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Hydronic Optimization for a good Heat Pump Performance

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Abstract

Many gas-fired boilers are likely going to be replaced with heat pumps in the very close future [1], supported by current energy plans. Air-to-water heat pumps will be increasingly used as sources for hydronic heating systems. Consequently, water-based systems need to have low OPEX for obtaining a solid business case with good ROI. As a common pragmatic solution an A/W heat pump is recommended with low temp. heating systems, typically floor heating, where the temperature curve is lower compared to conventional radiator heating system. However, in most boiler replacement cases radiators are installed in residential and residential like buildings. Acceptable ROI is obtained by having superior SCOP of the HP together with an optimized design of the hydronic system, including distribution and heat emission. This paper describes the role of hydronic controls, which in traditional radiator heating systems is governed by TRVs and Hydronic Balancing, the relation to the HP efficiency, with the goal to achieve best ROI. This is realized without compromising comfort, and is a marginal cost of the additional Building Automation and Control devices to be installed or upgraded together with the HP. Investigations and results are oriented to parameters which leads to reduced operational temperatures and longer lifetime for the HP.

Keywords: heat pump, low temperature readyness, TRVs,residential heating, condensing boiler replacement, electrification of heating, controls, thermostats;

1. Introduction

1.1 Methodology

Best practice and system design was investigated through interviews to technical specialist from the industry in focus markets, mainly designers, project engineers and installers in UK, IT, FR and DE and through a wide search of the recent literature (see Bibliography and References) including e.g., associations white papers, technical articles, and best practice manuals, dedicated to application, and design for residential buildings retrofit. Calculations and theoretical simulations were carried out to investigate limitations on hydronic flows for the building heating installation. Analysis of the building stock was made using available data from BPIE to show potential energy savings when reducing indoor temperatures and thus accepting the performance of the existing radiators, working at lower temperatures with a heat pump.
Unicity of the work is based on the combined knowledge of the authors on heat pumps technology and on building hydronics. These two perspectives are necessary to optimize the system in retrofit applications, as the main system components in heating distribution and emission of existing old buildings were not designed and commissioned to match the characteristics of heat pumps. The paper formalizes a pragmatic methodology based on steps, that helps installers in the system design evaluation and needed corrective actions when heat source technology is changed.

1.2 Acronyms and Nomenclature of relevance.

HP	Heat pump
A/W	Air to Water
SCOP	Seasonal Coefficient of Performance
COP	Coefficient of performance (kWhth/kWhel)
TRV	Thermostatic Radiator Valve
eTRV	Electronic Thermostatic Radiator Valve
W/W	Water to water
RV	Radiator Valve
CAPEX	Capital expenditure
OPEX	Operational Expenditure
ROI	Return on Investment
Tsupply	Supply water temperature from the HP
Treturn	Return water temperature to the HP
Supply	Supply water from the HP
Return	Return water to the HP
Heat sink	Entity to which an amount of energy must be or can be provided

1.3 Boiler replacement with HP in small systems.

The electrification of heating means a tremendous acceleration of the deployment rate of heat pumps. Heat pumps are used with different technologies and capacities, they can be adapted to natural heat sources (i.e., air and water) or recover energy from waste heat sources that would otherwise be lost. Large scale MW sized heat pumps will typically be used in connection with district energy systems and local planning needs to be done to establish the best size and distribution of the heat pumps in connection with heat source locations. In areas where district heating is not foreseen and in buildings where hydronic heat distribution is already installed, a ground source (W/W) heat pump or an air to water (A/W) heat pump will often be preferred as replacement for a gas or oil boiler.

In contrast to a boiler which has a nearly constant efficiency over supply temperature (condensing boiler efficiency mainly depends on return temperature), the heat pump has a more complex nature to observe if the optimal efficiency should be achieved. The energy output from the heat pump consists of the energy from the heat source and of the electricity provided to create the temperature lift between the heat source and heat sink. The electricity consumption increases with the temperature lift i.e., the supply temperature of the hydronic systems should be minimized to have an optimal COP. In new buildings – or building undergoing deep renovation - this can be done by using low temperature floor heating. However, in buildings where deep renovation is not done, the existing heat emitters are often kept, and the risk is that the newly installed heat pumps run with a far lower COP than nominal. This is often because basic optimization parameters on the buildings hydronic system are not sufficiently observed. With other words, the building hydronic system should be optimized for the heat pump operation to ensure consumers the full potential of the “boiler to heat pump” replacement.

