Seasonal heat performances of air-to-water heat pumps in the Greek climate

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Abstract. With the implementation of the European Union (EU) Energy-related Products (ErP) Directive, heat pumps (HPs) and in particular air-to-water heat pumps (AWHPs), are expected to be widely installed in heating systems of residential and of the tertiary sector buildings. Heat pumps are nowadays regarded as a key technology for achieving the EU strategy towards nearly Zero Energy Buildings (nZEBs) and for reducing the fossil primary energy consumption and the related CO₂ emissions. The awareness of HPs seasonal efficiency, which is affected by multiple parameters, is very important for choosing the best heat pump technology and the right equipment in a heating or cooling installation. The aim of this paper is to provide the Seasonal Coefficient of Performance (SCOP) of various AWHPs available in the Greek market from various manufacturers and installed in buildings located in the four Greek climate zones (A, B, C, D). The calculations are performed according to EN 14825 by using temperature data of four representative cities, one for each zone. Numerical results show the influence of various parameters, like HP’s compressor technology, water outlet temperature, and weather compensation to SCOP value, and highlight the importance of climate data for the accuracy of seasonal performance estimation.

1. Introduction

Heating and cooling represent the half of the EU’s final energy consumption. Most of this thermal energy, nearly 32%, is used in buildings for space and domestic hot water (DHW) heating and for space cooling. The rest 18% is used in industry for process heating and cooling [1]. Space heating accounts for more than 80% of heating and cooling consumption in colder climates. In warmer climates, consumption for space heating is lower, while the share of space cooling is higher with an increasing trend.

Buildings in the EU-28 are responsible for approximately 40% of final energy consumption and 36% of CO₂ emissions. A large percentage of the EU-28 buildings, nearly 35%, are more than 50 years old while the 75% of the building stock is energy inefficient [2]. These buildings were built when energy efficiency requirements were limited or non-existent, and most of these will still be standing in 2050. In Greece, the 52% of the buildings were built before 1979, without any thermal insulation, 44% were constructed between 1980 and 2010 according to the Greek Regulation for Building Insulation of 1979, and only 4% were built under the Greek Regulation for Energy Performance of Buildings of 2010. Since the impacts of energy use on the environment are crucial, integrating efficient heating and cooling into EU energy policies is of first priority, and efforts to achieve major cuts in energy-related CO₂ emissions must be accelerated rapidly.

The EU has put ambitious goals for the reduction of fossil primary energy consumption and the related CO₂ emissions. All new buildings must be nZEB by 31 December 2020. The targets for 2030...
are at least 40% cuts in greenhouse gas emissions (GHG) from 1990 levels, at least 32% share for renewable energy, and at least 32.5% improvement in energy efficiency. Global GHG emissions in 2030 need to be approximately 25% and 55% lower than in 2017 to put the world on a least-cost pathway to limiting global warming to 2°C and 1.5°C respectively. Furthermore, the EU has set itself a long-term goal of reducing GHG emissions by 80-95%, when compared to 1990 levels, by 2050. To achieve these goals, significant investments need to be made in new low-carbon technologies and at the grid infrastructure, the share of renewable energy is required to be increased, and energy must be used more efficiently.

The EU’s directives relating to efficiency of buildings, which are the main legislative instruments promoting the improvement of the energy performance of buildings are the 2010 Energy Performance of Buildings Directive [3], the 2012 Energy Efficiency Directive [4] and the Directive 2018/844/EU [5] which amended the existing Directives 2010/31/EU [3] and 2012/27/EU [4]. The new Directive 2018/844/EU aims at accelerating the cost-effective renovation of existing buildings, with the vision of a decarbonized building stock by 2050 [6].

Renovation of existing buildings and the energy upgrade of their heating and cooling systems is the most cost effective method to decrease energy consumption, to improve efficiency and to reduce GHG emissions. Heat pumps are among the most efficient and less polluting technologies today for heating and cooling with many applications in residential, commercial and industrial sector. Their use is expected to be widely expanded due to advancements in product design (more compact and easier to install units), advancements in the refrigeration cycle (higher efficiency, use of natural refrigerants), advancements in controls (connection with smart grids, deployment of their demand response potential), and advancements in heating and cooling systems design. Furthermore, with the implementation of the ErP Directive [7,8] concerning the eodesign and energy labeling of energy-related products and appliances, conventional high temperature hydronic heating systems are expected gradually to be replaced with low temperature ones. Low temperatures heating systems have the advantage of lower heat losses in the heat distribution and the possibility of using HPs with high coefficient of performance. Therefore, HPs as efficient heat generation systems are expected to be widely installed in low temperature heating systems and replace low efficiency heating technologies based on fossil fuels.

