature, i.e. type of emitters, are by far the most influencing parameters.

The two indicators, RES share and heat pump share, have similar trends: each of them is increasing with the heat pump capacity but is decreasing when the water temperature level is raised. This is shown in Figures 3 and 4 respectively.

A 2 kW capacity difference of the heat pump results in an increasee of the RES share by 500 to 1 000 kWh/year and of the heat pump contribution by 5 to 10%. This heat pump share is only ranging between 30 to 50%, except when low temperature emitters are used. However it is expected that low temperature emitters, i.e. 45°C, are seldom used in existing houses built prior 1990.

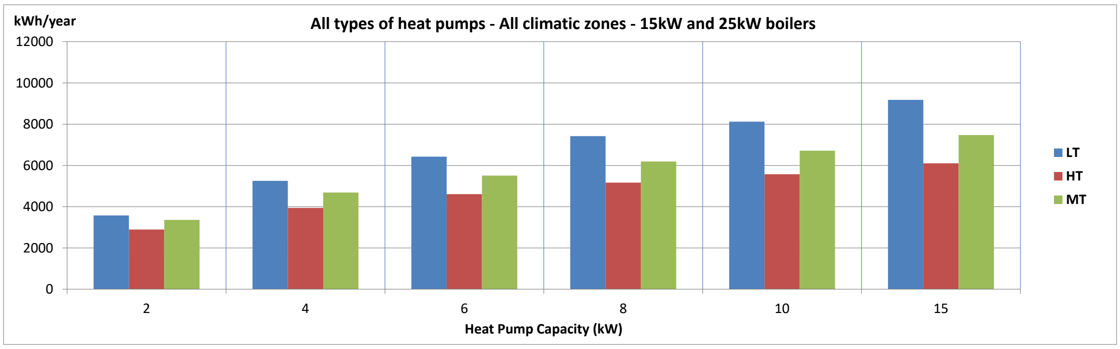

Fig 3. RES share as a function of the heat pump capacity and of the water temperature levels of emitters

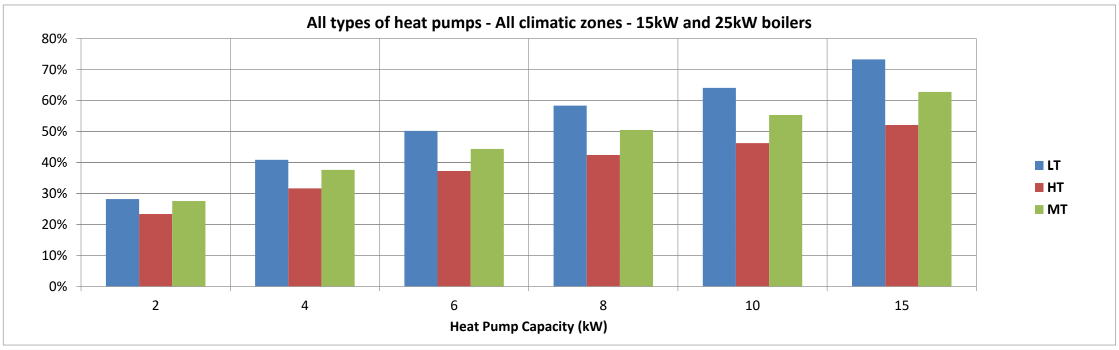

Fig 4. Heat pump share as a function of the heat pump capacity and of the water temperature levels of emitters

4.3.2. Primary energy efficiency

The detailed analysis identified the heat pump capacity as the main parameter for the primary energy efficiency.

Using this indicator will help selecting an "optimum" range of capacity for the heat pump. Figure 5 shows a relative flat trend for a 6 to 10 kW heat pump. This figure also shows the significant impact of the type of heat pump. An energy efficiency of about 92% is achieved with the low temperature heat pump, while a medium temperature heat pump allows reaching almost 105%, i.e. a 15% to 20% difference in energy efficiency. The decrease of the primary energy efficiency with larger heat pumps is due to a lower COP of the heat pump when operating at part load conditions.

