White Paper

Heat pump or boiler: what’s the business case?

Johnson Controls White Paper

Introduction

Managing energy consumption for the heating and cooling of buildings and industry is essential if nations are to achieve global carbon reduction and sustainability goals.

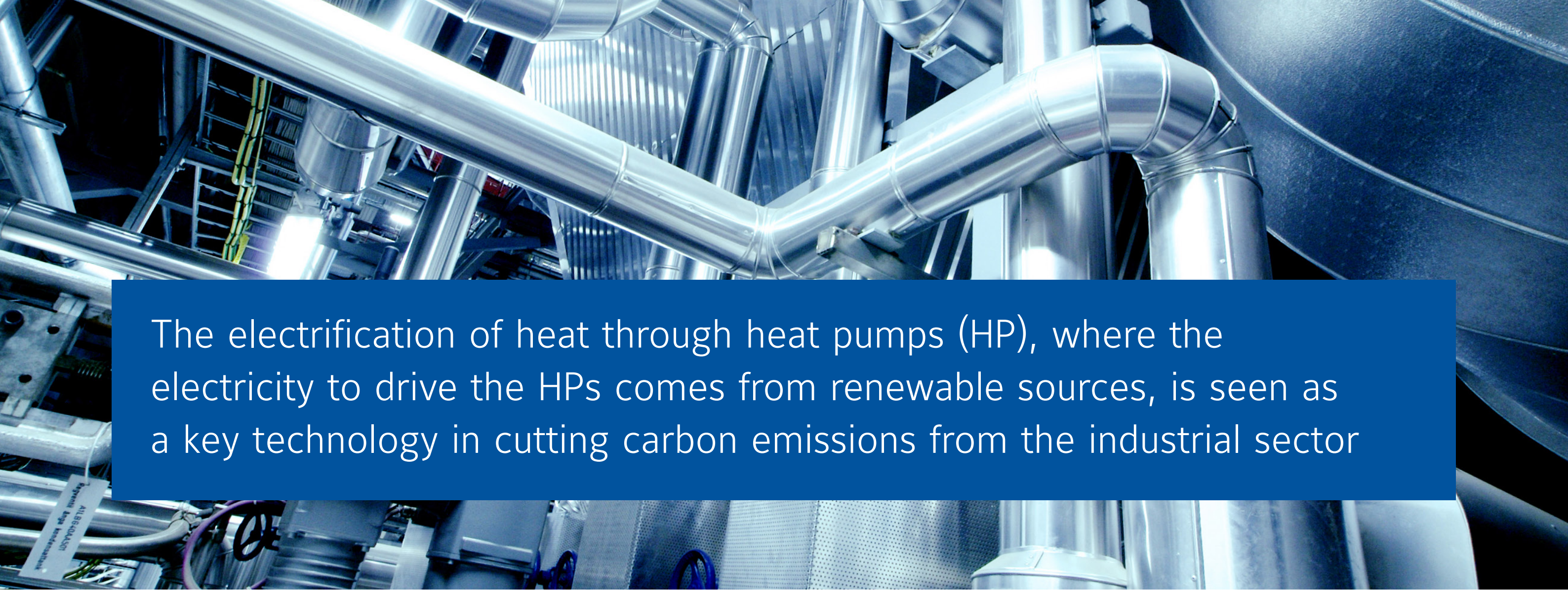
According to the International Energy Agency (IEA), almost a fifth of the growth in global energy use in 2018 was due to hotter summers pushing up demand for cooling, and cold snaps leading to higher heating needs. And looking at energy consumption by sector, data from the IEA’s World Energy Outlook 2019 shows that industry will replace the buildings sector as the biggest energy consumer by 2030.

The electrification of heat through heat pumps (HPs), where the electricity to drive the HPs comes from renewable sources, is therefore seen as a key technology in cutting carbon emissions in the industrial sector. Their use is also an integral part of decarbonising heat in the creation of smart, sustainable cities.

Driving the HP agenda

The growing movement of countries towards net zero carbon emissions by 2050 is likely to accelerate the replacement of fossil fuelled boilers with HPs. In the net zero 2050 (NZE2050) scenario of its latest World Energy Outlook 2020, the IEA forecasts that, together with other low-carbon heat sources, HPs displace an additional 80 Mtoe of fossil fuels on top of the 110 Mtoe reduction that occurs in its Sustainable Development Scenario between 2019 and 2030. In total, electricity and low-carbon fuels provide around one-quarter of heat demand in industry in 2030 in the NZE2050.

