Evaluating Environmental Performance in Low-Carbon Energy Systems

Case Studies with the Ecodesign Toolbox 3

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Nomenclature

Abbreviation	**Explanation**
AP	Acidification Potential
EP	Eutrophication Potential
GWP	Global Warming Potential
POCP	Photochemical Ozone Creation Potential
LEH	Low Energy House
ODP	Ozone Depletion Potential
NSH	Night Storage Heater
PH	Passive House

Glossary

Term	Definition
Standard House	Row house with houses attached on both sides. In general the U-value for houses after 1990 is below 0.4 W/(m2*K) (WSVO 1995 in Germany < 0.5) . See below for three examples defining some exterior walls for standard houses after 1990. Heat-absorbing glass (double) U-value 1.1 (noble gas)-1.8 (air), air exchange rate 0.7-0.5, concrete ceiling, pitched roof, heat load 70 -120 kWh/(m2*a) 1. Vertically perforated bricks 30 cm (650 kg/m3, λ= 0.12 W/(m*K)), light mortar (700kg/m3), exterior plaster lime cement, interior plaster lime gypsum U-Value 0.35-0.4 W/(m2*K); 2. sand-lime bricks 17,5 cm (1500 kg/m3, λ= 0.75 W(m*K)) + 12cm EPS (15 kg/m3, λ= 0.035 W/(m*K)) exterior plaster lime cement, interior plaster lime gypsum U-Value 0.25-0.3; 3. Aerated concrete bricks 30 cm (400 kg/m3, λ= 0.1 W/(m*K)) exterior plaster lime cement, interior plaster lime gypsum U-Value 0.3-0.35 W/(m2*K).
Low-Energy House	Row house with houses attached on both sides. Build after 1990, U-value exterior walls 0.15-0.30 W/(m2*K), roof 0.15-0.25 W/(m2*K), base plate 0.2-0.3 W/(m2*K), Window heat absorbing glazing (double or triple), noble gas) U-Value 0.7-1.4 W/(m2*K), mechanical ventilation, sometimes with heat recovery, air exchange rate 0.6, heat demand 15-60 kWh/(m2*a). Examples for exterior walls: wooden wallboard, sand-lime bricks + isolation, aerated concrete + isolation.
Passive House	Row house with houses attached on both sides. Build after 1990, U-value exterior walls < 0.15 W/(m2*K), roof < 0.15 W/(m2*K), base plate <0.16 W/(m2*K), Window heat absorbing glazing (triple) U-Value <0.8W/(m2*K), mechanical ventilation with heat recovery, efficiency for heat recovery > 80%), air exchange rate 0.6, heat demand <15 kWh/(m2*a). Examples for exterior walls: wooden wallboard including 25 cm mineral wool and more, 15 cm sand-lime bricks with 30 cm EPS, 24 cm aerated concrete + 20 cm mineral wool

1 Case study 1: environmental impact of the electricity mix

1.1 Background & Objective

Case study 1 was constructed with the intention of assessing how the choice of power grid mix influences the environmental impact of producing electricity. Electric power can be produced from various renewable and non-renewable resources, and the technologies to harvest renewable resources are gaining momentum, together with the global pressure to increase their contribution to energy provision. In the EU targets have been set for 2020 to generate 20% of the total energy demand from renewable resources. National schemes have been set up to reach this overall goal, stricter for the more advanced and economically stable nations and laxer for the economically more disadvantaged ones. Although the target is very demanding, the potential benefits are likely to compensate for the efforts within a short time. In this theoretical exercise, the environmental impact of the current grid mix is assessed against potential future scenarios of electricity production in 2020, 2030 and under conditions of “zero carbon” emissions. The baseline for the comparison is the provision of 1kWh of electric power.

1.2 System description

The provision of electricity occurs through the same efficiency parameters as in the standard case. Although efficiencies are likely to change over time, this will only further enhance the improvement the “future” grid mixes can provide. As shown in Table 1-1, the scenarios were distinguished by the relative share of the different renewable and non-renewable resources utilized in power provision. The power grid mix in the model was applied for the “use phase” only, i.e. for the provision of 1kWh of power, while the manufacture and EoL of the power plants providing this energy remained dependent on the current EU-25 grid mix in all scenarios.

Table 1-1: Share of renewable and non-renewable energy sources for the power grid mixes in the four scenarios under investigation.

Resource	Current EU-25	2020	2030	“Zero carbon”
Hardcoal (%)	19.45	10	-	-
Lignite (%)	11	6	-	-
Natural gas (%)	17.7	17	17	-
Fuel oil (%)	6.22	0	-	-
Nuclear (%)	33	33	33	50
Hydro power (%)	11.3	15	15	15
Solar (%)	0.1	3	10	10
Wind (%)	1.23	16	25	25
Total power (%)	**100**	**100**	**100**	**100**
Total renewables (%)	**12.63**	**34**	**50**	**50**

The definition of the current EU-25 grid mix is based on the latest GaBi standard dataset. The inventory is based on measured operating data taken from national statistics, literature and / or calculated via energy carrier composition in combination with (literature-based) combustion models.

Since the futuristic scenarios described in Table 1-1 are merely targets and intentions, the numbers in the table are barely more than projections and assumptions based on current trends and an optimistic outlook. As for the 2020 grid mix, some of the numbers were taken from the recommendations made by the Renewable Energy Road Map of the Commission of European Communities. The “Zero Carbon” scenario is only figurative of a “near-zero-CO_2-emissions” situation, not being necessarily realistic.

1.3 Results & Discussion

The results clearly demonstrate that with an increasing share of renewable energy sources, the environmental impact of power provision will decrease.

1.3.1 Primary Energy Demand (net calorific value): Figure 1-1

- Primary Energy Demand (PED) will decrease linearly, with an increasing share of renewables. The reason is that renewable energy sources, such as the energy of solar irradiation, wind and water, is considered a virtually unlimited supply and therefore, the losses incurred due to low efficiencies are not fully considered as *consumed* primary energy. With as little as one third of renewable share in power provision (2020 grid mix), over 1MJ is saved for every kWh used; with half of the energy coming from renewables (2030 grid mix), 2.5 MJ are saved for every kWh used.

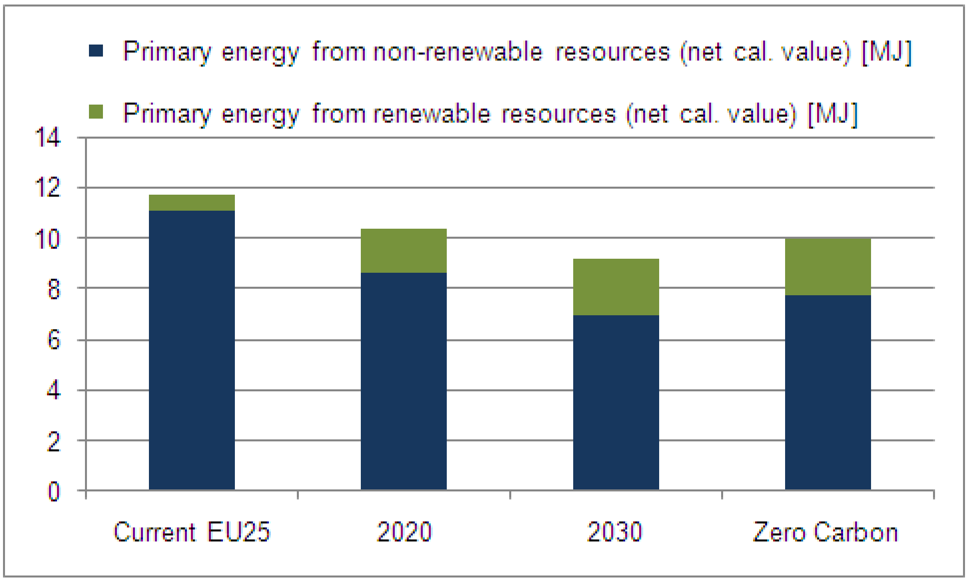

Figure 1-1: Primary Energy Demand (net calorific value, in MJ) of producing 1kWh power, as contributed by renewable and non-renewable energy sources

- The “green” share of PED in the figure quantifies the energy coming directly from a renewable resource such as wind or solar irradiation. In order to produce 1MJ of power from a wind power plant, there is a certain share of energy required for manufacturing the plant (the value of which diminishes the longer it is in use) and maintaining it. This energy derives largely from the power grid mix, and is unchanged throughout the scenarios, and therefore part of this energy is non-renewable. In addition, as mentioned before, the losses incurred in producing renewable energy are not fully considered, while these amount to ca. 60-70% of the PED in case of non-renewable power generation. The effect is that the share of non-renewables is much higher in the PED calculation than in Table 1-1 describing the contribution of power plants in the grid mix.

- With an equal share of renewables, but substituting natural gas with nuclear power, the efficiency of power generation decreases, resulting in a higher PED in the “zero carbon” scenario.

