Assessment of Replacing Gas Boilers with Heat Pumps for Hot Water Preparation in Car Washes

Ovidiu Talaba[1], *Alexandru* Serban[1], *Paul Daniel* Hiris[2], and *Mugur Ciprian* Balan[2*]

[1]Politehnica Bucharest National University of Science and Technology, Splaiul Independenței 313, Bucharest, Romania
[2]Technical University of Cluj-Napoca, Muncii 103-105, Cluj-Napoca, Romania

Abstract. The study provides a complex analysis for replacement of the natural gas boilers with air to water heat pumps, as the heat source for the hot water to be used in the car washing machines. It was considered heat pumps with R744 and with R290 as refrigerant, and it was proved that even heat pumps that seem to be undersized at negative temperatures, can still provide the required heat for 70 % of the full operating time. The feasibility was determined to be higher for the heat pumps with R290 and the payback period is lower than 2 years for the average car washing frequency of less than 5 cars washed / hour. The hot water storage tank can increase the period of continuous operation even at negative ambient temperature when the heat pump seems to be undersized.

1 Introduction

Complete replacing of gas consumption with renewable energy sources up to 2050 is one of the most important goals of the European Union [1,2]. Achieving this goal needs to increase the production of renewable energy by 6-8 times comparing to 2020 [3]. In this context, innovation in the use of renewable energy sources is one of the most important drivers [4].

Investigating the problem of replacing fossil fuels with renewable energy sources [5] concludes that emissions from all industries have higher negative impact than the high energy-consuming industries. Car washing is a very common activity, and probably very few of the owners of the about 1.45 billion cars existing in the world in 2024 [6] are concerned about the energy consumption and about the associated emissions.

Traditionally, the heating of the water used in the cars washers is realized with gas boilers, in small hot water storage. In this study it is investigated the possibility of using air to water heat pumps instead of gas boilers. Heat pumps are an important technology for decarbonization, being considered one of the most energy efficient and environmentally friendly technologies [7,8]. Apart from the traditional use in heating, the heat pumps can be also efficiently used in several industries [9,10]. Some applications require high temperature heat pumps [11,12], and this is also the case of the cars washing.

The application of car wash systems was investigated in this study due to the particular interest expressed by a manufacturer.

* Corresponding author: mugur.balan@termo.utcluj.ro

The problems of energy consumption and energy efficiency in cars washers are not investigated in the literature. From this perspective, this study is filling a gap in the literature.

2 Material and method

The automatic cars washers usually consume (5…8) l/min of hot water at 55 °C, while the temperature of the cold water is of about 10 °C. The common number of stations in the configuration of cars washers is 1 to 6, and sometimes even more. The thermal power of the gas boilers is 35 kW for 1 and 2 stations, up to 90 kW for 6 stations. Regardless of the number of stations, in the configuration of the heating equipment is also included a hot water storage of 200 l. This information is provided by a car washers manufacturer in Hungary, interested to replace the gas boilers heating with heat pumps.

The thermal power required to prepare the hot water ($\dot{Q}$ [kW]) can be calculated as:

$$\dot{Q} = \dot{m} \cdot c \cdot (t_f - t_i) \quad (1)$$

where:
$\dot{m}$ [kg/s] is the mass flow rate of the water,
c = 4.18 kJ/kgK is the specific heat of the water,
t_f=55 °C is the final temperature of the hot water,
t_i=10 °C is the initial temperature of the cold water.

In the context of the limited size of the heat storage tank of 200 l, it is important to evaluate the time (τ [s]) in which the quantity (m_{st} [kg]) of hot water from the storage tank will be completely consumed without the operation of any heat source was calculated as:

$$\tau = \frac{m_{st}}{\dot{m}} \quad (2)$$

The car washing process investigated in this study is characterized by intermittent but relatively constant thermal power requirement. This means that temperature variations inside the storage tank can occur, and the investigation of this parameter is important, especially in the context of the use of heat pump, with limited thermal power compared to the gas boilers.

The transitory thermal behavior of the stratified storage tanks was investigated at the Technical University of Cluj-Napoca. The detailed analytical model and its validation is presented in [13].

The heat pumps considered in this study are of the air-to-water type in monobloc construction, operating with R744 and R290, both natural refrigerants with very low Global Warming Potential (GWP).

For 1 station it was considered the following models of heat pumps, provided by the company RVS Energy Romania with R744 and the nominal thermal power (40…120) kW, and with R290 and the nominal thermal power (20…100) kW. The operating range of the ambient temperature, for these types of heat pumps is (-25…43) °C.