Europe, which is leading the move to be carbon neutral by 2050, has already committed to at least 40 percent cuts in greenhouse gas emissions (from 1990 levels) by 2030 and is proposing to increase this ambition to 55 percent under the European Green Deal (EGD). More recently it has also put climate change and the energy transition at the heart of its economic recovery from the COVID-19 pandemic, providing economic incentives for the implementation of low-carbon technologies and energy efficiency. HPs are an important part of the equation.



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Heat pumps explained

In simple terms, a HP is a heat engine operating in reverse. It reverses the natural heat flow process (where heat transfers from warmer places to colder spaces) by absorbing energy from a cold environment and releasing it as heat at a higher temperature. The process requires an external energy source such as electricity. This could come from a renewable source, which provides a carbon-free heat source.

A heat pump has four main components: an evaporator, a compressor, a condenser, and an expansion device. It essentially operates like a refrigerator. A mechanical heat pump, which is the most widely used in industrial settings, operates on the principle of compression and expansion of a working fluid, or 'refrigerant', that passes through all these components.

The evaporator is the heat exchanger between the low-temperature heat source and the refrigerant. In terms of heat source, ambient air, seawater and cleaned effluent water account for the majority of future district heating projects.

The refrigerant enters the evaporator as a low-pressure liquid and the outside air/waste heat source evaporates the refrigerant. The refrigerant leaves the evaporator as a low-pressure gas, which then enters the compressor, where it is compressed. The compression process turns the cool, low-pressure gas from the evaporator into a hot, high-pressure gas. This gas enters the condenser, which is another heat exchanger that serves to deliver this heat to the consumer at a higher temperature level. Electric energy is required to drive the compressor and this energy is added to the heat that is available in the condenser.

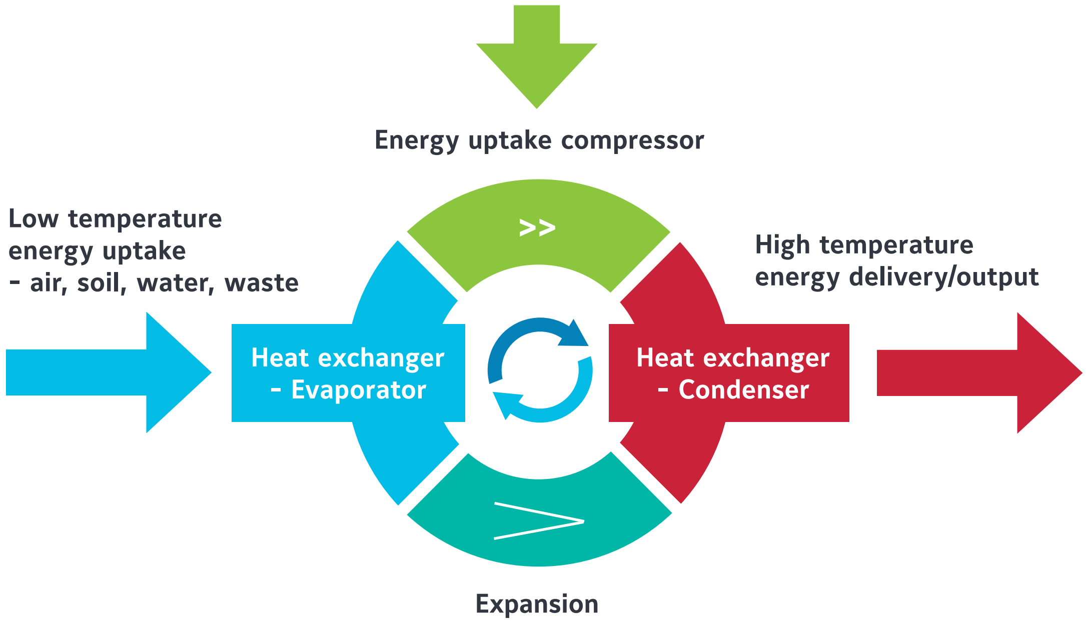

Figure 1. A heat pump has four main components: an evaporator, a compressor, a condenser, and an expansion device – it essentially operates like any refrigerator.