1.3.2 Global Warming and CO_2 emissions: Figure 1-2

- CO_2 and other greenhouse gas emissions will also be decreasing linearly with the increasing share of renewable, although at a considerably faster pace. For each kWh used one would be able to save 0.2kg CO_2 emissions with the 2020 scenario coming true, and almost 0.4kg with the realization of the 2030 scenario. This means 4kg to 8kg of CO_2 emissions saved per day and per household counting with ca. 20kWh used in an average household per day [PE INTERNATIONAL 2009].
- In case of substituting the 17% of fossil fuel-based resources still present in the 2030 grid mix with nuclear power (“zero carbon” scenario), the CO_2 emissions amount to only 7% of the current grid mix emissions. Although this scenario is called “zero carbon”, carbon dioxide emissions cannot be completely avoided - the GaBi model includes not only the use but also the manufacture of the power plants and their maintenance. These processes, as mentioned in section 1.2, rely on both liquid fuels for transport and power from the current grid mix, rather than from the new one.

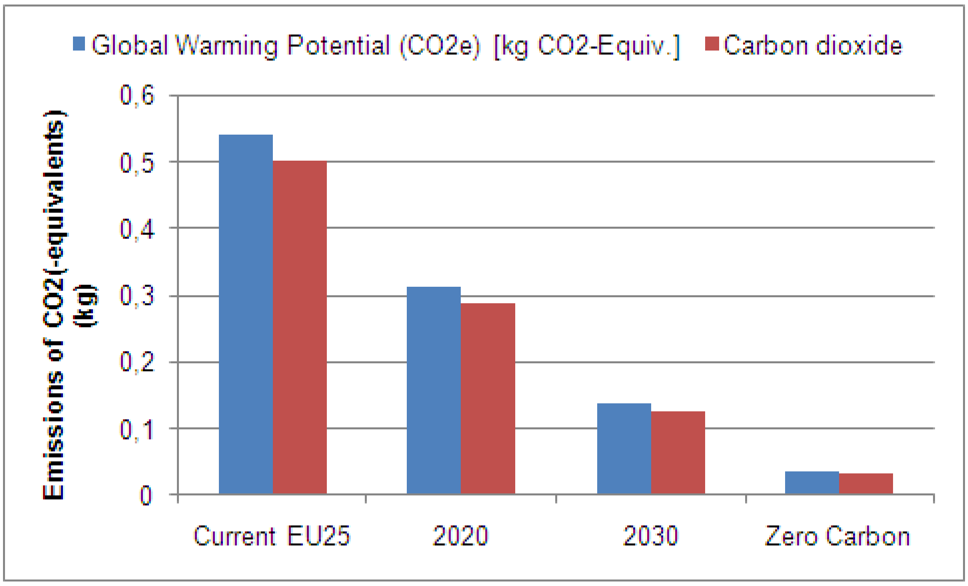

Figure 1-2: **Global Warming Potential (kg CO2-equiv.) and CO2 emissions (kg) from the production of 1kWh power**

1.3.3 Selected impact categories: Figure 1-3, Table 1-2

Along with Global Warming Potential (GWP), other categories also show considerable decline in the three "future" scenarios.

- Acidification Potential (AP) will decrease at a faster rate than GWP with the change from the current to the 2020 grid mix, and once again from the 2020 to the 2030 grid mix, because with the elimination of sulphur-rich lignite and coal, sulphur dioxide emissions will arise only from natural gas which has a much lower sulphur content.
- The Eutrophication Potential (EP) associated with burning coal is very high, but burning natural gas also has a relatively high EP. Therefore the decrease from 2020 to 2030 is not as steep as in case of AP, but steeper than in case of GWP which is still very high when natural gas is being burnt.
- Photochemical Ozone Creation Potential (POCP) follows a similar pattern: a mixture between AP and EP, because of the overlap of flows that influence POCP and EP, and POCP and AP.
- Radioactive waste is only influenced by nuclear power, and therefore only the change in contribution from 33% to 50% ("zero carbon") is visible.
- Ozone Depletion Potential (ODP) was also assessed, however, it is not shown here because with the ban of substances responsible for this impact, the values are no longer representative. Unless foreground data is presented demonstrating that the halogenic substances were indeed in use it remains an impact category whose figures are impossible to translate to a meaningful conclusion.

Table 1-2: Contribution of producing 1kWh electric power to selected impact categories.

Environmental Quantities	Current EU-25	2020	2030	Zero carbon
GWP (CO2e) [kg CO2-Equiv.]	5.39E-01	3.12E-01	1.38E-01	3.54E-02
AP [kg SO2-Equiv.]	2.86E-03	1.42E-03	2.52E-04	1.51E-04
EP [kg Phosphate-Equiv.]	1.29E-04	7.00E-05	2.56E-05	1.25E-05
ODP [kg R11-Equiv.]	1.31E-07	1.31E-07	1.31E-07	1.98E-07
POCP [kg Ethene-Equiv.]	1.67E-04	8.71E-05	2.36E-05	1.02E-05
Radioactive waste (kg)	1.75E-03	1.75E-03	1.75E-03	2.65E-03

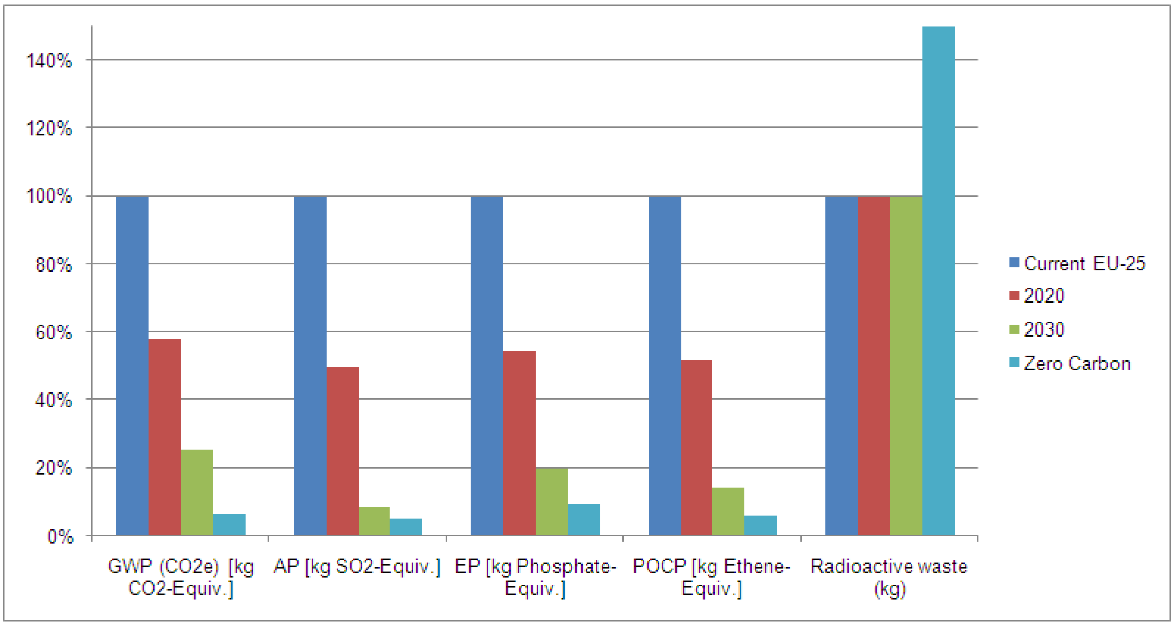

Figure 1-3: Relative contribution of 1kWh of power provision to selected impact categories;

2 Case Study 2: Low-Energy House heating system

2.1 Introduction

In this case study the analysis targets a comparison between heating systems in a Low-energy house. The definition of a low-energy house can be found in the Glossary. Heating systems today are still largely fossil fuel-based, although electric heating systems are also gaining ground. Considerable debate surrounds the use of electric heaters versus efficient (~100%) gas heaters. While gas is the cleanest of fossil fuels with regards to emissions, and the heat gain is also very high, electric power has the potential to improve its emission profile by the incorporation of more and more renewable resources. Today, however, electric power is both inefficient (for a single unit of usable energy produces 2 units of losses) and still largely dependent on fossil fuels. In this case study the Best Available Technology of both heating systems will be compared, namely *gas condensing boilers* and electric *heat pumps*. The efficiency of gas condensing boilers lies in their capacity to capture the latent heat of water vapour produced through the burning process that would otherwise (in older designs) escape through the vent. On the other hand, the heat pump utilizes the thermal energy in air or groundwater to pump heat into the house, and while the pumping itself requires energy, the produced thermal energy (heat) is four times higher than the electricity consumed by the equipment.

In addition to comparing different heating technologies, the case study also endeavours to assess them using different “future” grid mixes (see also Case study 1: environmental impact of the electricity mix). “Current” scenarios refer to the use of the latest GaBi power grid mix dataset for EU-25 countries. Therefore the analysis not only compares the best available technologies of today, but also looks at how the relationship may change in circumstances where electric power provision will derive increasingly from renewable resources (for more information see Case study 1: environmental impact of the electricity mix). While it may seem unfair to show potential improvement for only one of the technologies under scrutiny, it is indeed only realistic to expect an increase in renewable energy sources in the grid mix, while there is little to no room left for improvement in gas-based heating systems. The basis for comparison is the provision of heating for the life cycle of the same low-energy house.