Heat pumps are mentioned in the European Directives [3,4,7,8] as one of the environmentally friendly technologies which use renewable energy. Additionally, in the Directive 2009/28/EC on the promotion of the use of energy from renewable sources [9], they are recognized as appliances that use renewable energy sources (RES) from air, water and ground. The part of the energy output (useful energy) that exceeds the primary energy needed to drive the HP is considered as RES. Heat pumps are nowadays regarded as a technology, without which it is not possible to achieve the EU strategy towards nZEBs and to reach targets for a reliable, affordable and sustainable energy supply.

Heat pump market is expected to develop at a fast rate. This assumption is based on the current and short-term future policy framework and technology development that serves as accelerator: (1) the greening of the electricity grid, (2) decreasing cost for PV, and (3) the integration of heat pumps into the internet of things (IoT) due to the availability of sensors in heating systems and buildings as well as better connectivity to the internet to provide weather forecast data and allow for remote monitoring. The deployment and the expected market growth of HPs mean a transition in the primary energy sector from gas/fuel/carbon to electricity for the end uses of space heating, space cooling and water heating. This means increased electricity loads which must be served by the grid, even though the upgrading of buildings thermal insulation will reduce the needs for heating/cooling. By installing thermal storage in heating and cooling systems, HPs can serve as thermal batteries providing demand response services and allow more renewable electricity in electricity generation. Moreover, HPs can also use electricity produced on site, thus reducing the stress that an increased electricity demand may put on the grid.

Regarding the compressor technology, the basic type of HPs features a fixed-capacity compressor which can only operate at full power, and so it must regularly switch on and off in order to maintain a given internal temperature. This technology is gradually replaced by the fully modulated inverter driven technology which gives the ability to reduce power output to any desire level and thus control
precisely output temperatures, resulting considerable energy savings compare to fixed-capacity models.

2. Heat pump definition and performance factors
Heat pumps are machines, devices, installations that draw heat from the natural environment, i.e. air, water or ground, and transfer it to buildings (heating mode), by reversing the physical flow of heat such that it flows from lower to higher useful temperature with the use of mechanical work. Reversible HPs can also transfer heat from a building (cooling mode) to the natural environment [3]. Primary energy input from electricity, gas or fuel in needed to drive HPs, either with vapor compression or absorption refrigeration cycle. Only heat pumps with a heat output that significantly exceeds the primary energy needed to drive them and the additional heating, if needed, should be considered as sustainable energy devices [10] that use RES.

Heat pumps yield the thermal energy that “pump” from the environment to a higher temperature. Depending on the application, this energy can be used for space heating (low temperature hydronic systems, warm-air or convective systems with fan-coil units) and for water heating (DHW, swimming pools or hot water for processes). Generally, it is recommended the HPs to serve both for heating and cooling applications. This can be performed with either a reversible (heating–cooling) or a double effect system [11].

The efficiency in operation of a HP is characterized by the Coefficient of Performance (COP) in the heating mode and the Energy Efficiency Ratio (EER) in the cooling mode. These measures represent the ratio between the useful thermal energy and the energy consumed (drive energy), both expressed in W. The COP and EER are momentary values measured under steady state operating conditions, based on EN 14511 [12], in a lab environment. These indexes are comparable to the steady-state efficiency of oil- and gas-fired furnaces. The annual average performances on a seasonal basis are given by the Seasonal Coefficient of Performance (SCOP) and the Seasonal Energy Efficiency Ratio (SEER), for heating and cooling mode respectively. The SCOP is the ratio of output heating energy (expressed in thermal Wh) to input electrical energy (expressed in Wh of electricity), while the SEER is the ratio of output cooling energy to input electrical energy. HP’s seasonal efficiencies are similar to the seasonal efficiency of a fuel-fired heating system and include energy for supplementary heating. They are calculated by taking into account a series of external factors, like the ambient air temperature, which continuously varies with time during the heating and cooling season, the building thermal load, and the control system of the HP and of the heating system. Weather data characteristic of long-term climatic conditions (bin data) are needed for the SCOP and SEER calculation, based on EN 14825:2016 [13].