Increasing HP demand

Heat pumps are well suited to reducing emissions in the supply of low temperature (<100 °C) heat, which, according to the IEA, is the largest source of industrial heat demand today. In recent years, there has been a demand for industrial heating and cooling solutions that are increasing in scale and complexity. This pushes the envelope in terms of where industrial HPs are being applied.

For cooling, which is a necessity at a facility like a dairy or an abattoir, there is no other option but to use a cooling plant. But for a heating application, there is always an alternative. Depending on requirements, a plant owner could use a heat pump, a variety of fossil fuelled boilers, biomass boilers or an electrical boiler. Typically, a HP is more efficient than a conventional boiler from a heating perspective – whether in a district heat application or municipal application.

A heat pump might typically have a Coefficient of Performance (COP) of 3-5 (or higher depending on the application), i.e. it can transfer 500 percent more energy than it consumes. Put another way, it produces 5 kW of heat for every 1 kW input of electricity. In contrast, a high-efficiency gas boiler is about 95 percent efficient, meaning 95 percent of the energy in the gas comes out as useful heat, with the other 5 percent being lost as heat through the flue.

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Heat pump or boiler?

In the energy provider or utility space, HPs can be used as a primary source of generation, replacing fossil fuel boilers in the generation of heat. Over the years, they have been moving into a range of applications with outputs of between 40-70 MW, which would have traditionally been served by a series of boilers or a combined heat and power (CHP) plant.

Choosing between a boiler and a HP, however, is not a straightforward decision. Essentially, the decision is driven by the overall economic case, operator needs, and health, safety and environmental (HSE) requirements.

The plant owner's application and preferences are the first considerations before purchasing a HP. For the supplier, it is key to understand the owner's needs, e.g. are there special site requirements or preferences in terms of refrigerant handling? Is there a need for capacity redundancy? It is also important to understand financial parameters, such as inter-company rates, amortisation, energy cost, and value/profit on heat.

HSE and assessing the ambient surroundings are crucial. The toxicity, flammability, pressure, and safety of the refrigerants must be considered. At the same time, a plant owner should also think about its corporate, sustainability, and responsibility ethos.

All of this culminates in several key considerations when configuring a HP installation. These include:

Capacity: What are the design conditions?
Temperature conditions: What is the temperature of the coldest day in winter and the hottest day in summer, and how much heat is required during these extreme conditions? What is the replacing heat cost vs the electricity cost? A heat value/profit calculation must be performed for different scenarios.
Configuration: If there is a need for redundancy, it would be better to install several small units instead of a single large unit. The interaction of the HP with other sources of heat whether serially or in parallel is very important to offering the right HP for the best value proposition.
Risk: Damages and penalties are also an important consideration when supplying a HP. This is important when installing for district heating companies, whose earnings are regulated. This means all of the risk lies with the supplier.

What it boils down to is the case of choosing the technology that gives the lowest lifetime cost of ownership, or highest Net Present Value (NPV), and best return on investment.

Heat pump configuration: things to consider

Application

- Customer preferences
- Customer needs, capacity redundancy
- Customer installation site

Life Cycle Cost (LCC) – Economy

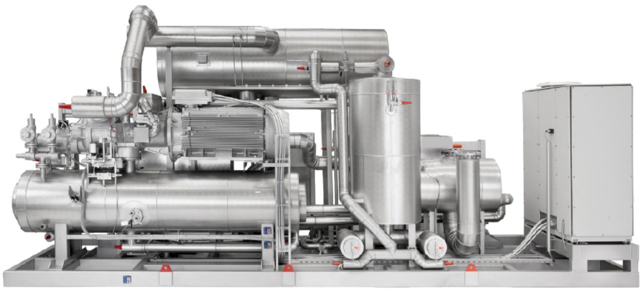
- Initial cost 10%
- Service cost 10%
- Energy cost 80%
- Value/profit of heat

Health, Safety & Environment (HSE) and ambient surroundings

- Toxicity
- Flammability
- Safety and pressure

Corporate Social Responsibility (CSR)

- Green image, Coefficient of Performance (COP) – European Seasonal Energy Efficiency Ratio (ESEER)
- Carbon footprint
- Global warming potential (GWP) of refrigerant



Capacity

What are the design conditions, and how do they influence investment?