2.2 System description

All systems under investigation are based on a Low-Energy House as defined in the Glossary. The main parameters distinguishing this housing type from other houses are summarized in 1.1.1.1Supplement A. The building of the house itself is part of the system, as well as the *use phase* including heating and the operation of a circulation pump and mechanical ventilation. (The latter two are electric equipment, the ventilator is required to maintain air quality inside the tightly insulated walls of the low energy house, and can also be designed with a heat recovery system.) The electric and heating equipment manufacture and disposal are modelled as part of the *use phase* of the house on account of the equipment’s function in the system. The lifetime of the house spans 50 years, all results refer to this lifecycle unless otherwise stated.

Table 2-1: Scenarios of heating equipment and grid mix

Scenario name	Heating equipment	Non-renewables in grid mix	Renewables in grid mix (%)
Heat pump: Current	Heat pump	Oil, coal, lignite, nuclear, natural gas	12.63
Gas condens: Current	Gas condensing heater	Oil, coal, lignite, nuclear, natural gas	12.63
Heat pump: 2020	Heat pump	Coal, lignite, nuclear, natural gas	34
Gas condens: 2020	Gas condensing heater	Coal, lignite, nuclear, natural gas	34
Heat pump: 2030	Heat pump	Nuclear, natural gas	50
Gas condens: 2030	Gas condensing heater	Nuclear, natural gas	50

2.3 Results & Discussion

Overall, the heat pump is the more environmentally solution, although with today's grid mix, the advantage is not as clear as using the "future" grid mixes.

2.3.1 Primary Energy Demand (net calorific value): Figure 2-1 and Figure 2-2

- In the two "current" scenarios the Primary Energy Demand (PED) of the house using the heat pump is considerably lower than using the gas condensing heater, which is the best fossil fuel-based heating equipment available today. In one year over 9GJ of PED can be saved using the heat pump, amounting to over 450 GJ over the life cycle of the house
- In the "future" grid mix scenarios the PED of the houses using both heating equipments will decrease, but the house using the heat pump will benefit from the changed grid mix to a larger extent.

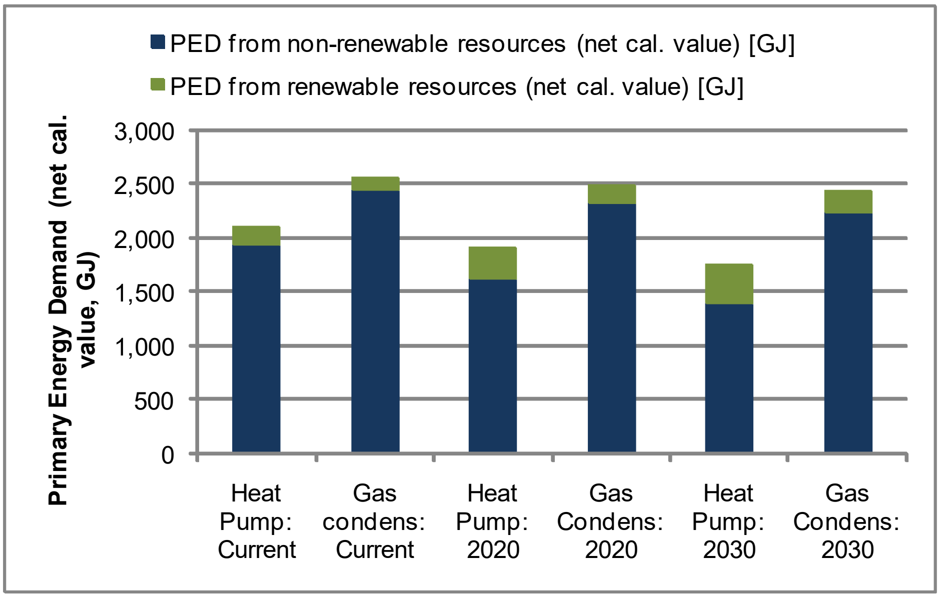

Figure 2-1: **Primary Energy Demand (net calorific value, in GJ) over the life cycle of the house, as contributed by renewable and non-renewable energy sources**

- Figure 2-2 demonstrates the contribution of life cycle phases towards the total PED of the house in each scenario. The manufacture of the house itself is constant in all scenarios (shown only once, although relevant for all four scenarios), and contributes between about 26 and 18%. The use of electric equipment has a contribution in each scenario, since the system in each scenario is based on a low-energy house, which requires the operation of a ventilator. In addition, the heat pump use is included in the electric equipment in the scenarios where a heat pump is used for heating. Fossil fuel-based heating equipment is only present in the “gas condens” scenarios. The figure demonstrates that already using today’s grid mix, the heat pump option is much more energy-saving under the circumstances of the Low-Energy House.

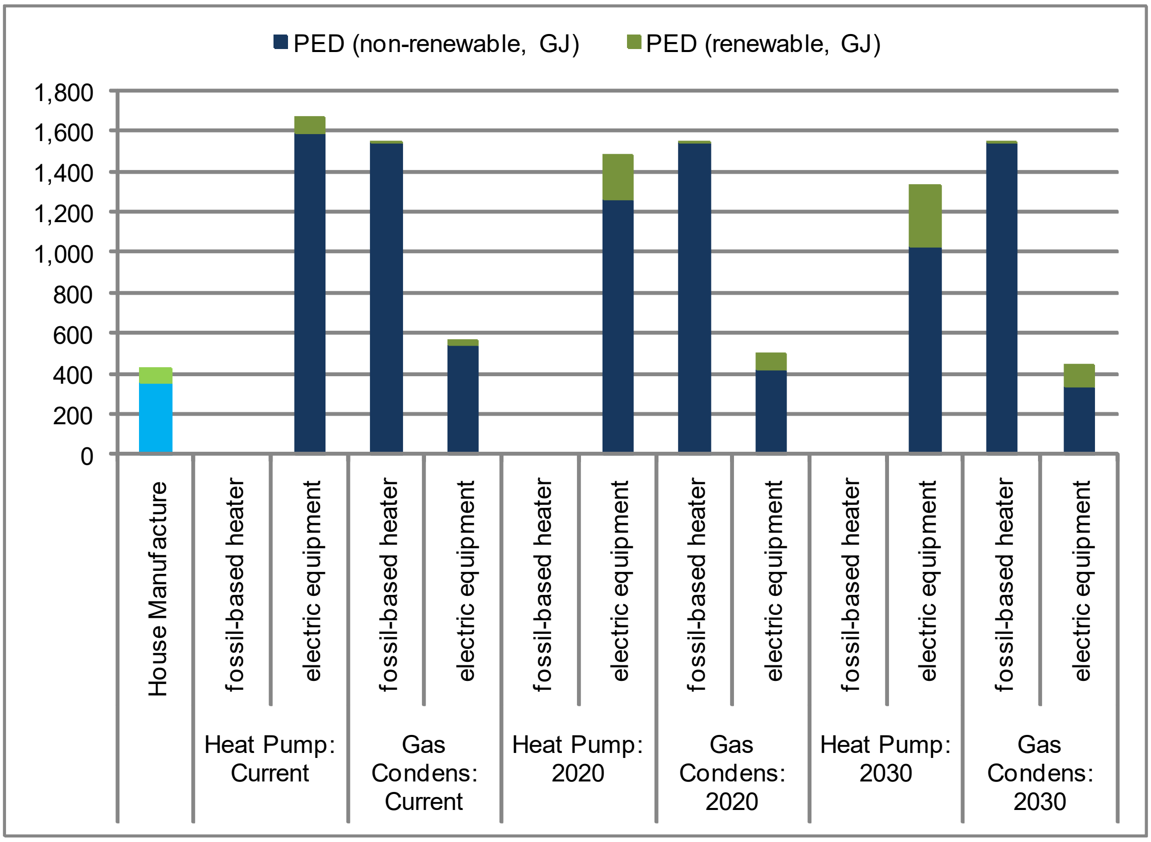

Figure 2-2: **Primary Energy Demand (net calorific value, in GJ) of the life cycle phases of the house, as contributed by renewable and non-renewable energy sources. The manufacture phase contribution is shown only once, since it is the same for all scenarios.**

2.3.2 Global Warming and CO_2 emissions: Figure 2-3

- Global Warming and CO_2 emissions show the same pattern as does PED: significantly lower impact coming from the house with heat pump than from the house with gas condensing heater.
- This pattern becomes more evident with the application of “future” grid mix scenarios, since the house with gas condensing heater does not benefit from the increasingly higher share of renewable resources as much, so long as the heating remains dependent on fossil fuels.
- Note that CO_2 emissions are sometimes higher than the GWP. This is in fact a result of the different methods in calculating the carbon footprint versus the impact category GWP. In the latter, carbon stored in materials such as wood is accounted for as a “negative emission” thereby reducing the total impact coming from carbon emissions. In calculating the carbon footprint on the other hand, this is not the case. The inherent assumption in the GWP calculation is that forests are being re-forested at the same rate as they are cut down, and so for every tree turned into timber, for example, there will be another tree to continue CO_2 sequestration through photosynthesis. While this assumption holds true in Europe, in most other regions deforestation takes place at a much higher rate than re-forestation.