Target objective of this paper is to describe what to observe when a small size boiler (typically wall hanging) is replaced in a single-family house or dwelling where radiators are used as heat emitters.

2. Low temperature readiness of buildings

Following EN14825 “low temperature readiness” of a building means its ability to provide the users good comfort when the energy source delivers supply temperatures at 35°C or lower.
The far majority of buildings including their heating systems were designed and built throughout the last century. Past retrofit measures may have changed the primary fuels used to service the building (e.g., coal replaced by oil, then by gas), but many heat distribution components and heat emitters still remain a part of the current heating systems.

2.1. Readiness evaluation

Typical other elements to evaluate the low temperature readiness of the building are:

1) Reduce the basic energy demand: evaluate and optimize the level of envelope insulation. Walls, windows, roofs can be insulated, but also minor means such as improving the backwall of the radiator by installing an insulating/infrared reflecting panel.
2) Optimise the ability to operate at reduced supply temperatures. The size of specific radiators: Often radiators are over dimensioned for the temperatures during boiler operation. This may turn into an advantage for the heat pump operation at lower temperatures, especially when adapting the right controls and using them in the right way. Replacement of critical radiators. A simple way to increase the heat output is change from e.g., 1 panel to multi panel radiators with convectors, of the same installation dimensions. This implies no change on the piping system.
3) Validate and upgrade the installed controls: building automation and control systems play a big role in energy efficiency and the ability to achieve heating needs at lowest possible supply temperatures. Controls should be checked or upgraded to ensure the low temperature demands. E.g., in relation to flow capacity and hydraulic balancing.
4) Behavior of occupants: Are they utilizing the available radiator surfaces in the optimal way by having all radiators emitting heat in a balanced way. Are they able to program the heating according to different time schedule? Low temperature heating needs a more stable temperature setting.

2.2. Resilient buildings

The water flow supply and return temperatures to the heating emitters are impacted by the type of heat source installed. A heating system using traditional boilers operates normally with supply temperatures of 70-80 degrees with temperature drops of 15-20 degrees trough the heat emitters. The high supply temperature is obtained without compromising the efficiency as traditional boilers are much less sensitive on this parameter. When installing a heat pump the supply temperature can be directly set, but this temperature setting has a high impact on the efficiency of the system and thereby also the OPEX. Heat pumps should as a rule of thumb always be operated with the lowest possible supply temperatures.

A good performing heating system, independent of the heating source, relies on efficient controls, appropriate temperature settings, and a well-balanced hydraulic system.
A balanced hydraulic heating system provides a uniform temperature drop across all radiators. This temperature drop, at nominal or design conditions, is expected to be 15-20 °C when applying a condensing boiler or even higher with a connection to district heating. With a heat pump, this drop due to the low supply temperature is likely in the range of 5-10°C. It means the heat emitter has a more uniform temperature distribution to compensate for the lower supply temperature.
A properly balanced building distribution enables to reduce supply temperature [2], as the balancing will avoid overflow by specific bad performing radiators or wrong operated TRVs. Specific radiators that are too small to emit the needed heat output at the desired supply temperature should be replaced. This will likely be limited cost wise, compared to the CAPEX for the heat pump. A study across the EU has shown that hydraulic balancing is unfortunately not common, and only 10% of buildings heating systems are correctly balanced. [3]

3. Radiator design and flow

3.1. Hydronic radiators physics

The heat rate, or emission, from a radiator is defined in EN442-2 and depends on the over temperature ΔT and the radiator constant K_m. Expressed by:

$\Phi = K_m * \Delta T^n$;

Where:
Φ is heat output in W
K_m is the radiator constant.
ΔT is the difference between the mean radiator temperature and the room temperature.
n is an exponent, also defined in the radiator model

Considering that the radiator is not replaced when a heat pump is installed and assuming K_m and n is held constant, the only way to maintain the heat output Φ is to maintain the ΔT of the radiator.
ΔT can be simplified to the difference between the average temperature of the radiator (T_{av}) and the room temperature (T_{amb}).

The simplest method is called the arithmetic over-temperature, where:

$\Delta T = T_{mean} - T_{amb} = (T_{inlet}+T_{outlet})/2 - T_{amb}$.