Temperature Condition(s)

- Multiple operating conditions for best business case, summer – winter, day, night, storage
- Replacing heat cost vs. electrical cost
- Evaluate heat value/ profit per scenario

Configuration

- Need for redundancy, big versus multiple small units
- Primary or secondary source of heat
- Number of units, service intervals vs. uptime

Risk

- Damages and penalties
- Performance testing

Argument:

No uniform solution as it is dependent on multiple conditions. The best solution is the highest Net Present Value.

Figure 2. The choice between a boiler and a HP is driven by the overall economic case, operator needs and health, safety and environmental (HSE) requirements.

Heat pump vs conventional boiler

The capital cost of an industrial heat pump is higher than an oil or gas boiler. However payback times can be shorter and it is therefore necessary to make a full economic analysis before making a decision between the two or whether to add a HP to an existing boiler installation.

Further, it is worth noting that various funding and government incentives are available, which make for an attractive business case.

The EU Strategy for Energy System Integration focuses on the direct electrification of energy demand. It therefore recommends the phasing out of fossil fuels and the use of technologies such as heat pumps, for example, in buildings and industry.

In the European Green Deal announced in 2019 the European Commission allocated €750 billion for initiatives that support investment in environmentally-friendly technologies; innovation in technologies aimed at decarbonising the energy sector; and more efficient use of energy.

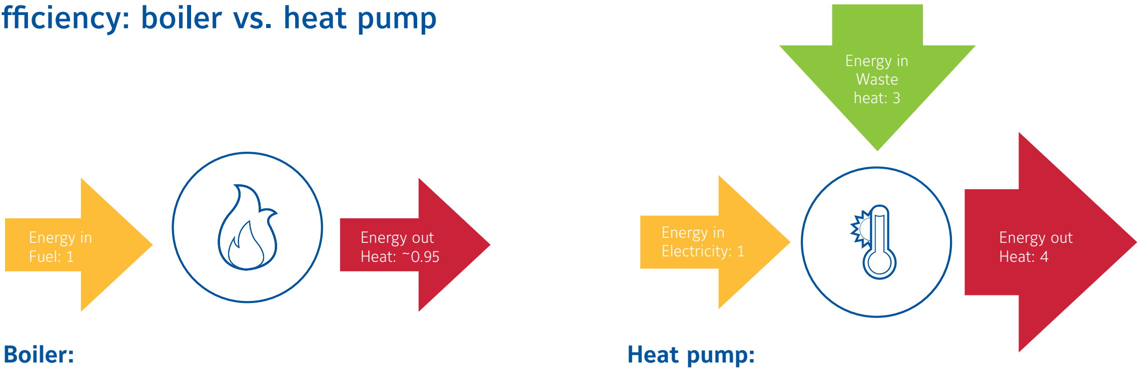
Potential heat pump installers also need to factor in the increasing costs of emission quotas and possible future carbon taxation on fuels. The International Emissions Trading Association (IETA) predicts that the average carbon price in the EU throughout the 2020s will be €32 per tonne of CO2 equivalent. This is an increase on the €27 average recorded between June 2018 and June 2019. The rise is likely to continue. By installing heat pumps, it is possible to avoid or mitigate these costs by being able to use low-carbon or renewable sources.

Local availability of heat sources for heat pumps, e.g. waste heat from manufacturing processes and data centres, lakes etc., also means there are no or low fuel costs. In buildings and future smart cities, installing heat pumps allows energy managers to combine heating and cooling, integrate and balance a large share of renewable power and then use them as thermal storage. According to the 'Decarb Europe 2018 report', thermal storage is 100 times cheaper than electricity storage (€0.5-3/kWh vs €170/kWh).

To analyse the economics, however, it is important to understand the difference between a HP and a conventional boiler.

Unlike a boiler, where the energy is controlled by the amount of fuel fired, an HP's energy is determined by a thermal equilibrium based on the hot/cold side temperatures. When the temperature at the cold side (heat source) is lower, physics dictates there are fewer molecules inside the refrigerant vapour, meaning that the amount of heat it can pump is less. This thermodynamic equilibrium determines the performance and therefore suitability of a HP for a particular application.

Efficiency: boiler vs. heat pump



Boiler:
The energy is controlled by regulating the quantity fired.

The efficiency **is not strongly dependent** on temperatures in the heating system.

Heat pump:
The energy is "determined" by a thermal equilibrium dependent on the hot/cold side application temperatures.