For the air to water heat pumps, the provided thermal power is influenced by the ambient temperature, as presented in table 1, for the considered models of heat pumps.

Table 1. The thermal power of the available heat pumps as function of the ambient temperature [kW].

Nominal thermal power [kW]	Refrigerant	Hot water temperature [°C]	Ambient temperature [°C]						
			-20	-10	0	10	20	30	40
40	R744	60	16.7	18.5	22.7	29.4	38.4	49.8	63.6
75	R744	60	31.3	34.7	42.6	55.0	71.9	93.3	119.2
120	R744	60	50.2	55.6	68.2	88.0	115.1	149.3	190.7
20	R290	55	11.6	14.5	17.1	20.2	22.9	19.4	19.7
50	R290	55	21.7	30.0	39.5	49.0	60.0	62.7	63.2
100	R290	55	43.4	61.0	79.0	98.0	120.0	125.5	127.2

***Remark**: The only reason why the tot water temperature is considered 60 °C for the heat pumps with R744 and 55 °C for the heat pumps with R290 is because the available characteristics are provided by the manufacturers of the two types of heat pumps, at these temperatures.*

It can be observed that the lower thermal powers correspond to the lower ambient temperatures.

For the considered types of heat pumps, the operating efficiency (*Coefficient Of Performance – COP*) is influenced by the ambient temperature, as presented in table 2.

Table 2. The COP for the available heat pumps as function of the ambient temperature.

Refrigerant	Hot water temperature [°C]	Ambient temperature [°C]						
		-20	-10	0	10	20	30	40
R744	60	2.1	2.8	3.6	4.5	5.3	6.3	7.2
R290	55	1.8	2.4	3.1	3.7	4.0	4.4	4.7

It can be observed that the lower COP corresponds to the lower ambient temperatures.

3 Results and discussion

3.1 Assessments about the storage tank

Table 3 presents the maximum possible operation time of the hot water storage tank with the capacity of 200 l, as function of the number of washing stations. The operating time was calculated as the time in which the water from the storage is consumed at the flow rate of 5 l/min/station or of 8 l/min/station.

Table 3. Operating time [min] from hot water storage tank without any heat source.

No. of washing stations									Remarks
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
25.0	12.5	8.3	6.3	5.0	4.2	3.6	3.1	2.8	Flow rate: 8 l/min/station
40.0	20.0	13.3	10.0	8.0	6.7	5.7	5.0	4.4	Flow rate: 5 l/min/station

It can be observed that even for 9 washing stations, the volume of 200 l can provide at least 4.4 min of operation time (with the flow rate of 5 l/min), without any heat source. This operating time corresponds to the typical car washing time of (3…5) min. With the flow rate of 8 l/min, the maximum number of stations capable of providing at less 4 minutes of continuous operation is 6.

Figures 1…4 presents the temperature variation of the water in the storage tank, considered split in 10 layers of equal width (of 20 l each), without heating, or with heating at different thermal powers. The temperatures in the considered layers are labeled T1, T2 … T10 from the top layer (1) to the bottom layer (10). The flow rate of the hot water is considered the one corresponding to 1 station, respectively 5 l/min.

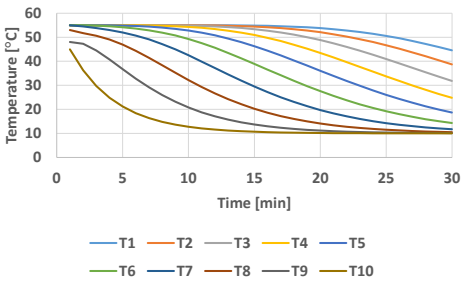

Fig. 1. Temperature variation without heating (0 kW).

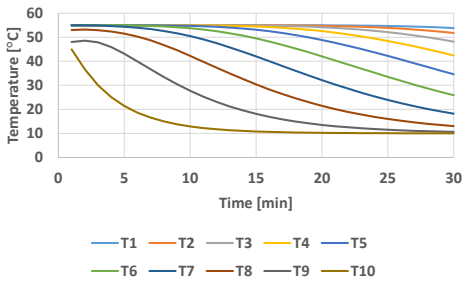

Fig. 2. Temperature variation with heating (5 kW).