A more representative method, which takes the nonlinearity of the temperature over the radiator into account, is the logarithmic over-temperature, and will be used in this article, where:

$\Delta T = T_{mean} - T_{amb} = (T_{inlet}-T_{outlet}) / \ln ((T_{inlet}-T_{amb})/(T_{outlet}-T_{amb}))$

Maintaining the ΔT requires that when reducing the T_{inlet} ,should be lowest possible for a good HP COP, T_{outlet} should increase, and this requires a higher flow through the radiator [4].

Above simple formulas are used to describe the radiator behavior in a simple way. A more detailed numerical description on the radiator physics can be read in [5] .

3.2. COP vs supply temperature

The COP of the heat pump will increase as the temperature lift is decreasing, see Fig 1 [6], the example of a air to water HP. It means the COP can be maximised by realising a heating system that requires a low supply temperature. This should also be considered when retrofitting a radiator system i.e., the supply temperature should be set as low as possible.

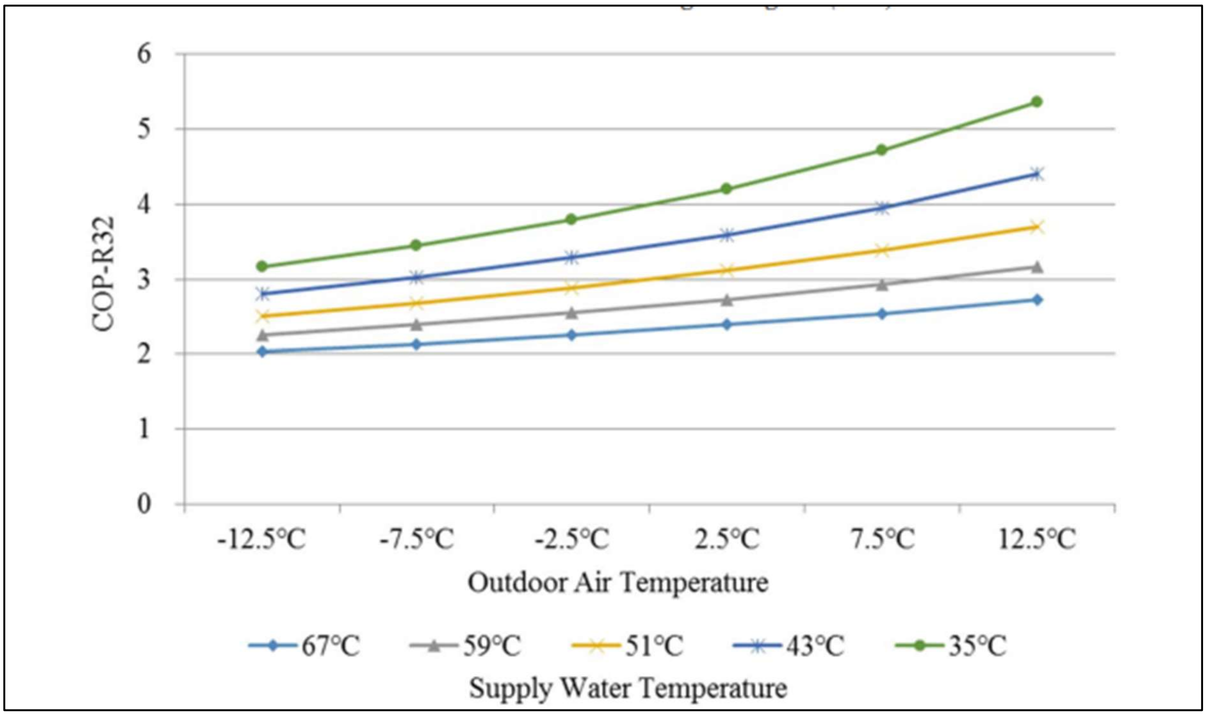

Fig. 1. The COP of air source heat pump operated with R32 under varied outdoor air and supply water temperatures.

3.3. Capacity evaluation and new settings

As mentioned, a challenge when retrofitting is to ensure sufficient capacity or heat emission from the existing radiators when operated at reduced supply temperatures. As described above, the heat emission from the radiators is based on the difference between the mean radiator surface temperature and the room air temperature. E.g., a constant heat emission can be achieved by various sets of inlet and outlet temperatures of the radiator. It basically means by reducing the inlet temperature, the outlet temperature should be increased, and this implies increasing the flow through the radiator. To illustrate this, an example is shown in figure 2. where the flow is uncontrolled, e.g., by a manual radiator valve, RV, and where the flow is controlled, e.g., by a thermostatic radiator valve, TRV.