The efficiency **is strongly dependent** on the source temperature and temperatures in the heating system.

Figure 3. Unlike a boiler, where the energy is controlled by the amount of fuel fired, an HP's energy is determined by a thermal equilibrium based on the hot/cold side temperatures.

So while boiler efficiency is not closely dependent on temperatures in the heating system, in a HP efficiency is closely tied to the heat source temperature and required temperature for the application. This makes it difficult to compare the two technologies.

Typically, as the process temperature increases for the application, so does the complexity of the equipment. It is therefore essential to optimise temperatures on the hot and cold sides for the application to assess and improve the business case.

Complexity and price: boiler vs. heat pump

Boiler:
The price is **not heavily dependent** on heating system temperatures

Heat pump:
The price is **heavily dependent** on the source temperature and temperatures in the heating system

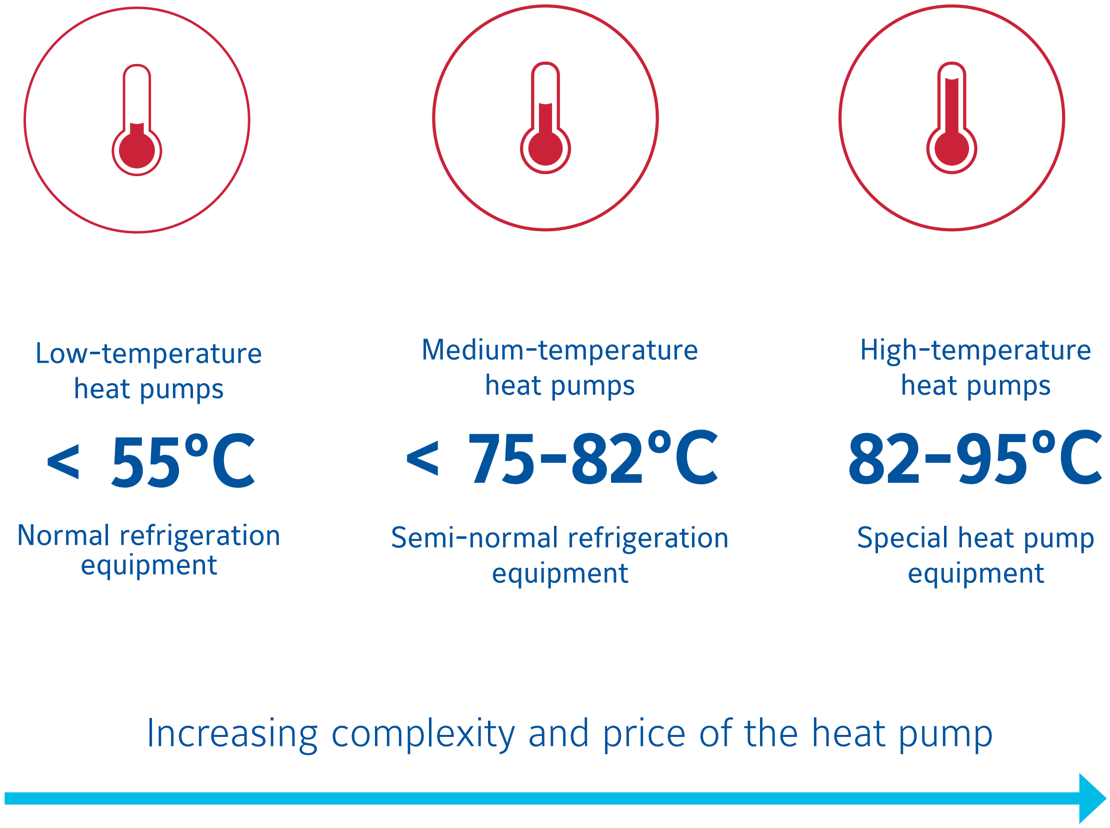


Figure 4. As the process temperature increases for the application, so does the complexity of the equipment and, therefore, the price.

Calculations show that on the heat sink or cold side, every 1°C rise in inlet water temperature delivers a 2 percent increase in capacity and a 2 percent boost in COP. On the heat output side, every 1°C increase in outlet water temperature gives a 0.3 percent decrease in capacity and an approximately 1.6 percent decrease in COP. In short, this means that optimum operating conditions for heat pumps are utilising waste heat at the highest possible temperature and pumping it to the lowest usable temperature in the heating system.

