HYBRID HEAT PUMPS MINIMIZE EMISSIONS AND MINIMIZE OVERALL COSTS

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Abstract

Heat pumps are more attractive than (many) conventional heating methods mainly due to their efficiency. A lot of research has been devoted to this merit. This paper describes the impact of heat pumps on the energy chain, not only in residential homes but specifically also on infrastructure and emissions.
Hybrid heat pumps offer specific advantages in a sense that the carrier can be varied depending on specific circumstances, thereby improving efficiency and reducing emissions with only limited impact on energy infrastructure costs. This is achieved through the following operations: Switching to gas where heat pump efficiency is poor reduces energy bills and also reduces electric peak load (reducing electricity infrastructure costs). At times when emission factors of electricity are poor, a switch can be made to gas as energy carrier. Switching to electricity during periods of abundant availability of clean electricity also reduces emissions. Switching to gas at very low outside temperatures avoids installing low-temperature radiators in existing homes and thereby reduces costs.
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Key Words: hybrid heat pumps, emissions, costs

1. Introduction

The most important target in energy transition is the reduction of CO_2 emissions. This paper will focus on this target for the residential heating sector: how can we reduce CO_2 emissions with minimal overall costs while maintaining the current levels of comfort and security of supply?

Specifically, we will investigate the impact of residential energy decisions on the energy chain as a whole. These decisions affect energy transmission, distribution, generation and production infrastructure that together comprise a significant amount of the energy cost. Only by looking at the whole energy chain can sensible choices be made about societal benefits.

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2. Energy transition target: emission reduction at lowest overall cost while maintaining current comfort level

CO_2 is an important factor in global warming. Both the EU and its member states individually have set targets to reduce CO_2 emissions. To support these targets, the EU has developed an Emission Trading System[‡]. Emissions in the residential sector, however, do not fall under this scheme. National policies have been developed to help support emission reduction in this market sector.

In this paper, emission reduction has been defined as overall emission reduction, whether it be ETS or non-ETS.

The costs involved are defined as costs for the society as a whole. Choices made in homes are often made for the benefit of the resident or owner of the building. These individual choices may not lead to the lowest overall cost, in particular because infrastructure cost is heavily socialized. Therefore, in this paper, only the total costs for society are used when comparing alternatives. The way these costs translate into tariffs and taxes and potentially affect the behavior of individuals is not investigated in this paper. We assume that tariffs and taxes and underlying laws will be defined such that the optimum solutions for the society as a whole will be reached by the appropriate behavior of individuals.

The residential heating market in the Netherlands is currently supplied with natural gas. The standard used for reliability is a one-in-fifty winter, which means that infrastructure must be sufficient to cope with the demand of a winter day that happens once in fifty years, which is an average effective daily temperature of -17°C. This study assumes that this standard will also be applied to any future energy infrastructure for the residential heating market.

Results presented in this paper are specifically applicable for the Dutch residential heating market.

3. Residential heating market (space and hot water)

As already mentioned, residential heating in the Netherlands is almost completely supplied by natural gas. Condensing boilers are currently the most common heating appliances with an 80% market share, up from approximately 20% some 20 years ago, see Figure 1 below[§]. The market share of heat pumps is currently only 1,5% but this is increasing.

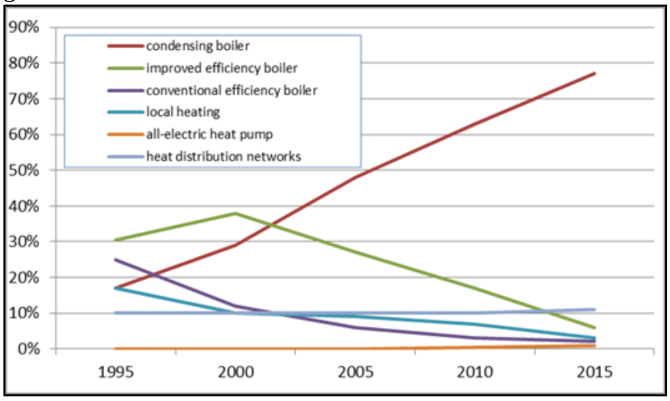

Figure 1 Market share of heating systems in the residential sector in the Netherlands

‡ http://ec.europa.eu/clima/policies/ets/index_en.htm

§ http://energietrends.info/wp-content/uploads/2016/09/EnergieTrends2016.pdf

The residential heating market is very temperature-dependent. Figure 2 below [1] shows this behavior for a particular recent winter 2011/12.