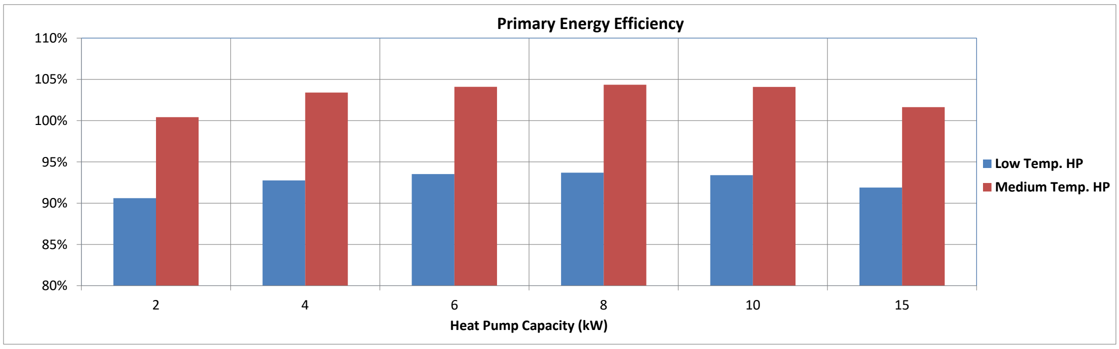

Fig 5. Primary energy efficiency vs. low temperature and medium temperature heat pump capacity

4.3.3. Costs

The annual operation cost, as shown in Figure 6 is mostly dependent on the climatic zone as the heating demands are very much different. Operating a medium temperature heat pump is less costly than a low temperature heat pump by 200 € per year, where ever the building is located. This is mainly due to the larger contribution of the medium heat pump to the preheating of the domestic hot water, considering French energy prices.

The same magnitude of the cost reduction is also achieved when choosing a 15 kW rather than a 2 kW heat pump.

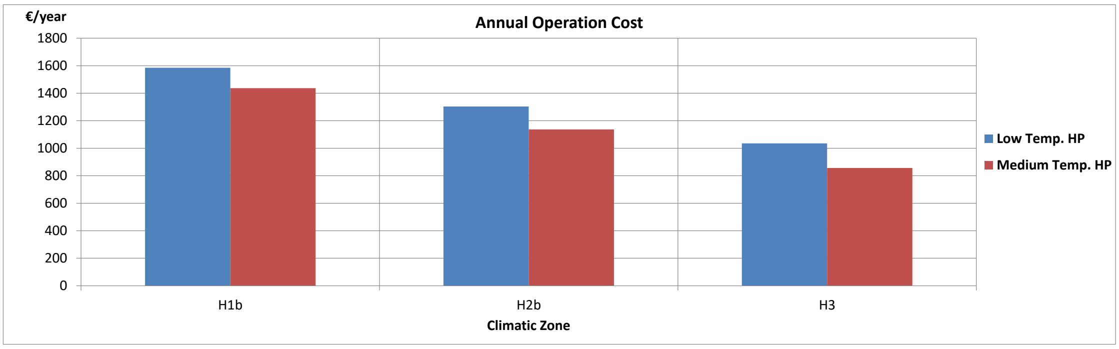

Fig 6. Annual operation cost vs. low temperature and medium temperature heat pump capacity

Considering the overall cost, which includes the investment cost, Figure 7 shows the same trend for all climatic zones and types of heat pumps, with a marked change of slope of this trend for an 8 kW heat pump.

It can be concluded that the overall cost is limited up to 8 kW and choosing a medium temperature will provide a reduced cost of 1500 to 2000 €.