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Take the example of a machine with a 40°C heat sink, where the hot side goes from 40°C to 85°C. This gives the machine a capacity of 1,500 kW and a COP of 4.5. If the exact same machine is exposed to just 10°C instead of 40°C on the energy uptake side, but the hot side temperature range is the same 40–85°C, the machine's capacity falls to only 775 kW and the COP drops to 2.8.

What is achievable and what are the impacts of heat source, capacity and COP

Heat sink, increasing inlet temperature:
Cold side impact
~ +2% increase in capacity per degree
~ +2% increase in COP per degree

Heat output increasing outlet temperature:
Hot side impact
~0.3% decrease in capacity per degree
~ 1.6% decrease in COP per degree

Figure 5. HP performance and capacity are dependent on the temperatures on the cold and hot sides.

This obviously doubles the investment since the owner would need two heat pumps to achieve the same capacity. Increasing the temperature on the cold side by 10°C would also increases COP by 20 percent, resulting in a 20 percent lower electricity bill. At the same time, lowering the temperature on the hot side, e.g. of the outgoing water temperature, further improves performance and running cost.

It is important for potential HP owners to realise that the performance of the machine cannot be controlled via buttons on the unit – the thermodynamics of refrigerants cannot be changed. It can only be changed by optimising the temperature conditions of the application.

Making the business case

Arriving at the optimum business case therefore involves examining a number of iterations or scenarios to assess the outcomes of adjusting various conditions over the period of a year. This allows for variations in seasonal ambient conditions and energy costs (electricity vs gas, for example) to be taken into account. Other key inputs are HP efficiency, load, and running hours.

Figure 6 presents an example of how the business case changes for nine different scenarios. For an operator that already has a gas-fired boiler installed, such scenario-building can indicate when to run a boiler vs a HP.

Transparency in scenarios is mandatory to make the optimum solution

Scenario		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Full year
Capacity	kW	2500	3500	5000	8000	7800	7000	6300	5400	4000	3000	
Temperature source	°C	25	20	18	12	5	0	-5	-7	-10	-12	
Temperature heating application	°C	80/50	80/50	75/45	75/45	75/40	75/40	65/40	65/40	60/40	60/40	
COP heat	-	4,80	4,32	4,48	3,94	3,39	3,05	3,18	3,06	2,87	2,76	
Operating hours	hours	100	750	750	1650	1800	2200	800	400	200	110	8760
Heat production	MWh	250	2625	3750	13200	14040	15400	5040	2160	800	330	57595
Heat pump running cost	€/MWh	15,5	17,0	16,5	18,5	21,2	23,3	22,4	23,3	24,6	25,6	20,9
Heat pump heat cost	k€	3,39	39,50	54,42	217,68	269,23	328,12	102,86	45,92	18,09	7,77	1087
Heat pump service cost	k€	0,5	5,25	7,5	26,4	28,08	30,8	10,08	4,32	1,6	0,66	115
Heat pump running cost	k€	3,9	44,7	61,9	244,1	297,3	358,9	112,9	50,2	19,7	8,4	1.202
Substituting heat cost	€/MWh	30	30	30	30	35	35	35	45	45	45	33,9
Substituting heat cost	k€	7,5	78,8	113	396	491	539	176	97,2	36,0	15	1.950
Savings	k€	3,6	34,0	50,6	152	194	180	63,5	47,0	16,3	6,4	747
Electricity cost	65	€/MWh										

- Running hours, capacity and COP per scenario
- Price of substitutional heat varies over the year
- Calculate value/savings per scenario

Remember iterations to optimise the heat pump for the best business case.

Figure 6. How the business case changes for nine different scenarios.

Clearly much depends on the domestic price of fuel versus electricity. If electricity is very expensive and fossil fuel is cheap, there is generally no case for installing a HP. If the COP is bigger than the electricity price divided by heating price,the owner has a business case. Figure 7 shows the ratio between the electricity price and the price of fuel.