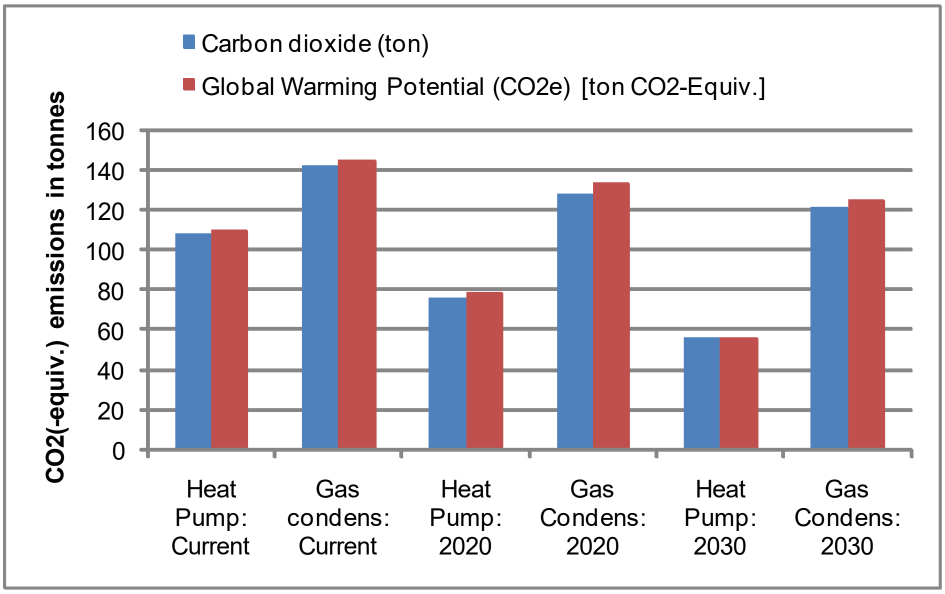

Figure 2-3: **Global Warming Potential (ton CO2-eq.) and CO2 emissions (ton) throughout the life cycle of the house**

2.3.3 Selected impact categories: Figure 2-4

- Acidification Potential (AP) demonstrates a slightly different pattern than was seen from the PED and GWP figures. Compared with the house using the heat pump, the house that uses gas condensing heating has about 40% lower impact when the current grid mix is applied. Using the 2020 grid mix the heat pump still has a higher impact, but using the 2030 grid mix, heat pump becomes more beneficial for the environment. The reason for this is the low sulphur-content of natural gas fuelling the boiler, while high-sulphur containing fuels (like coal and lignite) are still included in the current and the 2020 grid mix (see also Case study 1: environmental impact of the electricity mix). In the 2030 grid mix natural gas is the only fossil fuel, and since this resource constitutes only 17% of the grid, the impact of the heat pump becomes lower than that of the gas boiler.

- Eutrophication Potential (EP) demonstrates a similar but attenuated pattern: while using the current grid mix the gas heater is more advantageous, already in 2020 the heat pump becomes more beneficial. This is due to the fact that emissions of nitrogen oxides are associated with all fossil fuel burning processes and therefore only their complete elimination will decrease the EP impact category substantially.

- Photochemical Ozone Creation Potential (POCP) is influenced by NO_x emissions as well, and therefore the pattern is very similar as with EP.

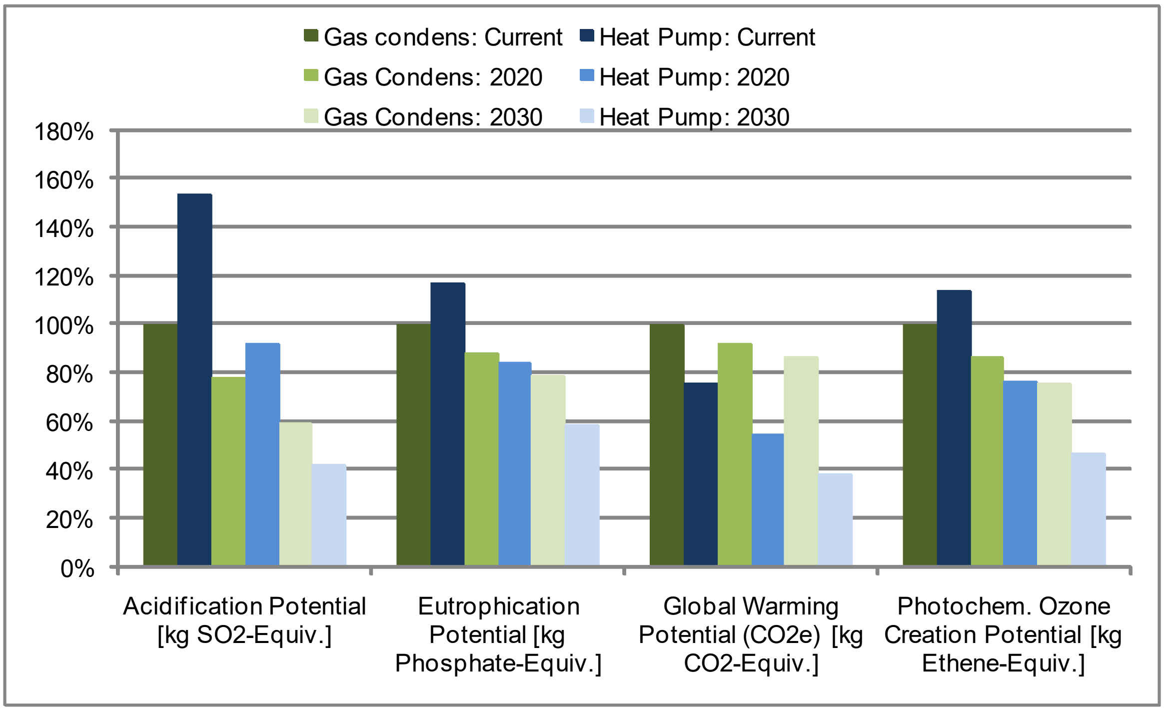

Figure 2-4: Relative contribution of the houses with different heating equipment to selected impact categories. The gas condensing heater with current grid mix scenario represents 100%.

2.4 Conclusions

- Heat pumps (assuming 4:1 output-to-input energy and no additional heating required) are a more environmentally friendly solution and still with potential for improvement in the future.

- With regards to Global Warming and Primary Energy, already with the current grid mix in place they provide the best available technology.

- With higher volume of renewable energy sources contributing to the power grid mix, however, heat pumps will beat gas condensing boilers in all impact categories. While today's gas boilers may show further improvements, they will always be dependent on a fossil resource, whose burning will produce CO_2, SO_2 and NO_x emissions, among others, responsible for many of the environmental problems, such as Global Warming, Acid Rain, Eutrophication (over-fertilization), Summer Smog creation etc.

3 Case Study 3: Low Energy House versus Passive House

3.1 Introduction

Low Energy and so-called Passive Houses (LEH and PH, respectively) represent innovative design and technologies implemented in favour of energy efficiency. Compared to a standard house, both of these housing types have increased window surface area facing South, increased insulation on both walls and windows, sand-lime brick replacing the traditional bricks. The general description of the housing types is provided in the Glossary, while the list of parameters defining the houses in the model is provided in 1.1.1.1Supplement A. The difference between LEH and PH is mostly question of degree of efficiency: insulation is better in the PH and therefore the total heat demand of the same size house is much reduced. To match this high level of efficiency an electric heat pump is the desirable choice, while in the LEH the best available fossil fuel-based heater, i.e. the gas condensing boiler, is implemented. (More on the two heating systems can be gleaned from Case Study 2: Low-Energy House heating system.

In Case Study 2: Low-Energy House heating system, the gas condensing heater was compared to the heat pump inside the LEH. In the present Case Study the comparison is between the two houses with their standard heating system, i.e. gas condensing boiler for LEH and heat pump for PH. In addition to comparing different heating technologies, the case study also endeavours to assess them using different “future” grid mixes (see also Case study 1: environmental impact of the electricity mix). “Current” scenarios refer to the use of the latest GaBi power grid mix dataset for EU-25 countries. Therefore the analysis not only compares the best available technologies of today, but also looks at how the relationship may change in circumstances where electric power provision will derive increasingly from renewable resources (for more information see Case study 1: environmental impact of the electricity mix.

3.2 System description

Both LEH and PH have the same size and climate conditions, while differing slightly in their insulation materials etc (see 1.1.1.1Supplement A). The heaters in both represent Best Available Technologies. The LCA study includes the building of the house itself in both cases, as well as their *use phase* including heating and ventilation. (The ventilator is an electric equipment required to maintain air quality inside the tightly insulated walls of both the LEH and PH, and can also be designed with a heat recovery system.) The electric and heating equipment manufacture and disposal are modelled as part of the *use phase* of the house on account of the equipment’s function in the system. The lifetime of the house spans 50 years, all results refer to this lifecycle unless otherwise stated. Table 3-1 summarizes the most important distinctions between the scenarios investigated in this study.