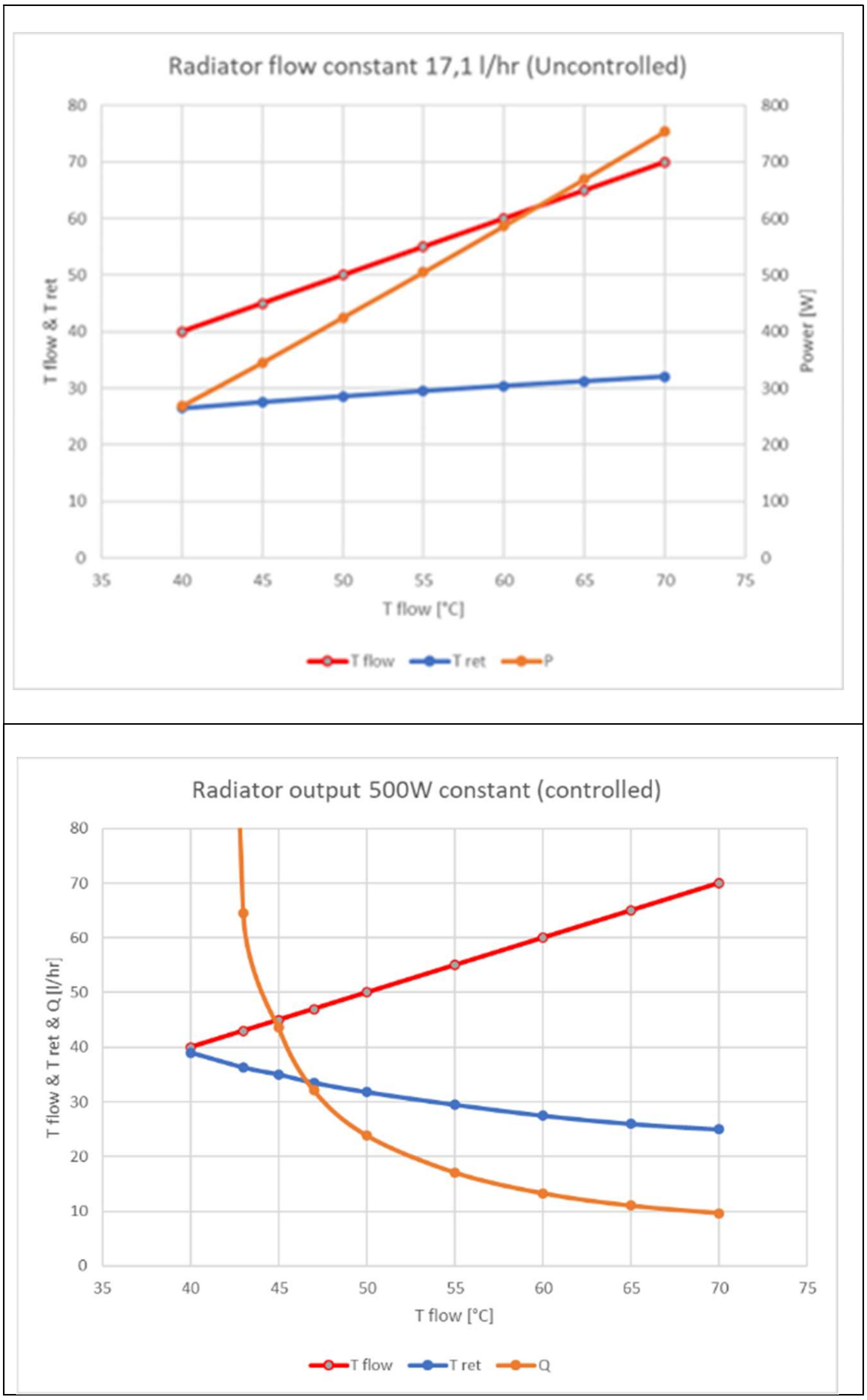

Fig. 2. Radiator basics (example): T flow is supply temperature, T ret is return temperature, P is the heat emission and Q the flow.