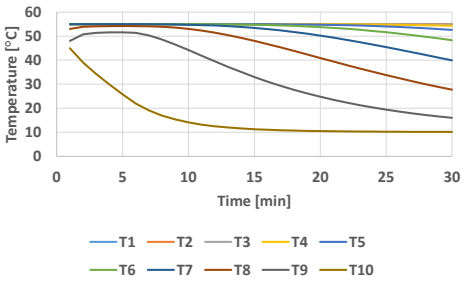

Fig. 3. Temperature variation with heating (10 kW).

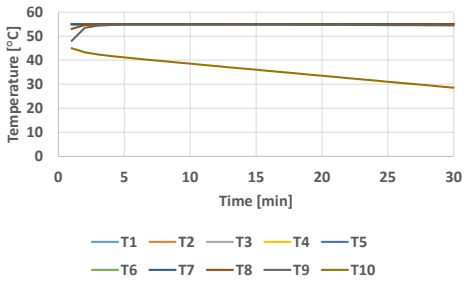

Fig. 4. Temperature variation with heating (15 kW).

Even without heating (0 kW), after 20 minutes, in the upper layer the water temperature is still 55 °C and after 25 minutes in the upper layer, the water temperature is still higher than 50 °C.

With heating (5 kW), after 20 minutes, in the upper 3 layers the water temperature is still 55 °C and after 25 minutes in the upper 3 layers, the water temperature is still higher than 50 °C.

With heating (10 kW), after 20 minutes, in the upper 5 layers the water temperature is still 55 °C and after 25 minutes in the upper 6 layers, the water temperature is still higher than 50 °C.

With heating (15 kW), in all the layers except the lower one the water temperature is maintained constant at 55 °C.

This behavior of the hot water storage tank suggests that at less for low number of stations (up to 3-4 stations), it is possible to operate the car washers with a heat source having the thermal power lower than the nominal 15 kW/station, with the condition to have (from time-to-time) downtime periods for reheating the water in the storage tank.

The figures 5…7 presents the temperatures variations in the layers of the storage tank, in one hour of full operation time, when hot water consumption is compensated with the heating powers corresponding to the heat pump with R290 of 20 kW nominal power at negative temperatures:

- 10 kW almost the heating power at -25 °C
- 13 kW almost the heating power at -15 °C
- 15 kW almost the heating power at -10 °C

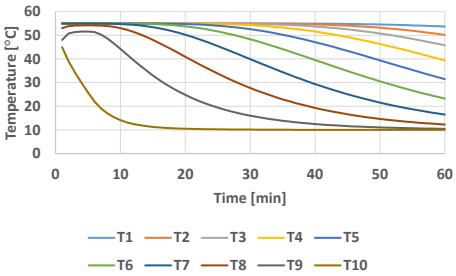

Fig. 5. Heating with 10 kW.

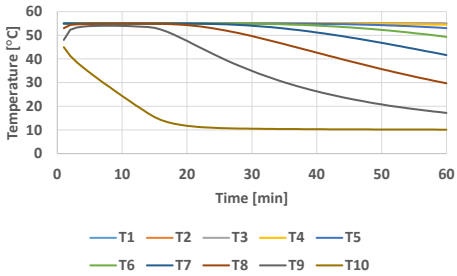

Fig. 6. Heating with 13 kW.

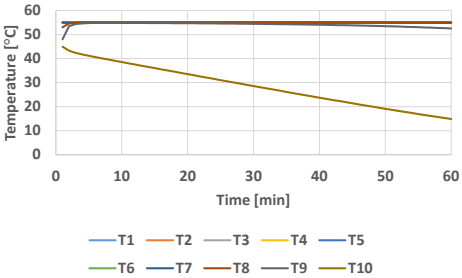

Fig. 7. Heating with 15 kW.

With the heating power of 10 kW after 60 min, the temperature in the upper layer is 53.7 ≈ 54 °C.
With the heating power of 13 kW after 60 min, the temperature in the upper 3 layers is ≈ 55 °C.
With the heating power of 15 kW after 60 min, the temperature in the upper 8 layers is ≈ 55 °C.

The temperatures variations inside the hot water storage tank, shows that with the size of 200 l, the storage allow the correct operation of the car's washers with 1 station, for 60 min of full operation time, even if with a heat pump of 20 kW nominal power, even at negative

ambient temperatures down to -25 °C, when the heating power of the heat pump is closed to 10 kW. If the ambient temperatures are of -15 °C or -10 °C, when the thermal power of the heat pump increases at about 13 kW or at about 15 kW, the water temperature remain constant at 55 °C in the upper 30 % to 80 % of the tank (depending on the ambient temperature). Thus, it is possible the continuous and correct operation even in the second consecutive hour of full operation time.