The more efficient HPs become, the larger their RES contribution and their field of applications towards the nZEBs. On the other hand, the more efficient the average EU power mix is, the better the efficiency of HPs primary energy use. With the 100% greening and decarbonization of the electricity sector, heat pumps will provide 100% renewable, emission-free heating and cooling.

Heat pumps work most economically when the difference between the heat source and the heat sink temperature is as low as possible. Therefore, low temperature heating systems, such as radiant-floor or wall heating are the ideal partners for the HP. In large cities, due to the good accessibility of air as a heat source, air-to-water heat pumps (AWHPs) will be preferred as an environmentally friendly solution with high efficiency and low operation cost. AWHPs are cost-competitive, have a simple design, are easily installed, even in renovations of buildings, and the available product range is covering a wide range of applications.

The awareness of HPs seasonal efficiency, which is affected by multiple parameters, is very important for choosing the best HP technology and the right equipment in a heating or cooling installation. Efficiency also, is strongly affected by local climatic conditions of where the device will be installed. Since the initial investment cost of an AWHP is quite considerable, operation cost, depended mostly on seasonal performance, should be as low as possible.

The aim of this paper is to provide the average SCOP of AWHPs available in the Greek market from various manufacturers and located in the four Greek climate zones. The parameters which are examined are the local climate, the heating capacity of the HP, the hot water outlet temperature to the
heating system, and the water outlet temperature variance (operation with weather compensation). The calculations are performed according to EN 14825 [13] by using bin data of four representative cities (Heraklion, Athens, Thessaloniki and Florina), one for each climate zone (A, B, C, D).

3. Climate data and bin distribution
For the evaluation of the SCOP, the European Standard EN14825 [13] suggests the bin-method in order the variation of outdoor temperature to be considered. Bins are temperature intervals, usually of 1K size, in which the external air temperature occurs, on average, a certain number of hours during a given month or during the whole heating or cooling season. Since the climate varies across Europe, EN14825 considers three different climate zones (colder, average and warmer, with design temperatures of -22°C, -10°C and 2°C respectively) and provides the number of hours in each bin, for each of the climate zones.

Greece is classified in the “warmer” zone and the bin data given in [13] for this zone are supposed to be used for the calculation of SCOP in all country locations. In this work, in order to take into account the particular climatic conditions of the various climate zones in Greece, SCOP values were not calculated with the bin profile of the “warmer” zone, but by using bin data of four representative cities [14] [15] [16], one in each of the four climatic zones of Greece [17]. These cities are Heraklion (35.34 N, 25.14 E, in zone A), Athens (37.98 N, 23.72 E, in zone B), Thessaloniki (40.64 N, 22.94 E, in zone C) and Florina (40.72 N, 21.57 E, in zone D) with outdoor design temperatures of 7°C, 2°C, -2°C and -7.5°C respectively [18]. Additionally, the SCOP calculations were also performed by using the data of the “warmer” zone, given in [13], in order to compare the results with those at the four above mentioned locations.

4. Building heating load
The method for the evaluation of the SCOP is given in [13]. According to the calculation procedure, the heating load of the building at each bin \( P_h(i) \) in (W) is determined with the following equation:

\[
P_h(i) = P_{des} \cdot \left[ \frac{T_{bal} - T_{oa}(i)}{T_{bal} - T_{des}} \right]
\]

where, \( T_{oa}(i) \) is the corresponding outdoor air temperature at the i-th bin, \( T_{des} \) is the design outdoor temperature (°C) of the building location, \( T_{bal} \) is the balance-point temperature (°C), and \( P_{des} \) is the design heating load of the building in (W), calculated according to EN12831.

The balance-point temperature \( T_{bal} \) is the outdoor temperature at which, for a given inside building temperature \( T_{int} \), the total thermal losses of the building are equal to its internal and solar heat gains, that is the outdoor temperature at which the building requires no heating.

Figure 1: Building heating load and HP’s heating capacity curves
An example of a building heating load curve (BHL), which determines the heating demand at various outdoor temperatures, is shown in figure 1 with the red line drawn. The maximum heating load, equal to 30kW in this example, corresponds to a \( T_{des} \) of -2°C, and the zero heating load corresponds to a \( T_{bol} \) of 16°C.

In the present work, the SCOP values of the HPs were calculated with this assumption: the building’s maximum heating load (design load) was matched exactly with the maximum heating capacity of the HP at the \( T_{des} \) (green line at figure 1), namely for each calculation case the HP was neither oversize nor selected with a declared capacity at \( T_{des} \) lower than the design load \( (P_{des}) \). Supplementary back-up heating is needed only when the outdoor temperature falls below the design outdoor temperature \( T_{des} \).