Table 3-1: Scenarios considered in Case Study 3.

Scenario name	Heating equipment	Heat demand per year (kWh)	Renewables in grid mix (%)
LEH: Current	Gas condensing heater	4979.8	12.63
PH: Current	Heat pump	2168.6	12.63
LEH: 2020	Gas condensing heater	4979.8	34
PH: 2020	Heat pump	2168.6	34
LEH: 2030	Gas condensing heater	4979.8	50
PH: 2030	Heat pump	2168.6	50

3.3 Results & Discussion

3.3.1 Primary Energy Demand (net calorific value): Figure 3-1 and Figure 3-2

- Figure 3-1 demonstrates that the total life cycle's Primary Energy Demand (PED) in the PH is considerably lower than in the LEH with the current grid mix in place.
- Changing the current grid mix to the 2020 and 2030 grid mixes further barely changes the scene, although the decrease in PED is more noteworthy in the PH, where heating is also electricity-based.
- The increase in the share of renewables is also more evident in the PH for the same reason: using electric heat pumps allows for higher penetration of renewables in the mix.
- Figure 3-2 demonstrates the individual contribution of the use phase and manufacture of the house. In both houses, the manufacture phase accounts for ca.450 GJ, a little less in case of the LEH and a little more in case of the PH. However, due to different energy demands, this translates into ca. 18% (LEH) up to 35% (PH) of the total impact including 50 years of use.
- It becomes obvious that while the manufacture phase is slightly more energy-intensive for the PH, the extra input pays off rather quickly.
- With an electric heat pump meeting the heating needs, the PED is much lower in the PH in both current and "futuristic" scenarios. This is due to the combined effect of lower heat demand of the better insulated house (see heat demand in Table 3-1) and the higher efficiency of the heat pump. While the gas boiler is roughly 100% efficient, the heat pump's 400% efficiency[1] overcompensates for the losses of the power grid mix (~65%).
- It is also quite clear from Figure 3-2 the decrease over time in total PED which is related to the power grid mix increasingly relying on renewable resources that are not subject to the same losses as with non-renewables.

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[1] Coefficient of performance (COP) is equal to 4, meaning that the heat pump delivers 4 times more heat in kWh than the electricity it consumes

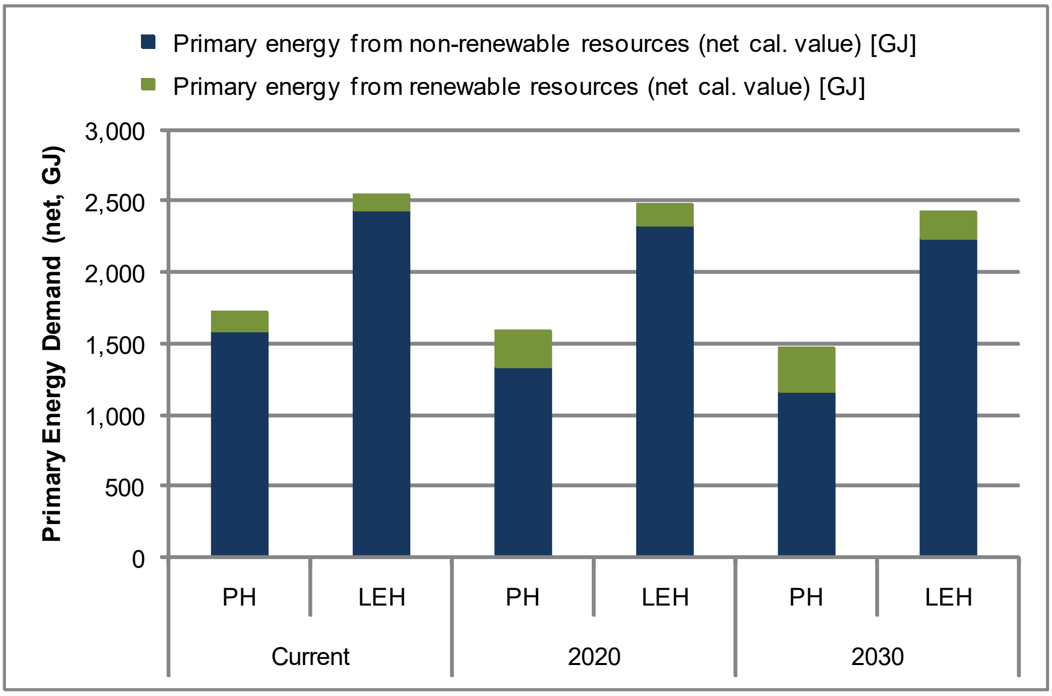

Figure 3-1: Primary Energy Demand (net calorific value, in GJ) over the life cycle of the house, as contributed by renewable and non-renewable energy sources

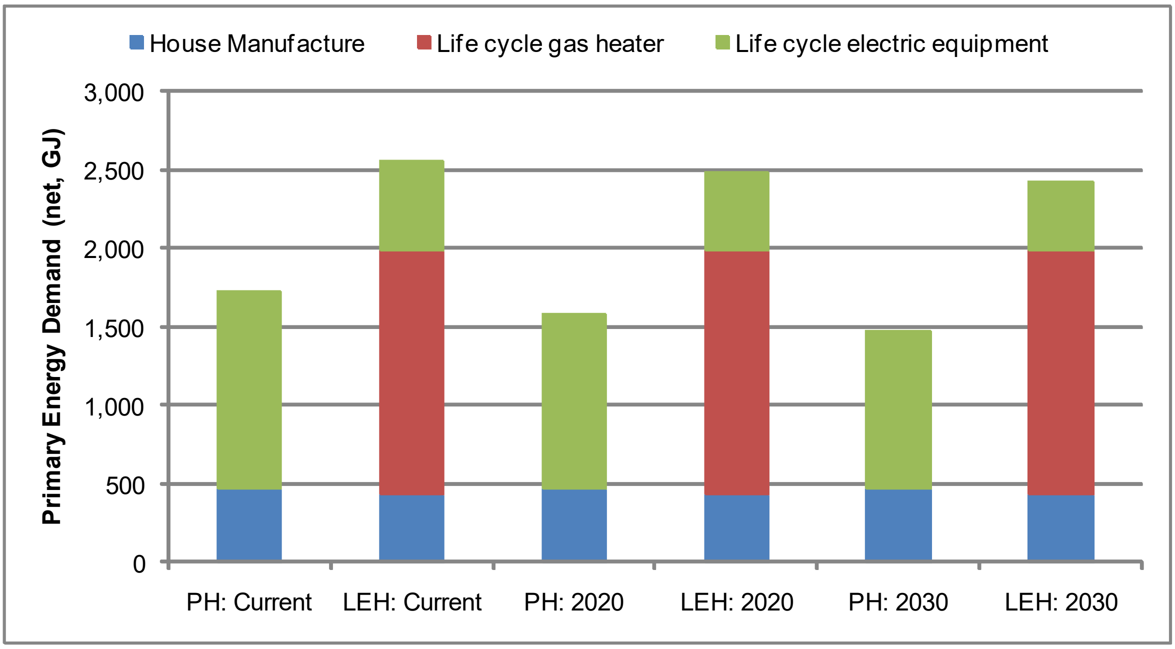

Figure 3-2: Primary Energy Demand (net calorific value, in GJ) over the life cycle of the house, as contributed by house manufacture, gas heater life cycle and electric equipment (heat pump and ventilator) life cycle

3.3.2 Global Warming and CO_2 emissions: Figure 3-3

- As compared to the LEH with gas condensing boiler, the PH with an electric heat pump can save over 1 ton of CO_2 emissions every year already with today's grid mix in place.

- In future scenarios, with increasing amount of renewable energy sources largely free of emissions, this can grow to be almost 1.5 tons a year!
- Note that CO_2 emissions are sometimes higher than the GWP. This is in fact a result of the different methods in calculating the carbon footprint versus the impact category GWP. In the former, carbon stored in materials such as wood is accounted for as a “negative emission” thereby reducing the total impact coming from carbon emissions (see also Case Study 2: Low-Energy House heating system section 2.3.2).