If the full operation time is maintained for many hours, and the ambient temperature is negative, after (1…3) hours (depending by the ambient temperature) it will be required the operation of an auxiliary heat source (natural gas boiler or electric heater mounted in the hot water storage tank).

If there are some downtime periods (without hot water consumption), the heat pump will be able to reheat the water in the tank (at least partially), increasing the period of possible continuous operation.

It should be also mentioned that usually at negative temperature, the cars washers do not operate continuously, because the cars owners avoid washing the cars in these conditions when exists the risk of residual water freezing.

3.2 Assessments about the heat pumps

Table 4 presents the recommended heat pumps to replace the natural gas boilers on the current car washers.

Table 4. Recommended heat pumps to replace the natural gas boilers on the current car washers.

No. of stations	R744 (CO_2)		Min. ambient temperature [°C]	R290 (Propane)		Min. ambient temperature [°C]
	Nominal thermal power [kW]	No. of HP		Nominal thermal power [kW]	No. of HP	
1	40	1	-	20	1	-
				50	1	-
2	75	1	-	100	1	-
3	120	1	-	R50	3	-
	75	1	+2	100	1	-15
4	75	2	-	100	2	-
	120	1	0	100	1	-7
5	120	2	-	100	2	-
6	120	2	-	100	3	-
				100	2	-15
7	75	4	-	100	3	-
	120	2	-5	100	2	-12
8	75	4	-	100	3	-

	120	3	-	100	2	-10
	75	3	0			
9	120	3	-	100	4	-
	120	2	+2	100	3	-15

The recommended heat pumps with limitations in the minimum ambient temperature, can only partially replace the gas boilers, only if the ambient temperatures are higher than the indicated minimum values. For each number of stations exist solutions to completely replace the gas boilers, without ambient temperature limitations.

As follows it is investigated the capability of the heat pump with R290 and the nominal heating power of 20 kW to cover the heating load in the case of 70 % of the full operation time in the case of one washing station.

Table 5 presents the considered operation periods and the considered thermal powers required for consumption and that can be produced by the heat pumps, during 70 % of the full operation time. The operation periods are marked with gray on the first line of the table.

Table 5. The considered 70 % of the full operation periods and thermal powers [kW].

Operation													**Total**
Time [min]	5	10	15	20	25	30	35	40	45	50	55	60	
Consumption	15.7	0.0	15.7	0.0	15.7	15.7	0.0	15.7	15.7	0.0	15.7	0.0	***109.9***
-25 °C	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	***116.4***
-15 °C	13.0	13.0	13.0	0.0	13.0	13.0	13.0	13.0	13.0	0.0	13.0	0.0	***117.0***
-10 ° C	14.5	14.5	14.5	14.5	14.5	14.5	0.0	0.0	14.5	0.0	14.5	0.0	***116.0***
+20 °C	22.9	0.0	22.9	0.0	22.9	0.0	0.0	22.9	22.9	0.0	0.0	0.0	***114.5***

The heat pump can provide almost the almost the whole required heating power at ambient temperatures higher than -15 °C (13.0 kW instead of 15.7 kW) or at temperatures higher than -10 °C (14.5 kW instead of 15.7 kW). The heat pump is oversized when the ambient temperatures are positive and is undersized when the ambient temperatures are negative.

When the heat pump is oversized, it will operate at reduced capacity and will stop when heating is no longer needed.

Even at negative ambient temperatures, when the heat pump is undersized, during the downtime periods, the heat pump can reheat the water from the tank and can completely provide the required heat, without the need of any backup gas boiler or electric heater. At -25 °C the heat pump will operate continuously but at ambient temperatures higher than -15 °C there will be alternative operation of the heat pump. Additionally, it should be mentioned that the contribution of the heat storage tank was not considered in this analysis.

It should also be noted that the hypothesis of 70% full operation periods is highly overestimated at negative temperatures, as the demand for car washes decreases dramatically due to the risk of freezing after washing. From this perspective, it appears that under expected normal operating conditions, the heat pump will not be undersized at all.

Economic analysis

The economic analysis is realized considering the following parameters:

- Operating time / car wash: 5 min.
- Number of cars washed / hour: (1…12).
- Number of operating hours / days: 15.

The calculated parameters, corresponding to 1 washing station, are presented in the table 6.