5. Heat pump characteristics

The heating capacity of an AWHP depends on the outdoor temperature. The heating capacity curves, at different fixed values of the hot water temperature \( (T_w) \) supplied by the heat pump, can be found at the technical data sheets of the heat pump manufacturers (or can be plotted by the HP’s technical data given in these sheets). According to the AWHP type, the number of the characteristic heating capacity curves is different. A single curve (green line in figure 1) represents the heating capacity of mono-compressor fix capacity (ON-OFF) HPs, while the heating capacity curves of inverter-driven HPs are at least two (green and blue line in figure 1), corresponding to the maximum and minimum inverter frequency respectively, or a group of curves between the maximum and minimum.

In this work, sixty-six models (sizes) of AWHPs from nine manufacturers [19-27] were selected with a declared capacity equal to the building design heating load in each case study. Data were collected from manufacturer’s data books, available either at the companies’ websites or from their commercial sales offices in Greece [19-27]. As an example, in table 1, the minimum and maximum declared heating capacity along with the COP, at water outlet temperatures \( (T_w) \) of 35°C and 45°C, for one of the selected HPs are given. The TOL is the operating limit temperature of the HP.

| \( T_w \) (°C) | Min | Max | Min | Max |
|---------------|-----|-----|-----|-----|
| TOL (-20)     | 0.59 (2.40) | 2.34 (2.40) | 0.51 (1.90) | 1.37 (1.90) |
| -7            | 0.82 (2.88) | 4.50 (2.27) | 0.72 (2.35) | 3.93 (1.85) |
| 2             | 1.07 (3.43) | 5.95 (2.78) | 0.94 (2.79) | 5.21 (2.27) |
| 7             | 1.40 (4.28) | 8.00 (3.53) | 1.23 (3.49) | 7.20 (2.87) |
| 12            | 1.60 (4.93) | 9.38 (4.10) | 1.41 (4.02) | 8.39 (3.32) |

6. Energy calculations

An energy analysis was conducted for the estimation of the seasonal performance of the 66 models of AWHPs, as described in [13]. This analysis includes the calculation of: a) the total thermal energy of the building \( (Q_h) \), b) the total electricity consumption of the HP \( (E_{HP}) \), c) the total electricity consumption of the back-up heater \( (E_{bup}) \), and d) the total electricity consumption of the HP when it is in nonoperational mode \( (E_{off}) \), namely in thermostat-off, in stand-by, in crankcase heater or in off mode.

The building thermal energy demand corresponding to the i-th bin, expressed in Wh, is estimated as:

\[
Q_h = P_h(i) \cdot t_{bin}(i)
\]
where, \( t_{\text{bin}}(i) \) is the occurrence in hours of the \( i \)-th bin.

After performing the calculations at all bins and summing up all energy quantities, the seasonal coefficient of performance (SCOP) is calculated according to the equation:

\[
SCOP = \frac{q_h}{E_{HP} + E_{in} + E_{off}}
\]

(3)

The variables of this analysis are: a) the climate at the building location (Heraklion, Athens, Thessaloniki and Florina), b) the water temperature produced by the HP (35°C and 45°C) and c) the water outlet temperature variance, namely either fixed water temperature (FWT) or variable water temperature (VWT) (with or without weather compensation respectively).

7. Results and discussion

In figures 2 to 5 the minimum, the average and the maximum SCOP values, of all the AWHPs of the sample examined, at the four cities (Heraklion, Athens, Thessaloniki and Florina) are illustrated. These values are presented both for fix capacity HPs (charts at the left of figures) and for inverter driven HPs (charts at the right of the figures), with water outlet temperature of 35°C (charts at the top of figures) and of 45°C (charts at the bottom), in correlation with the HP’s heating capacity (0÷15, 15÷30, 30÷50 and >100kW) and the water outlet temperature variance (FWT or VWT).

From the results shown in all diagrams, it can be seen that the lowering of the water outlet temperature from 35°C to 45°C the performance of the HPs increases drastically. The estimated average SCOP at 35°C water outlet temperature as compared to the corresponding at 45°C outlet temperature is 21÷29% (0.60 to 0.75 in SCOP values), for HPs without compensation, and 13÷19% (0.4 to 0.60 in SCOP values) higher, for HPs with compensation, depending on the HP’s capacity range and the local climate.