In the upper figure the uncontrolled situation or no flow control is shown (RV), represented by a constant flow through the radiator. The heat output is a direct result of the supply temperature, thus only one specific supply temperature is matching the heat load of the room. In this case the example of 500W is used at a supply temperature of 55°C and here the flow of 17,1 l/hr fits. On the lower figure the situation is shown where a flow control is applied (TRV or eTRV). The heat output of the radiator is constant independent on the supply temperature. The supply temperature cannot be below 40°C when emitting 500W is to be kept, and even before reaching 40°C, the maximum flow of the radiator or system is reached. It can also be seen that the radiator return temperature increases when the supply temperature is decreased, this to maintain the mean temperature difference of the radiator surface to the surrounding air, and thus maintaining the same heat emission.

When replacing a traditional high temperature heat source with a Heat pump, with the intention of optimising CAPEX and OPEX, the difference of the radiator inlet and outlet temperature, should be in the range 5-10°C. (Fig.3) The radiator's control concept will therefor need to adapt to the reduced operating temperature. This basically means that the pre-setting and balancing of the radiator and distribution system should have the ability to operate at increased flow levels.

As stated above, it is possible to maintain the heat output of a radiator by increasing the flow rate through it and at the same time reduce the supply temperature (till a maximum acceptable flow level that depends on the radiator, the piping, the flow noise level, the circulation pump head pressure, and control valve capacity). Increasing flow rates create significantly higher head pressure losses and associated higher pump circulator power input. A balance between heat pump COP optimisation, circulation pump consumption and radiator maximum heat emission compared the needs can be simulated. (Fig. 3). The shown COP includes the electricity consumption of the HP and the circulation pump. The HP COP used in the present calculation is based on [7] .

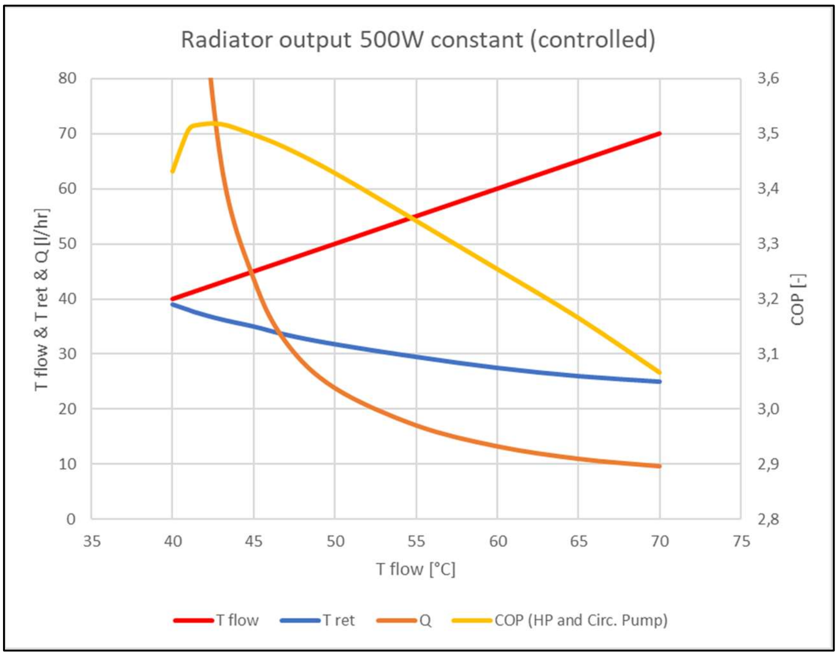

Fig. 3. COP vs other main radiator parameters.

As seen from figure 3, then there is a maximum COP. This point represents the situation where the increased flow, due to the reduced supply temperature, results in reduced electric consumption for the HP but at the same time results in a similar increased electric consumption of the circulation pump. If it is possible to operate at maximum COP depends on the factors mentioned above.

A simple mathematical model has been developed to describe radiator heat emission and flows through radiators when a boiler is being replaced with a heat pump. Through this model it is possible to be guided on different options and parameters when analysing the feasibility of the retrofit. (Fig.4)