Table 6. The operation parameters (corresponding to 1 washing station).

Parameter	**Values**				**U.M.**
No of car washed / hour	1	5	10	12	-
No of car washed / day	15	75	150	180	-
No of car washed / year	5475	27375	54750	65700	-
Operating time / day	75	375	750	900	min
Operating time / month	2250	11250	22500	27000	min
Operating time / year	27000	135000	270000	324000	min
	450	2250	4500	5400	hours

The technical parameters considered are:

- The natural gas combustion heat: 35.8 MJ/m^3
- The gas boiler efficiency: 80 %
- The average COP for heat pumps with R 747 (CO_2): 4.5
- The average COP for heat pumps with R 290: 3.7

The cost parameters considered (for Hungary, the location of the cars washers manufacturer) are:

- The cost of the electricity: 0.18 Euro/kWh (180 Euro/MWh)
- The cost of the natural gas: 0.16 Euro/kWh (160 Euro/MWh) (1.54 Euro/m^3)

The technical and economic parameters, calculated for 1 station, for different cars washed frequency, and for different types of heat pumps, are presented in table 7.

Table 7. The technical and economic parameters for different cars washed frequency, and for different heat pumps.

Parameter	**No. of cars washed / hour**			
	1	**5**	**10**	**15**
Thermal power [kW]	15.7			
Thermal energy[kWh/year]	7054	35269	70538	105806
Thermal energy by gas [kWh/year]	8817	44086	88172	132258
Electric energy by HP R744 [kWh/year]	1568	7838	15675	23513
Electric energy by HP R290 [kWh/year]	1906	9532	19064	28596
Cost of gas heating [Euro/year]	1367	6833	13667	20500
Cost of electricity heating (HP R744) [Euro/year]	282	1411	2822	4232
Cost of electricity heating (HP R290) [Euro/year]	343	1716	3432	5147
Economy with HP R744 [Euro/year]	1085	5423	10845	16268
Economy with HP R290 [Euro/year]	1024	5118	10235	15353
Heat pumps				
Model of heat pump	**40 kW / R744**			
No. of heat pumps	1			
Price of heat pump [Euro]	29800			
Total price of heat pump [Euro]	29800			
Payback period	27.5	5.5	2.7	1.8
Model of heat pump	**50 kW / R290**			
No. of heat pumps	1			
Price of heat pump [Euro]	9980			
Total price of heat pump [Euro]	9980			
Payback period	9.8	2.0	1.0	0.7
Model of heat pump	**20 kW / R290**			
No. of heat pumps	1			
Price of heat pump [Euro]	5120			
Total price of heat pump [Euro]	5120			
Payback period	5.0	1.0	0.5	0.3

For the heat pump of 50 kW with R744, the feasibility begins from 10 cars washed / hour and the payback period is 2.7 years. For the heat pump of 50 kW with R744, the feasibility begins from 5 cars washed / hour and the payback period is 2 years. For the heat pump of 20

kW with R744, the feasibility begins from 3…4 cars washed / hour and the payback period is lower than 2 years.

Similar results were performed for 2…9 cars washing stations and each time the higher feasibility corresponds to the heat pumps with R290 that apparently seems to be undersized.

4 Conclusions

Both the heat pumps with R744 (CO_2) and with R290 (propane) can provide the required heat for preparing the hot water needed for the car washers.

For any number of stations (between 1 and 9) in the car washers it is possible to prepare the hot water with heat pumps of air to water type.

The feasibility is higher, and the payback period is lower for the heat pumps with R290 (propane).

The heat pumps with R744 (CO_2) became feasible from the average car washing frequency higher than 10 cars washed / hour (which seem to be too high).

The heat pumps with R290 (propane) became feasible from the average car washing frequency of less than 5 cars washed / hour (which seem to be reasonable).

For 1 station with a heat pump that seems to be undersized, even in periods with negative ambient temperatures, it was proved that is possible to provide the required heat for up to 70 % of the full operating time, with any ambient temperatures down to -25 °C. Anyway, it is not reasonable to consider a high percentage of operating time of the car's washers under very low negative temperature, because of the risk of residual water freezing.

The feasibility of the heat pumps that seems to be undersized is the higher possible and the payback period is the lower possible (less than 2 years with an average car washing rate of 3…4 cars / hour, and less than 1 year with an average car washing rate of 5 cars / hour).

The study revealed that the size of the hot water storage tank can increase the period of continuous operation even at negative ambient temperature when the heat pump seems to be undersized.

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