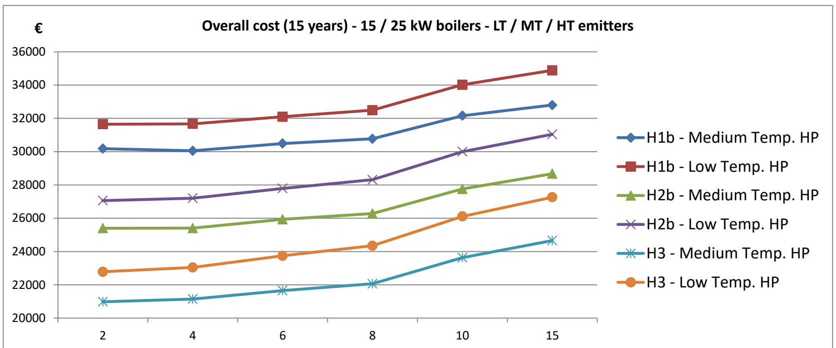

Fig 7. Overall cost vs. heat pump capacity in the existing house with fuel boiler

4.3.4. Recommendations

The overall trends of the studied performance indicators versus the capacity of the heat pump are plotted in Figure 8, all sets of other parameters being considered, in order to make recommendations.

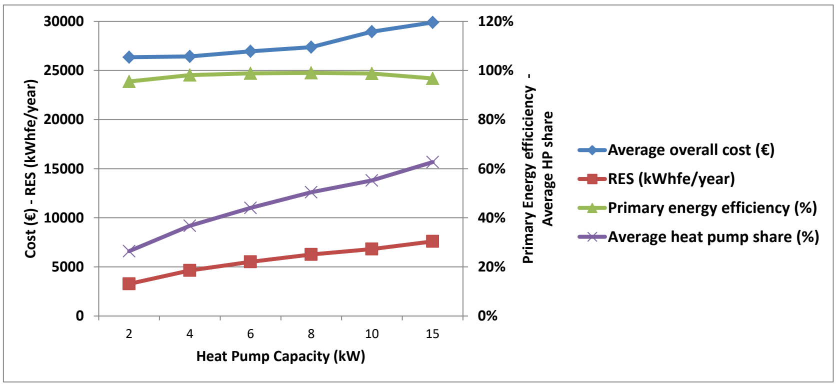

Fig 8. Evolution of the four performance indicators vs. heat pump capacity in the existing house with fuel boiler

Environmental indicators are increasing with the capacity of the heat pump. The overall cost is also increasing but with a significant emphasis for capacities above 8 kW. In the range of 6 to 8 kW is also found the optimum, quite flat, of the overall energy efficiency.

With a heat pump share of 50%, a 6 to 8 kW heat pump will allow contributing to a RES share of 5 000 kWh/year and reaching a primary energy efficiency of 100%. In these running conditions the overall cost is estimated to be 28000€ over 15 years.

4.4. New built houses with gas boiler

The overall trends of the studied performance indicators versus the capacity of the heat pump are plotted in Figure 9, all sets of other parameters being considered, in order to make recommendations.

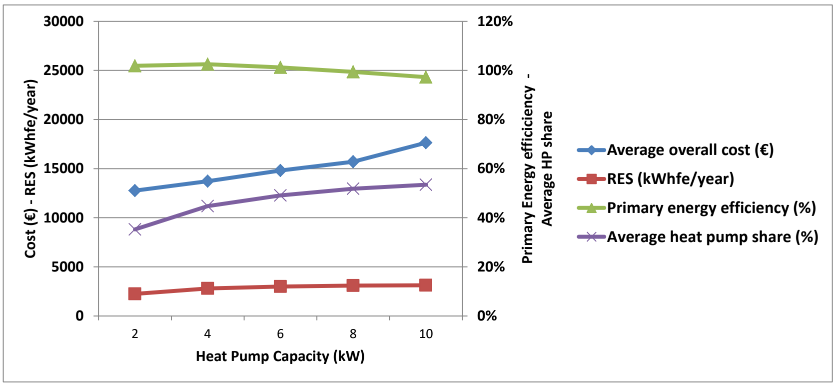

Fig 9. Evolution of the four performance indicators vs. heat pump capacity for a new built house with gas boiler

Between 2 and 6 kW capacity of the heat pump the RES share is increased by 300-700 kWh/year every 2 kW step. From 8 kW and above, this increase is reduced to 100-200 kWh/year. For the heat pump share, the trend is an increase of about 2% to 10% per 2kW.