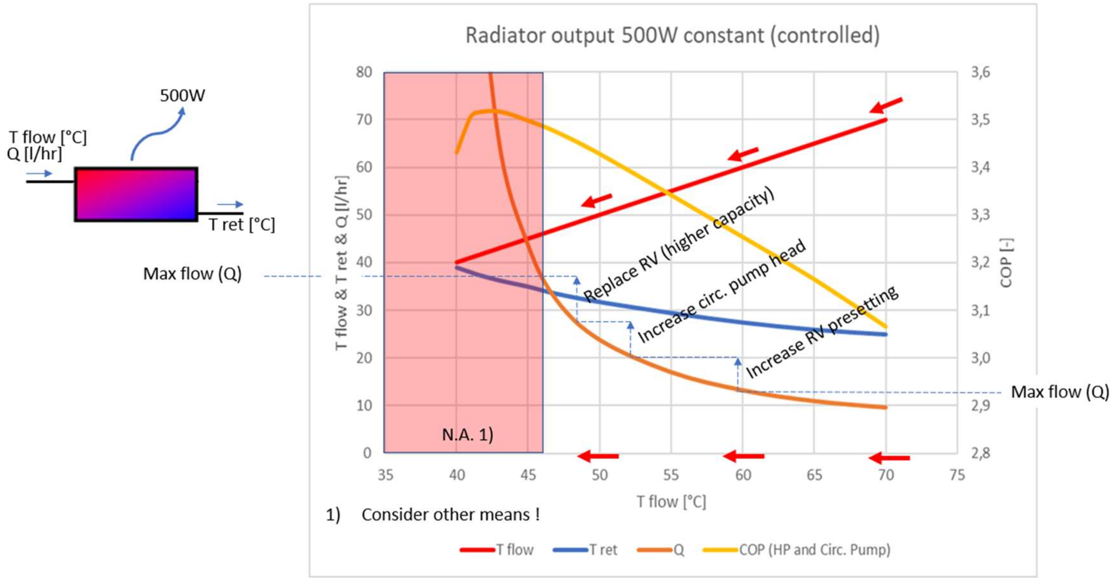

Fig. 4. Relevant steps and changes in parameters at Heat Pump retrofit.

When a heat pump is introduced in the system [8] the temperature drop over the radiator is to be decreased (if possible in the mentioned interval of 5-10°C) and flows are subsequently to be increased. This implies TRVs should be able to provide higher flows through change in the presetting if applicable. Presetting is the predetermined maximum flow at a given differential pressure the valve will pass through the radiator valve. The feasibility of a higher presetting should be evaluated when rebalancing the hydronic system for HP operation. The circulation pump head pressure must likely be increased assuming a reserve as is available. If the radiator valve (RV) is limiting the flow, they can be replaced to RVs with a higher capacity. In the example of figure 4, going even to a lower supply temperature (below 47°C) would require other and more costly means, like replacing radiators and/or pipes.

The tradeoff is found in balancing the investment costs in relation to the operational saving due to a higher COP. In this example the supply temperature to the radiator is reduced from 70°C to 46°C, and at the same time the COP is increased from 3,05 to 3,46. The flow through the radiator is increased from 10 l/hr to 38 l/hr, basically a factor 4. For this example, the maximum COP cannot be fully reached, due to flow limitations, see red area Fig. 4 marked N.A. The remaining potential for improving the COP is anyhow limited. The steps mentioned here are options, and an example of priority.

3.4. End users' behaviour and indoor temperatures

BPIE fresh Hotmaps Building Stock Analysis issued in 2022 [9] was used to check energy demand for space heating for the 3 representative abundant building types in 3 European countries (IT, DE, UK), at the hypothesis that heating is turned on when indoor temperature drops below 19-21°C depending on user behaviour. The calculation on equivalent kWh/m2/y thermal need (fig.5) based on national heating degree days shows the space heating demand at different heat 'turn on', or heating degree base temperature, starting conditions. Besides saving energy in general, the heat emitting area relative to the heating demand can be increased tremendously for the sake of efficient heat pump operation in the light of the previous section 3.3. Consequently, it is heavily recommended, when a heat pump is introduced in a traditional radiator heating system, to explain end users they should set indoor temperature at a reasonably low but still comfortable temperature (ideally max 19-20°C), to fully benefit from the retrofitted HPt and avoid changing the radiators. The market investigation reveals that in many cases designers and installers, over the last 50 years over dimensioned radiators and further the building was improved thermally during the years resulting in a basis for a potential well working HP.