Weather compensation causes an increase of the performance by 5÷12% (0.20 to 0.35 in SCOP value) and by 11÷23% (0.30 to 0.65 in value) for 35°C and 45°C water outlet temperature respectively.

Figure 2: SCOP values with bin data of Heraklion
The SCOP is also associated with the HP’s compressor technology. This is highlighted by the fact that the estimated SCOP values of inverter driven HPs are 2÷17% (0.10 to 0.6 in SCOP values) and 0÷19% (up to 0.60) higher than the SCOP of fix capacity HPs, for 35°C and 45°C water outlet temperature respectively, depending on the HP’s capacity range and the local climate.

Figure 3: SCOP values with bin data of Athens

Figure 4: SCOP values with bin data of Thessaloniki
As it was expected, SCOP values are increasing progressively from the northern locations (city of Florina, at climate Zone D) locations to the southern (city of Heraklion, at climate Zone A). In table 2 the average SCOP values range are presented both for fix capacity and for inverter driven HPs, with water outlet temperature of 35°C and of 45°C as parameter. Additionally, the results in figures 1 to 5 show that there is not any strong correlation among the SCOP average values and the HP’s heating capacity. Only, in some cases, at heating capacities above 100kW the estimated values are higher than in smaller capacities, especially for the city of Florina.

Table 2: Range of average SCOP values in the four representative cities

| FIX CAPACITY HPs | INVERTER HPs |
|------------------|--------------|
| T_w = 35°C       | T_w = 45°C   | T_w = 35°C | T_w = 45°C |
| Heraklion        | 3.23 ± 3.66  | 2.59 ± 3.15 | 3.49 ± 3.90 | 2.79 ± 3.34 |
| Athens           | 3.20 ± 3.63  | 2.50 ± 3.21 | 3.65 ± 4.15 | 2.87 ± 3.61 |
| Thessaloniki     | 3.08 ± 3.56  | 2.41 ± 3.11 | 3.52 ± 3.91 | 2.74 ± 3.44 |
| Florina          | 2.81 ± 3.35  | 2.21 ± 2.96 | 3.15 ± 3.61 | 2.46 ± 3.11 |

In figure 6, the average SCOP values of the 66 AWHPs under consideration, which were estimated with the climate data of the four cities as well as with climate data of the Warmer zone of Europe, as this is defined in [13], are presented. This figure highlights how important is the climate of the region where the building is situated for the accuracy of the results. This influence of the local climate to HP’s efficiency was also shown by other researchers [28, 29, 30]. To be more specific, the average SCOP values estimated by using the bin data of the Warmer zone, given in the EN14825, are 3±7% higher (0.10 to 0.25 in average SCOP values) than the estimated values for the city of Athens, according to the operation features. Additionally, the differences in the corresponding results for Thessaloniki and Florina are greater (8±12% and 15±28% respectively according to the operation features), by using local climate data.
Figure 6: Comparative SCOP values in the four representative cities and the EN 14825

It has to be mentioned that in figure 6 and in the most cases, the average SCOP values in Athens are greater than those of Heraklion, even though the $T_{des}$ of Heraklion is higher than the $T_{des}$ of Athens. This is explained by the fact that, in Heraklion the frequency in hours at bins below the $T_{des}$ (7°C) are significantly more than those in Athens. Since in all cases the HPs were selected with a heating capacity equal to the building’s design heating load, it can be concluded that the HPs operate with back-up heaters for more hours in Heraklion than in Athens, resulting in lower SCOP values.

8. Conclusions

In this paper, estimated values of SCOP for AWHPs installed in four cities, representative of the four Greek climate zones, are presented. The procedure described in the EN 14825 was followed for the calculations, with actual climatic data of these cities. Additionally, SCOP values with the use of the climate data of the Warmer European zone, as defined in EN 14825, were calculated. The variables of this analysis, instead of the climate data, were the water outlet temperature, the operation mode, and the HP’s heating capacity. The results are the minimum, average and maximum values of SCOP in the four cities, classified according to the above variables. Instead of the differences between the four cities, from the obtained results it is evident that the water outlet temperature affects significantly the HP’s SCOP, especially in HPs without weather compensation. Also, it is demonstrated that higher SCOP are achieved in VWT operation mode, especially with 45°C water outlet temperature. Additionally, the importance of HPs compressor technology in overall performance is highlighted. Finally, the results indicate how important the climate data are for the accuracy of SCOP estimation. These can be used for updating the average SCOP values for AWHPs installed in Greece [17].

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