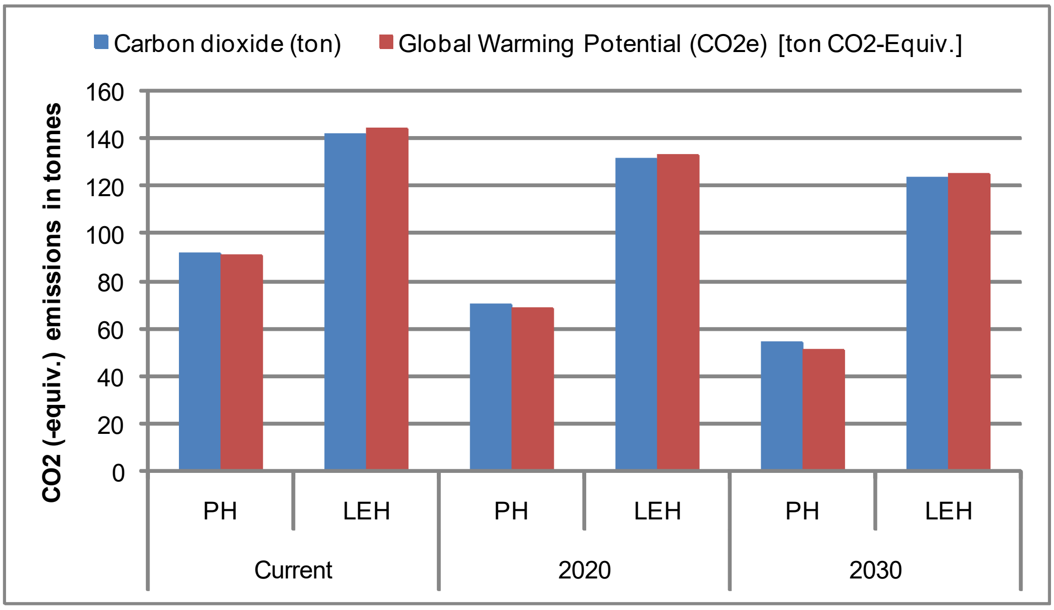

Figure 3-3: **Emissions of CO2 and other greenhouse gases (ton CO2-equiv.)**

3.3.3 Selected impact categories: Figure 3-4

- Acidification Potential (AP) demonstrates a slightly different pattern than was seen from the PED and GWP figures. The PH has a higher AP than does the LEH under current conditions of power generation. Using the 2020 grid mix the PH has roughly the same impact as the LEH, but using the 2030 grid mix, the PH becomes more beneficial for the environment. This is almost the same pattern as was shown in Case Study 2: Low-Energy House heating system where the two heating systems were compared within the LEH. The reason, as was explained there, is the low sulphur-content of natural gas fuelling the boiler, while high-sulphur containing fuels (like coal and lignite) are included in the current grid mix (see also Case study 1: environmental impact of the electricity mix) resulting in SO_2 emissions contributing to acidification. On the other hand, the PH has a lower heat demand than the LEH and therefore much less electric power needs to be consumed, therefore offsetting the difference in SO_2 emissions already with moderate renewable share in the grid mix (2020).
- The Eutrophication Potential (EP) of the two houses are identical assuming current grid mix conditions, but increasing the share of renewables (2020 and 2030) the balance is quickly tilted in favour of the PH. Fossil fuel burning generates NO_x emissions, and gas burning is not so much more favourable than coal burning that

it could offset the advantage of the PH gained by the decreased heat demand and the higher efficiency of the heat pump. As more of fossil fuels are being replaced by renewable resources, NO_x emissions reduce drastically together with EP.

- Photochemical Ozone Creation Potential (POCP) is influenced by NO_x emissions as well as carbon monoxide and VOCs, and therefore the pattern visible is some sort of a mix between the EP and GWP patterns in the graph.

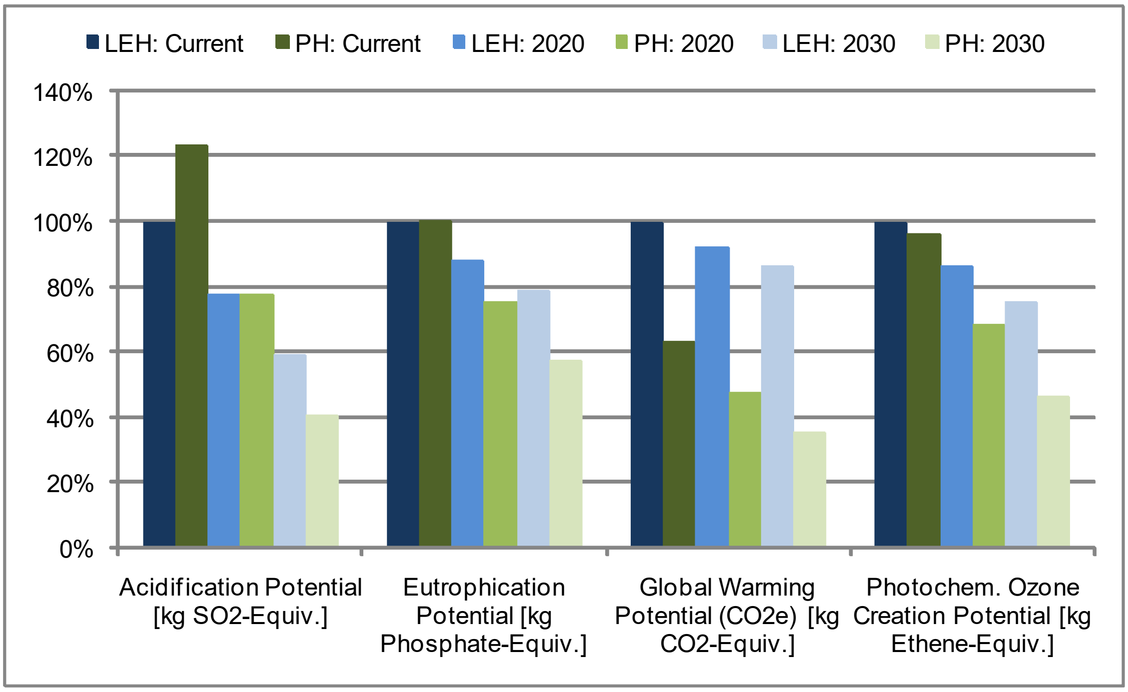

Figure 3-4: Relative contribution of the housing types to selected impact categories. The LH with current grid mix conditions represents 100%.

3.4 Conclusions

- The conclusion from Case Study 2: Low-Energy House heating system was confirmed and reinforced: the system PH + electric heat pump is more environmentally advantageous than the system LEH + gas condensing heater, given the high efficiency of the heat pump and tight insulation of the PH.
- Building a PH results in environmental benefits that quickly offset the initial environmental “investments”, e.g. PED, due to consequent low energy needs.
- The combined effect of a lower heat demand (as a direct result of better insulation and other building parameters) and the high-efficiency heat pump compensate for the losses incurred through electric power provision in both energetic and environmental terms
- Although in most impact categories (with the exception of AP) the PH fares better already using the current grid mix, the future holds much potential for improvement with increasing shares of renewable resources contributing to the power grid

4 Case Study 4: Primary Energy versus Global Warming

4.1 Introduction

In previous case studies, the best available fossil fuel-based heating system was compared with the best available electric heating system (Case Study 2: Low-Energy House heating system, Case Study 3: Low Energy House versus Passive House). A relatively outdated technology of heaters, however, may in the future prove to imply the environmentally cleaner solution. *Night storage* (or accumulation) heaters are electric appliances that produce and store heat overnight when electricity from the grid is cheaper due to a situation of more available provision than demand, and release it throughout the day. Although intended more as an economical incentive for customers, the long-term environmental consequences are worth considering and re-visiting. On the one hand, using night time electricity may re-distribute the power demand over day slightly better resulting in so-called “peak-shaving” or a decrease in the peak-time energy demand. This effect is very difficult to quantify though and is therefore purely speculative. On the other hand, future power grid mixes may contain sufficiently high shares of renewable resources that make it possible to (partially) shut down the fossil-fuel based plants overnight. While electricity is still consumed, and the losses through the grid are considerable (~65%), the benefits in terms of emissions can become significant, and shall be investigated with this case study.

4.2 System description

In the scenarios investigated, four out of the six have already been looked into in Case Study 3: Low Energy House versus Passive House (LEH and PH, respectively). The additional scenarios are the LEH fitted with a night storage heater using today’s power grid mix (GaBi 2006 Databases), and the LEH fitted with a night storage heater using the “night tariff” of the grid mix in 2030 (theoretical mix, for more information see Case study 1: environmental impact of the electricity mix). The “night tariff” in this case means that during the night, which is when the night storage heater is operational, the grid mix contains 7% natural gas, 42% nuclear power, 19.2% hydropower, and 31.8% wind power. Compared to the day tariff, this means that the natural gas plant was downscaled, the solar panels are not functional and the other three sources are proportionally compensating for the decreased sources. Table 4-1 summarizes the scenarios investigated according to the major differences between them.

The LCA study includes the building of the house itself in all cases, as well as the house’s *use phase* including heating and ventilation. (The ventilator is an electric equipment required to maintain air quality inside the tightly insulated walls of both the LEH and PH, and can also be designed with a heat recovery system.) The electric and heating equipment manufacture and disposal are modelled as part of the *use phase* of the house on account of the equipment’s function in the system. The lifetime of the house spans 50 years, all results refer to this lifecycle unless otherwise stated.

According to the model, the night storage heaters work with 90% efficiency. This means that about 10% of the consumed power is lost and 90% is converted to heat used to warm the house to the required temperature. This efficiency figure is a worst-case estimate, also accounting for any extra heating required if the storage heater proves insufficient for the house.