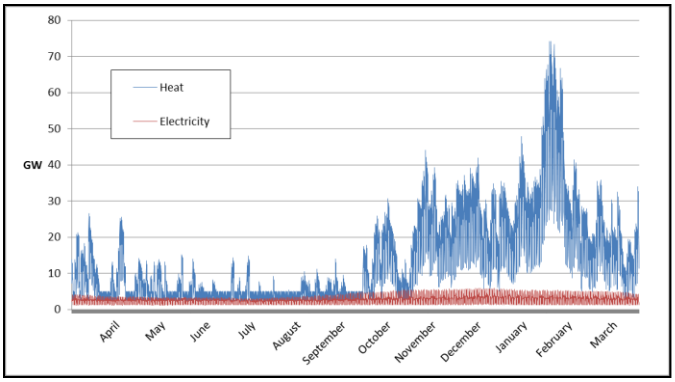

Figure 2 The peak demand of gas and electricity in the residential sector in the Netherlands. Note the large difference during winter.

In this winter, a peak gas demand of about 75 GW has been observed for the residential heating market with a peak electricity demand of only 5 GW.

Under severe winter conditions, with colder temperatures, the peak gas demand will even be higher. Since this is the characteristic demand profile of the residential heating market, any alternative energy carrier taking over this role from natural gas will have to cope with this profile.

In this paper, we specifically compare a transition from condensing boilers to either all-electric heat pumps or to hybrid heat pumps. The first being a mix of air-sourced heat pumps, mainly for existing homes, and ground-sourced heat pumps, mainly for new homes, and the latter are defined as a combination of an air-sourced heat pump with a condensing boiler. In a hybrid heat pump, both electricity and gas can be used (the choice being made can vary from hour to hour) to generate the required heat for space heating and domestic hot water. See figures 3, 4 and 5 below.

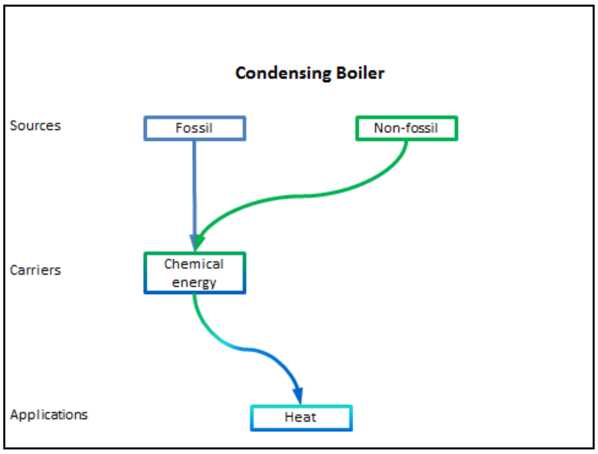

Figure 3 The current path from energy source, energy carrier to heat in the residential sector

Currently, 90% of Dutch homes are heated with natural gas (figure 3). The only energy carrier to heat homes is gas and therefore the gas network is the only infrastructure to deliver the energy. The two figures below show how one could move away from this situation. The left figure below (figure 4) shows the path where homes are heated with all-electric heat pumps, the right figure (figure 5) shows the two distinct paths where homes are heated with hybrid heat pumps.