The optimum of the primary energy efficiency is obtained in the range of 2 to 6 kW.

The overall cost is very much dependent on the investment cost of the heat pump, and thus on its capacity, as the annual operating cost is almost constant.

When considering the two domestic hot water productions, instantaneous production will lead to lower annual operating and overall costs than a hybrid heat pump with a storage tank, even though from an environmental point of view the hybrid heat pump with storage tank is far better.

4.5. Existing houses with gas boiler

The overall trends of the studied performance indicators versus the capacity of the heat pump are plotted in Figure 10, all sets of other parameters being considered, in order to make recommendations.

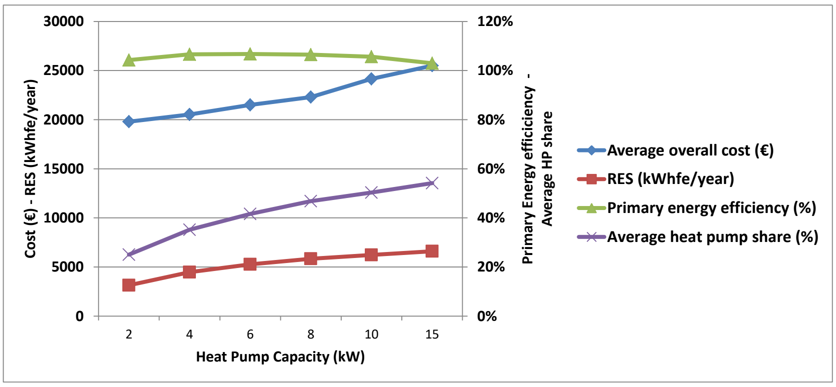

Fig 10. Evolution of the four performance indicators vs. heat pump capacity for an existing house with gas boiler

Both environmental indicators are increasing with the capacity of the heat pump; the heat pump contribution being doubled when the capacity of the heat pump goes from 2 kW to 15 kW.

The optimum of primary energy efficiency is obtained for a 4 to 8 kW heat pump.

With a hot water tank, the contribution of the heat pump to the hot water production is not negligible; especially when a medium temperature heat pump is used. The RES share is increased by 1000 kWh/year, the primary energy efficiency is raised by 15% and the annual operating cost is reduced by 150€/year compared to the use of a low temperature heat pump.

In any case, all performance indicators are the best with an instantaneous production of hot water, i.e. with no preheating by the heat pump.

5. Conclusions

The use of modeling tools allowed to simulate not less than 5000 study cases of hybrid heat pumps in order to study the influence of several design parameters (capacity, control strategy, hot water production,…) and of location and usage (climatic zones, building loads, type of energy,..) on 5 indicators representing the energy, environmental and economic performances of the hybrid heat pump in its environment of use.

Additional sensitivity analysis show that heat pump performance, domestic hot water load profile, maximum operating temperature of the heat pump may also have an influence on the resulting values of the chosen indicators but not on the observed trends.

Furthermore, several other characteristics in the design of the product (position of heat exchanger and temperature sensor in storage tank,), operation settings (temperature set points,) or change in energy prices, and assumptions in the models used for the study (occupancy scenario) may also have significant influence on the results. They should need to be investigated to mature the first conclusions given by this study.

Nevertheless, these first recommendations will help the professional sector to design optimized products for different markets, to install differentiate and dedicated products and thus to develop the recent but promising market of hybrid heat pumps in France.

Acknowledgements

The authors thank their colleagues Jean Noel and Pedro Jorquera-Ferrat (CETIAT), Cedric Beaumont (COSTIC), Christian Cardonnel (CARDONNEL Ingénierie) for their contributions to this work and the financial sponsors of the study: AFPAC, UNICLIMA, EDF, Alliance Solution Fioul, ENGIE.

References

[1] COMMISSION REGULATION (EU) No 813/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to Ecodesign requirements for space heaters and combination heaters, Annex III, table 5