Table 4-1: Scenarios considered in Case Study 4

Scenario name	Heating equipment	Heat demand per year (kWh)	Renewables in grid mix (%)
LEH: Current	Gas condensing heater	4979.8	12.63
PH: Current	Heat pump	2168.6	12.63
LEH: Storage Current	Night storage heater	4979.8	12.63
LEH: 2030	Gas condensing heater	4979.8	50
PH: 2030	Heat pump	2168.6	50
LEH: Storage 2030	Night storage heater	4979.8	50

4.3 Results

4.3.1 Primary Energy Demand (net calorific value, in MJ): Figure 4-1 and Figure 4-2

- Primary Energy Demand (PED) is lowest for the PH with the heat pump under both current and future grid mix scenarios.
- The LEH with gas condensing heater ranks second in terms of PED in both current and future grid mix scenarios.
- The LEH with the night storage heater has ca. 1.5 times higher PED than the LEH and ca. 2.5 times greater PED than the PH in both grid mix scenarios.
- The increased share of renewable sources of energy benefits the electric equipment using houses the most.
- In Figure 4-2 one can observe that the manufacture phase of all scenarios is relatively small and roughly the same. It becomes obvious that the differential total PED derives from the use phase of the house, i.e. the use of heating equipment.

4.3.2 Global Warming and CO_2 emissions: Figure 4-3

- The picture painted by the chart showing Global Warming Potential and CO_2 emissions demonstrates a strikingly different pattern from that of PED: The PH is still the environmentally least harmful option among the systems observed in both grid mix scenarios, but the LEH fitted with night storage heating is almost equally low in emissions when taking into account night tariffs and the renewable resources in the grid mix of 2030.
- Although both night storage heaters and heat pumps are electric equipment, the night tariff system has only 7% of fossil fuel dependence under the 2030 grid mix scenario, while heat pump continues to rely on daytime tariff, therefore utilizing 17% of fossil fuels. This difference compensates for the lower efficiency of the

night storage heater, making both PH and the LEH with night storage heater almost equally advantageous options in this category.

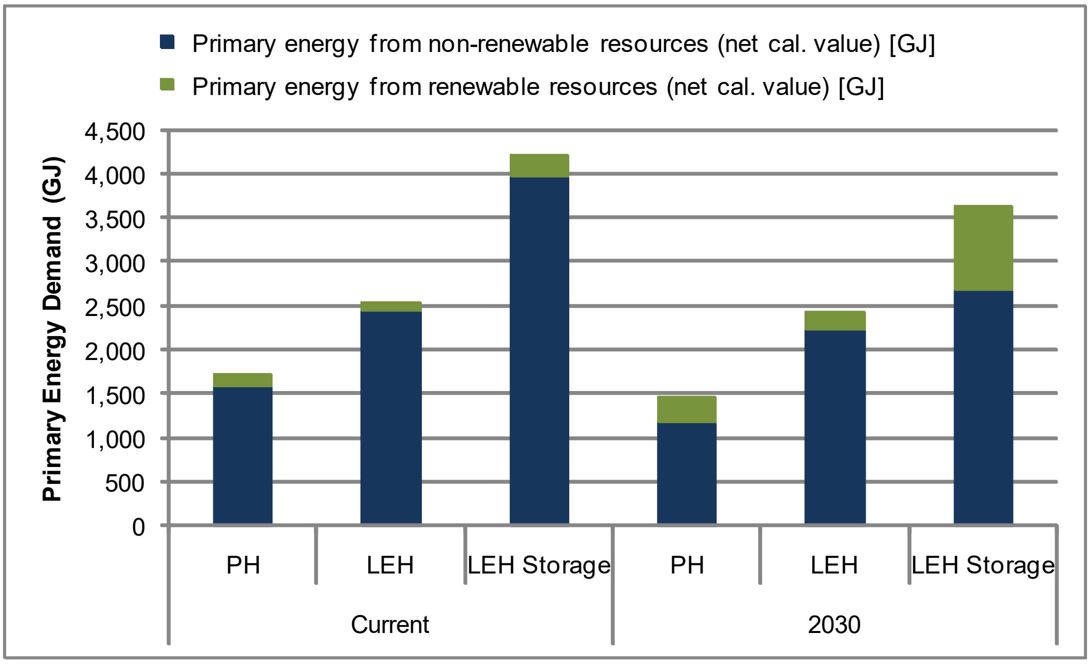

Figure 4-1: Primary Energy Demand (net calorific value, in GJ) over the life cycle of the house, as contributed by renewable and non-renewable energy sources

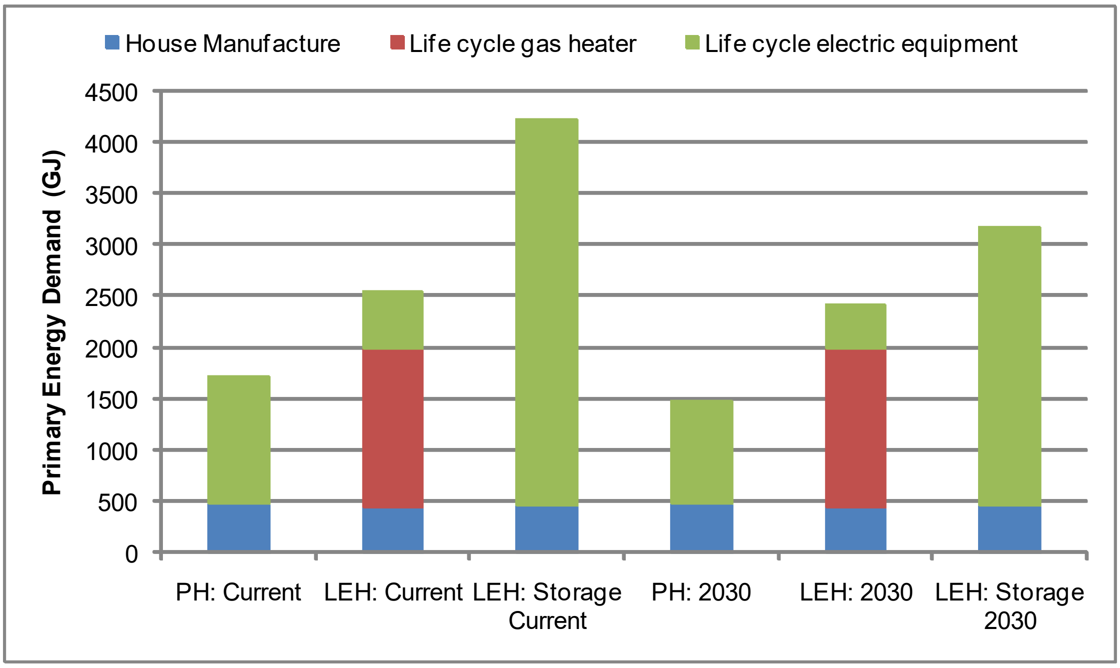

Figure 4-2: Primary Energy Demand (net calorific value, in GJ) over the life cycle of the house, as contributed by house manufacture, gas heater life cycle and electric equipment (heat pump and ventilator) life cycle

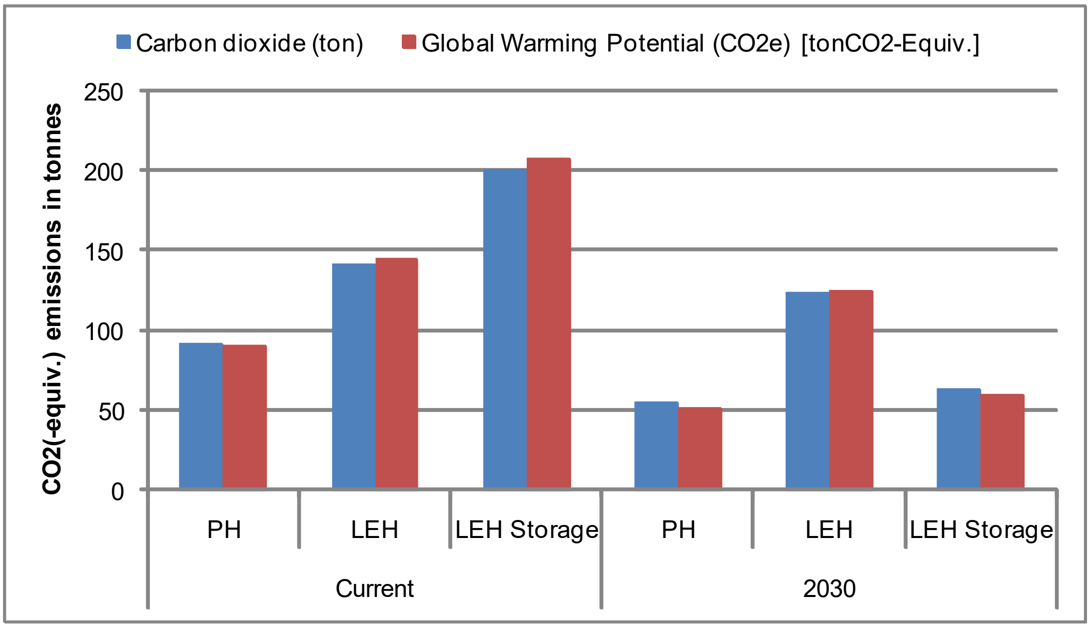

Figure 4-3: Emissions of CO_2 and other greenhouse gases (ton CO_2-equiv.)