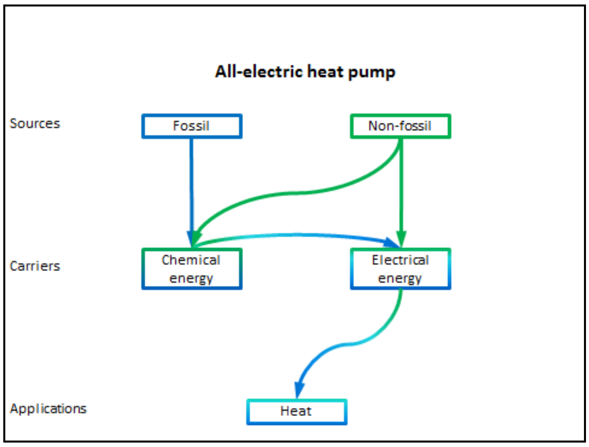

Figure 4 Paths with all-electric heat pumps

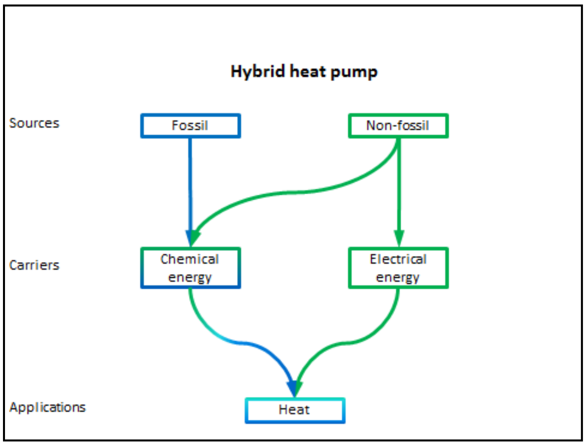

Figure 5 Paths with hybrid heat pumps

The all-electric situation (figure 4) will greatly increase the required electrical energy load such that networks would need to be expanded. In contrast, hybrid heat pumps (figure 5) can choose between two energy carriers. Flexibility in carrier management can reduce the load on electricity generation and networks and make expansion investments unnecessary. It can also reduce emissions and costs, which is further elaborated upon in chapter 5.

4. Trias energetica should be followed.

The Trias Energetica** - a model developed by the Delft University of Technology - acts as a guide when pursuing energy sustainability in the building sector. The Trias Energetica makes it clear that energy savings have to come first on the path to environmental protection. Only when a building has been designed to minimize energy loss should the focus shift to renewable energy solutions, such as solar panels or heat exchange and recovery systems.

In practice, however, there is a limit on energy savings depending on their return on investment. This limit strongly depends on the energy price.

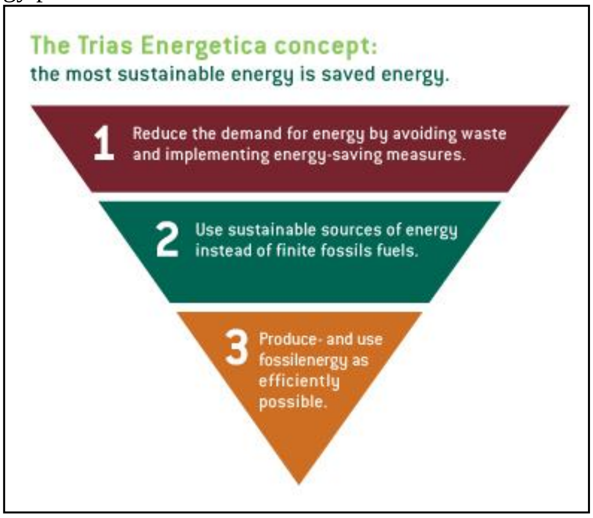

Figure 6 Trias Energetica

** http://www.eurima.org/energy-efficiency-in-buildings/trias-energetica

Applying this concept in the residential sector has the following effects.

<u>Effect of the first part of the Trias Energetica</u>

Improving the quality of homes may come at a high cost, especially for the existing housing stock. Pay-back time may be very long and people sometimes do not achieve the expected energy savings. Interestingly, Majcen [2] recently showed (see figure 7 below) that actual consumption in poor-quality homes is lower than would have been expected from models and that, in high-quality homes, the actual consumption is higher than theories would lead us to expect. Human behavior plays an important role.

The Dutch energy label scheme shown in the graph has been applied since 2008 and is based on a theoretical calculation of the energy consumption. The energy label by means of a rating (G to A) provides an indication of the home's energy efficiency where G stands for poor energy efficiency and A for high efficiency.