Influence of ratio between fuel and electricity cost

Example:
Gas cost: 33,0 €/MWh
Electricity cost: 65,0 €/MWh

Ratio: $\frac{65}{33} = 1,97$

Realistic heat pump COP ≥ 3,0

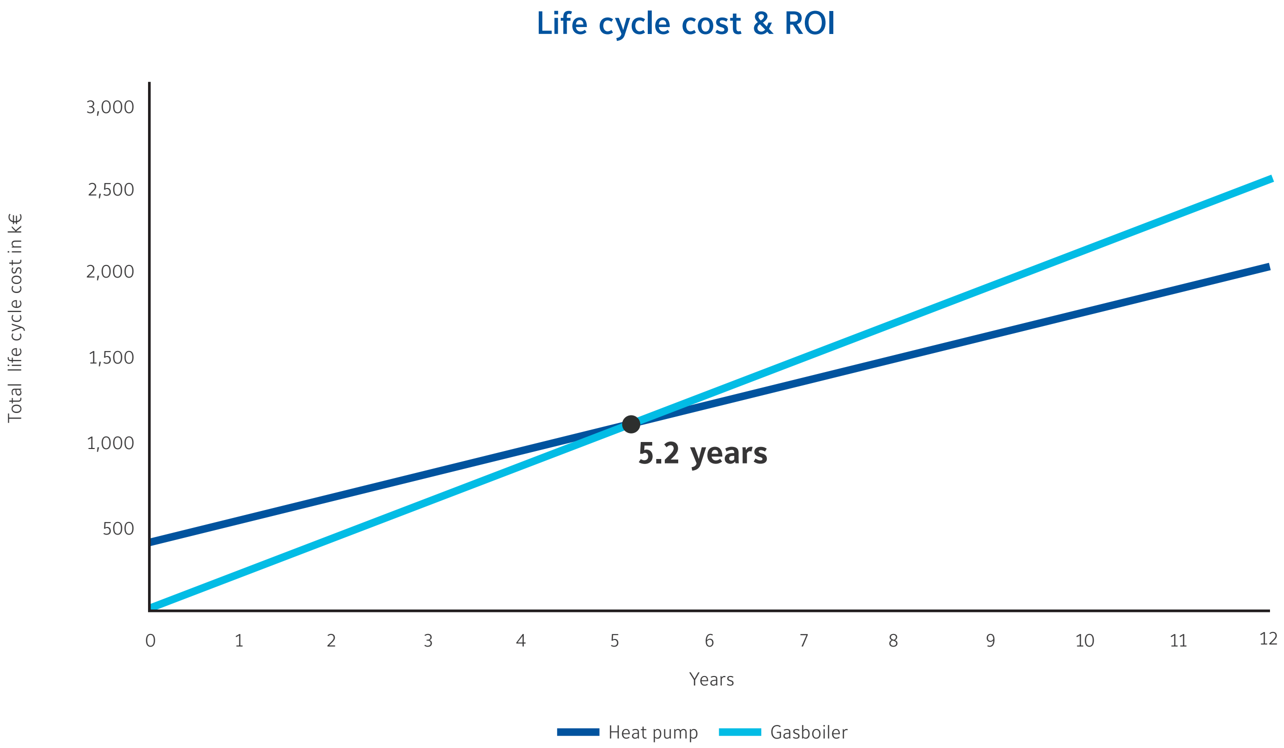
COP > Ratio

Savings on energy cost: $\frac{(33-\frac{65}{3.0})}{33} \approx 34\%$

Figure 7. The business case for replacing fossil fuel is determined by the ratio between the cost of fuel and electricity.

This ratio calculation must be conducted for each scenario since the price of heat can be very different for an energy company depending on the time of year. For example, during the summer at a waste incineration plant where the waste still has to be burned, the cost of fuel is very cheap and would therefore favour operation of the boiler. However, at high loads there is a scenario in favor of a heat pump replacing the high fuel costs of the boiler.

Figure 8 summarises the economic case for a potential HP installation at a site that already owns a gas fired boiler. This could for example be at a food and beverage (F&B) facility. Here, the additional investment would need to cover the full capital cost of the HP as well as its running cost. The figure shows that the HP would deliver a return on investment (ROI) of 5.2 years and a saving of just over €1.140 million over the 20-year life of the installation.



Investment	Unit	Heatpump	Gas boiler
Solution lifetime	Years	20	20
Project investment	k€	403	0
ROI simple	Years	**5.2**	
Total life cycle cost	k€	3,120	4,260
Total Life cycle saving	**k€**	**1,140**	

Figure 8. Economic case summary for a potential HP installation at a site that already operates a gas fired boiler.