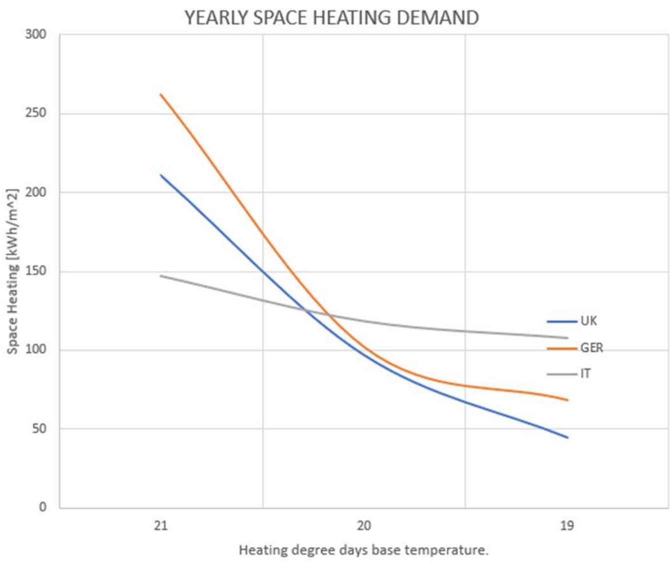

Fig. 5. Yearly space heating demand in UK, GER, IT most abundant buildings.

4. Best practice approach when retrofitting

Previous chapters have described the needed methodology of a efficient retrofit solution.
In practice, there are typical measures to evaluate, that can turn the system into low temperature ready.
Below is a short description of the different options that should be considered prior to retrofit, improving CAPEX, OPEX and ROI:

- Decreasing basic heating loads/losses: when possible and feasible the thermal demands of the building should be decreased by adding insulation to the envelope (walls and roof), changing the windows, or adding winter gardens. The size and cost of the heat pump is related to the improved heating load and thus ROI should be calculated when deciding which means to go for, especially what to do first when doing staged renovation.

- Adding heat emitters. This should be done in the critical rooms only. In fact, the larger the total surface area of the heat emitters, the lower the required supply water temperature for a given rate of heat transfer/thermal load. Normally some of the radiators are over dimensioned for the given room, at the same time their size is set to provide the needed heat power in the coldest day of the winter, while for the remaining time they are more than adequately sized. This means in many cases there is only a need to adding surface in few selected rooms if at all.

- Changing type and/or size of emitters. This includes panel radiators, fan coils, fan assisted panel radiators, fin tube solutions or radiant heating. By changing the emitters, we refer to the intention of adding radiant surface and have a system that can deliver at lower supply temperature. Mostly it is possible to limit this to the critical rooms and the radiator area can be increased by replacing to multi panel radiator on the same wall surface with the same build in dimensions.

- Auxiliary heat source: evaluate how much space-heating energy is needed during the coldest days, when the heat pump due to the limited upper water temperature cannot provide sufficiently high supply water temperature. During that period, an auxiliary heat source is typically used in combination with the HP. If the amount of energy used under such conditions is relatively small in comparison to the total seasonal heating energy required, it would be reasonable to use the heat pump for the majority of the heating load and rely on the auxiliary heat source on top of the HP for the peak load conditions. This represents a typical hybrid system where the auxiliary heat source can be biomass, solar, or more easily direct electric which can be installed into the tank as an resistance based heat coil or alternatively be electric radiators (or hybrid radiators with a small electric resistance that turns on very limited hours a year) or electric underfloor heating. Traditional condensing boilers still represent a solution for an auxiliary source, but this is a transitional and non-logical opportunity when intention is to move towards a fossil free energy system.

- Evaluate the heat demand/supply profile, also including a thermal storage tank. This is out of scope for the present paper and will be investigated in further studies, i.e.: buffer tank and other components for hydraulic separation are needed to properly use controls and avoid over cycling of the HP.

5. Conclusions

The potential market for retrofitting heat pumps in existing building heating systems is substantially larger compared to new buildings. Thereby this is the first opportunity for decarbonising heating through electrification, also in small applications such as phasing out single-family fossil fuel boilers. Retrofitting of heating systems with heat pumps has its own specific characteristics, of which the high distribution/emission temperature used in existing hydronic heating systems is the most prominent.

Old hydronic systems are often designed for higher heating capacities than the actual design heat demands (especially with climate change!). In that case, the distribution temperatures may be reduced below the original design values. The distribution temperatures (supply temperature) may be reduced further by reducing the specific heat demand (W/m2/y). In all cases it should be ensured that the heat pump in combination with the new controls (not only on the primary circuit but even more on distribution and emission components) really saves energy, by a proper design for the new type of heat source.

Approaching retrofit design through the elements described in this paper potentially using the systematic stepwise approach can make clean heating through heat pumps the financially most attractive choice, create trust, and meet the technology acceleration that climate desperately needs.

Acknowledgements

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