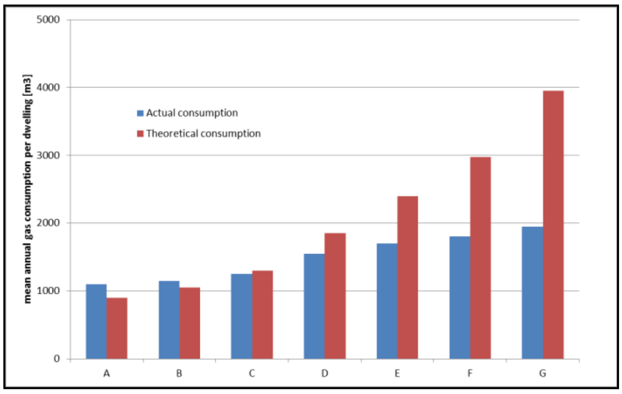

Figure 7 Actual and theoretical gas consumption per energy label

<u>Effect of the second part of the Trias Energetica.</u>

Renewable sources in the residential sector are solar (PV and boilers), wind farms and green gas. Renewable energy based on solar radiation will only be available during the day and virtually only in summer. Relying on this source implies that either excess energy can be stored in summer to be able to consume it in winter or that a backup source is required for the winter months.

<u>Effect of the third part of the Trias Energetica.</u>

One option for winter months (which show a limited supply of renewable energy in the residential sector so rely heavily on fossil fuels) is the use of heat pumps. Unfortunately, the efficiency of air-sourced heat pumps is strongly dependent on outside air temperatures, see Figure 8 below [3]. At moments of low outside temperatures the heat demand will be highest but the efficiency of the heat pump is lowest. This puts severe limitations on the applicability of air-based heat pumps.

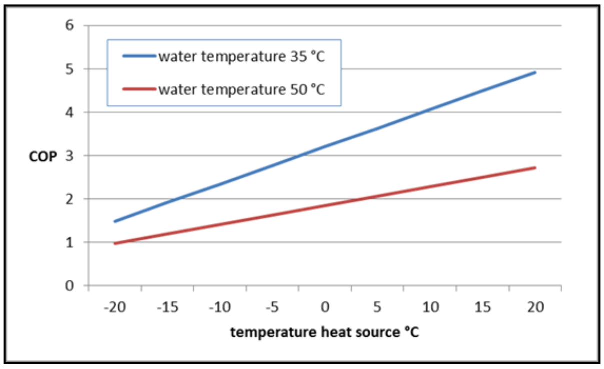

Figure 8 Efficiency of air-sourced heat pumps

Figure 8 indicates (using a currently observed emission factor for electricity of 0.586 and for gas of 0.183 kg CO_2/kWh) that under poor efficiency circumstances it would be better to use natural gas to achieve lower carbon emissions.

5. Overall costs

Costs of home refurbishment and changes to heating appliances are important when considering the reduction of CO_2 emissions from residential heating. Infrastructure costs are, however, often overlooked. An abrupt transition from natural gas to electricity represents a tremendous hidden cost to electricity transport, distribution, and power generation.

In an extensive study conducted recently [3], the costs of residential heating scenarios have been compiled. In this study, six scenarios are used, consisting of two insulation levels (medium and high) and three heating technologies (condensing boilers, all-electric heat pumps and hybrid heat pumps). The total costs in each scenario have been calculated, consisting of energy, infrastructure and home adaptations (such as insulation, water radiator surface, ventilation and appliances). Costs are calculated on an annual basis with an expected lifetime for infrastructure and insulation of 40 years and for appliances of 15 years. The condensing boiler with a medium insulation level is used as a reference.

Results are shown in figure 9. The hybrid heat pump scenarios are marginally more expensive (+17%) compared to the current condensing boiler. In contrast, a transition to an all-electric system represents a more-than-doubling of the cost, in large part due to the extreme infrastructure investments required for the all-electric medium insulation case. This can be explained as follows: Infrastructure reinforcements (and thus costs) are caused by electricity demand under peak circumstances on a very cold winter day. Under these temperature conditions, the COP of air-sourced heat pumps becomes very poor. A combination of high thermal demand and low efficiency causes an extreme peak in electricity demand and thus a heavy load on electricity infrastructure. Hybrid systems can be operated in such a way that, under circumstances of high thermal demand, gas will be used as an energy carrier putting less pressure on the electricity network infrastructure.