It should be noted, however, that the evaluation criteria for a F&B company is different to that of a utility company. Wherein a F&B company makes a decision based on ROI, a utility always uses NPV since the price of heat is relevant for their business model.

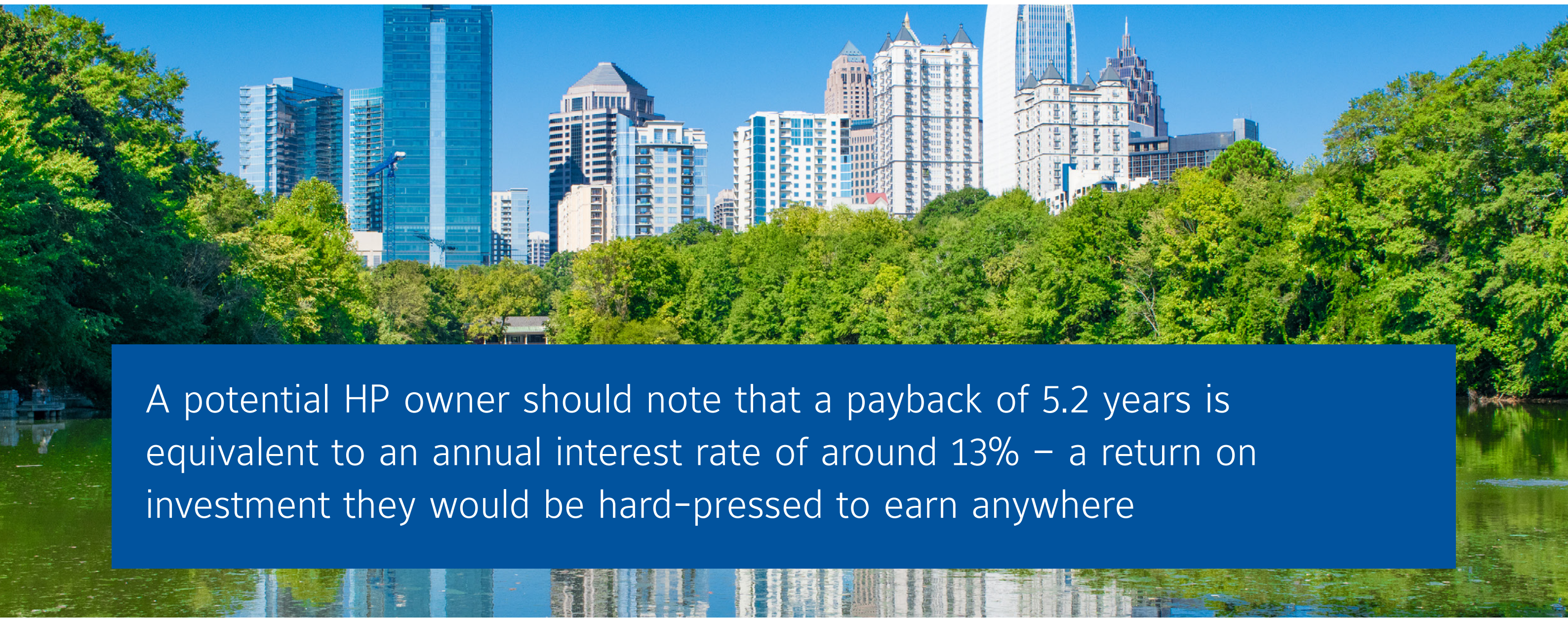
For a utility, 60-70 percent of the evaluation criteria is around NPV, perhaps 30 percent around technical issues and about 10 percent is related to the HP supplier's capabilities and project management expertise, HSE, risk etc.

The choice is down to economics

In summary, at a facility where there is an existing boiler, the projected savings on the energy cost has to cover the full investment of the new HP. At a greenfield site, where the capital cost for a HP is only perhaps 30 percent more than that of a new boiler, the economic case is clear – the energy savings over the lifetime of the installation only has to cover the additional 30 percent investment which makes the HP almost always more favorable.

Ultimately, there is no uniform solution when installing HPs, as it depends on a number of conditions. The best solution is therefore the one that provides the highest net present value or return on investment. A potential HP owner should take note that a payback of 5.2 years is equivalent to an annual interest rate of around 13 percent – a return on investment they would be hard-pressed to earn anywhere.

Figure 9. Different HP heat sources and related COPs.



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