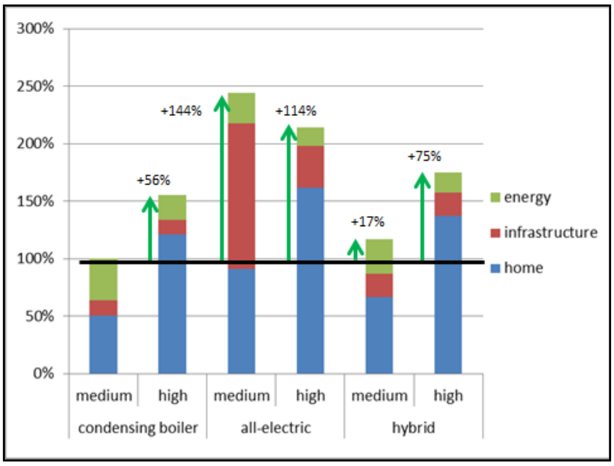

Figure 9 Costs of insulation and appliances on an annual basis.

Next, we investigated the CO_2 emission reductions of all-electric versus hybrid heat pump systems. To arrive at these results, future expected emission factors of 0.25 and 0.17 kg CO_2/kWh have been used [3] for electricity and gas respectively. We find that hybrid solutions offer higher reduction of emissions than the condensing boiler and all-electric solutions (see figure 10).

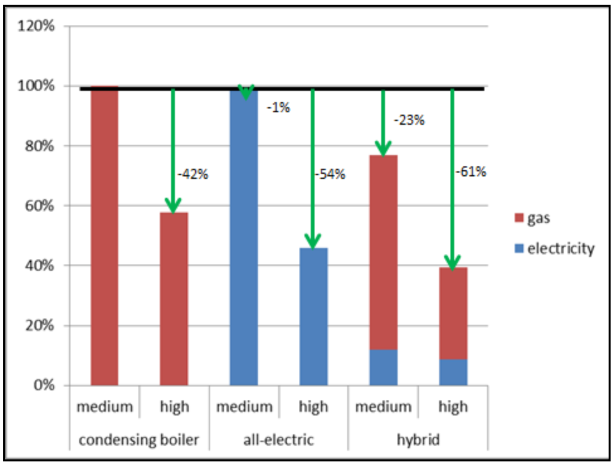

Figure 10 CO_2 emissions at medium and high insulation levels and three heating appliance technologies.

Comparing both graphs provides insight into the costs of realizing further emission reductions, using the condensing boiler, medium insulation home for comparison. See table 1 below:

Table 1 Costs of realizing further emission reductions

	Condensing boiler		All-electric heat pump		Hybrid heat pump	
	medium	high	medium	high	medium	high
Costs (€/ton CO_2)	-	€716	€79500	€1149	€411	€676

Taking a home with medium insulation equipped with a condensing boiler as a reference (which is the situation in the Netherlands), it can be seen from table 1 that the next step in CO_2 emission reduction should be to install a hybrid heat pump and then insulate from here to a further, higher level. This way, the highest reduction is obtained at the lowest cost. From the table, it is also very clear that installing an all-electric heat pump in a medium-insulated home is extremely expensive (mainly due to high infrastructure cost which is currently socialized) and barely reduces emissions.

Also note that, even if the residential sector were part of ETS (which is not the case), current CO_2 prices will never incentivize the residential sector to reduce CO_2 emissions.

6. Further benefits of hybrid heat pumps

A further comparison of hybrid heat pumps and all-electric heat pumps provides the following considerations:

6.1. Adaptations in homes

The efficiency of heat pumps depends on the temperature difference between source and destination; the smaller the difference, the more efficient. Therefore, the temperature of radiators for space heating should be kept as low as possible. This however requires a certain minimum radiator area for cold winters. Homes currently heated with condensing boilers are generally equipped with radiators that do not have this minimum area. These homes have to be modified (larger radiators, floor heating) in order to heat the home with a heat pump. This comes at a high cost.

Hybrid heat pumps do not require any changes to home radiators, since they can easily deliver high-temperature water during cold winters, making them an extremely attractive option.

6.2. Avoiding conversion between energy carriers

As time goes on, our electricity supply will be increasingly from renewable sources and intermittent. Both all-electric and hybrid heat pumps increase electricity demand. All-electric heat pumps, however, also require electricity supply when no renewable sources are available. Electricity conventionally generated (usually by gas) must then fill the gap. This conversion from gas to electricity is associated with high energy losses which can be prevented by using gas as the energy carrier in a hybrid heat pump. Using gas as the energy carrier instead of electricity will be more energy-efficient especially in circumstances involving a poor COP (at low outside temperatures and when preparing hot water).

6.3. Congestion management

The electricity network is vulnerable to congestion caused by increased demand (electric vehicles and heat pumps) and/or increased production (e.g. PV on sunny days). Both all-electric and hybrid heat pumps can play a role in reducing congestion caused by PV production if equipped with a thermal storage unit.

However, hybrid heat pumps can play a role in reducing congestion caused by high heat demand simply by switching to gas as an energy carrier. In contrast, all-electric heat pumps will only further increase demand. These congestion concerns are particularly relevant with the introduction of electric vehicles, which will draw power during the evening hours when PV supply is low. This has been investigated by Berenschot [4].

6.4. Flexibility services to aggregators and other market parties

High electricity demand or high production from PV may cause, respectively, high or low electricity prices. Both all-electric and hybrid heat pumps can play a role in enabling customers to take advantage of low electricity prices, but only hybrid heat pumps can play a role in avoiding high electricity bills simply by switching to gas as an energy carrier thus reducing the overall energy bill. When electricity prices are low, customers can switch to electricity. This flexibility can offer services to energy companies through arbitrage between gas and electricity.

6.5. Hybrid systems enable virtual conversion of electricity to gas

During sunny and windy days, overproduction of electricity from RES would result in a costly real conversion to gas in the current electricity market. Heat pumps, whether hybrid or all-electric, can partially cope with this overproduction and use the electricity to heat water.

In contrast, during winter days, low RES would result in a costly conversion of non-renewable energy to electricity if homes were installed with all-electric heat pumps. Hybrid heat pumps or condensing boilers would be the preferred appliance during winter.

Thus, on an annual basis, hybrid heat pumps reduce gas consumption and can be viewed as energy convertors (power-to-gas, storing gas, and gas-to-power) without actual physical conversion and the associated efficiency losses. They therefore help to reduce electricity peak supply demand (by switching energy carrier).

7. Discussion

Space heating and domestic hot water demand represents a large share of the energy consumption and greenhouse gas emissions. Renewable supply to meet this demand therefore warrants a thorough analysis that includes affordability and reliability.

Natural gas as the main energy supplier comes at a low cost (transport and distribution of energy through natural gas pipelines is much cheaper than through electricity infrastructure) and high flexibility (natural gas is available on demand all year because of cheap underground storage while electricity cannot be stored in these large amounts).

Electricity as an alternative energy carrier cannot offer these advantages. Therefore, a combination of energy carriers must be pursued to obtain “the best of both worlds”. Use electricity when it is abundantly available from renewable sources and use gas when electricity is not readily available. Hybrid appliances are capable of accommodating both gas and electricity as energy carrier. Using these appliances offers an evolutionary approach of gradually accommodating renewables whenever they become available while also maintaining a reliable energy carrier as a backup.

All-electric appliances, on the other hand, are dependent on the availability of electricity, also in times where there are insufficient supplies of renewable electricity. The market requires an energy carrier that can be stored.

It must be mentioned that the benefits of hybrid systems are highest in areas with a well-developed gas infrastructure. This will be the case in many northwest European countries like the UK, Belgium, France, Germany and the Netherlands.

8. Conclusion

- Electricity supply in the future will be increasingly diverse, consisting of a mix of intermittent renewable electricity supply and reliable backup. Electricity demand should match this supply.
- Installing all-electric heat pumps in a medium insulated home is extremely expensive (mainly due to high infrastructure cost) and is hardly reducing emissions. Due to the current legal framework, these costs are socialized and do appear on the bill of the owner/resident of the home.
- In situations where both gas and electricity infrastructure are present, hybrid heat pumps offer the lowest cost and highest emission reduction and are therefore preferable to all-electric heat pumps.

Acknowledgements

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