4.3.3 Selected impact categories: Figure 4-4

- Using the current grid mix, the LEH with the night storage heater has by far the highest impact in all investigated categories
- By contrast, using the future grid mix and night tariff of 2030, the LEH with night storage heater competes with the PH for the best place
- Acidification Potential (AP) behaves slightly differently from other categories due to the influence of SO_2 on this category. Fossil fuels have general high sulphur content, and when burnt, release SO_2. However, comparing a gas condensing boiler with an electric heat pump, natural gas has a low sulphur content and therefore reliance on purely gas has a relatively lower impact than reliance on the current grid mix which contains other fossil fuels. (See also Case study 1: environmental impact of the electricity mix.)
- Eutrophication Potential (EP) is affected by nitrogen oxides (NO_x), which are associated with any fossil fuel burning process to different degrees. Therefore, the general rule is that the more fossil fuels are burnt the higher this impact scored in a category.
- Photochemical Ozone Creation Potential is impacted by a combination of combustion gases, and therefore it behaves somewhat similarly to NO_x in this specific case.

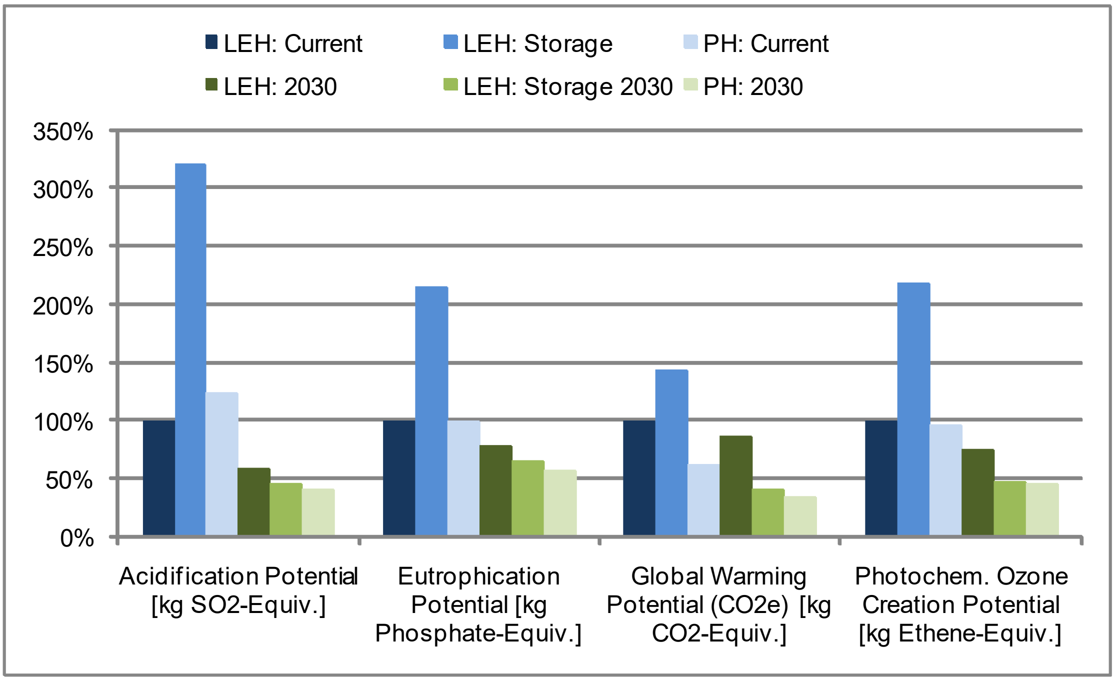

Figure 4-4: Relative contribution of the houses fitted with various heating equipment to selected impact categories. The LEH with current grid mix represents 100%.

4.4 Conclusions

- Night storage heaters, due to the relatively low efficiency of energy provision and conversion, have the highest environmental impact considering today's power grid mix composition.
- With higher shares of renewable resources in the grid mix, however, the night tariff could become almost completely independent of fossil resources. Harvesting this off-peak energy, night storage heaters would avoid considerable amounts of emissions making them comparable to heat pumps.
- In addition to decreased emissions resulting from the heating of the house, the power demand could become better distributed and possibly allow for diminished total power production in the grid given the two-tariff system. On the other hand, the re-distribution of power usage must go hand-in-hand with an increase in utilization of renewable resources. Otherwise the renewable share of the grid will not be able to meet the demand posed by the night tariff system. The long term effects of an increasing number of night storage heaters on the grid is difficult to predict and especially to quantify. Although the outcome may be overall positive, structural and functional requirements of such a system are numerous. This system would have to be capable of covering for unexpected power surges during the day, while also ensuring that increasing power demand during the night due to more and more storage heaters can be provided from renewable resources.
- The impact of a single house with night storage heater on the other hand, is predictable: the energy requirements (PED) will still be higher than other heating solutions even if the energy provision becomes more and more burden-free for the environment. In other words, the (primarily) technical challenge of higher energy demand must be tackled.

- At the same time, the heat pump, while requiring higher initial investment for installation, already today and even more so with the prospect of a cleaner grid mix, offers to reduce both environmental impacts and PED, given the assumptions on efficiency in our system (see Case Study 2: Low-Energy House heating system).

5 Case Study 5: Investment into higher efficiency motors or wind turbines

5.1 Introduction

In case studies 1-4, considerations of energy use were purely environmental. Decision-making processes, however, need to factor in economics as this may change rankings entirely: if a limited amount of money has to be spent, cheaper solutions may be implemented numerous times and thus the multiple uses of smaller changes may even outperform a single grandiose scheme. To assess the economic aspects of electricity use, a simple yet powerful exercise will be conducted in this chapter. A million Euros can be invested a million ways, but two of them were chosen for this purpose: (1) a wind-power turbine that will allow electric power generation with almost no carbon dioxide emissions, and (2) an electric motor with a high efficiency construction. While the one creates practically emission-free power, the other reduces the electricity consumed. The question investigated here is which one prevails when environmental gains are factored in with their costs.

5.2 System description

There are two systems compared: investment of 1 million Euros into wind power and 1 million Euros into higher efficiency motors.

5.2.1 Wind turbine Life Cycle Costing (LCC)

Wind turbine installations and maintenance costs have been on the decrease as developing technologies facilitate these operations more and more. The following assumptions are based on the German on-shore wind farms (ISET2005, WINDGUARD2007) representing average European continental conditions.

- The installation cost of turbines average around 1304.75 €/kW capacity
- The maintenance cost of turbines average around 50 €/kW capacity per year
- The average lifetime of a turbine is 20 years
- This means that a 1MW(=1000kW) turbine would cost:

  1304.75 *1000 + 50 *20*1000 = **2.305 million €**
- **With 1 million investment 0.43 MW wind turbine capacity can be bought**
- The average efficiency of a continental wind turbine in Central Europe is ca. 20%. This includes wind availability as well technical limitations of power conversion.
- The power production capacity of a 1MW wind turbine is then:

  1*0.2MW
- Over the lifetime of the wind turbine this means:

  0.2MW*24*365*20*1000 = 35,040,000 kWh
- Therefore the buying power of 1 million translates to

  35,040,000 kWh * 0.43 = **15,203,384 kWh of energy**

The improvement potential will be quantified by comparing the environmental impact of the equivalent amount of energy from the current EU-25 grid mix with the energy from the wind power bought.

5.2.2 Electric motor LCC

Industrial-scale uses of electric motors (e-motors henceforth) require medium or large motors. In this case study we examined a medium-sized e-motor, with 11kW power and 4 poles at 50Hz (European standard). Efficiency classes today can be ranked into one of three categories: Standard (IE1), High (IE2) and Premium (IE3). The material specifications of the different efficiency classes are taken into account (based on ECOMOTORS2008). The efficiency scenarios considered are summarized in Table 5-1. Efficiencies are taken from the Motors MEPS Guide (MEPS2009). The standard (IE1) scenario represents the baseline against which the improvement potential of the other two efficiency classes can be measured.

Table 5-1: Efficiency scenarios of the e-motor (11kW, 4 poles)

Specification	**Efficiency Class**		
	Standard (IE1)	**High (IE2)**	**Premium (IE3)**
Load (0-1)	0.5	0.5	0.5
Efficiency	87.6	89.8	91.4
Operation (hours/year)	4000	4000	4000
Lifetime	15	15	15

The costs of two improvement scenarios specified above are summarized in Table 5-2 (taken from ECOMOTORS2008).

Table 5-2: LCC of the e-motors in the different efficiency scenarios. Figures are taken from ECOMOTORS2008, but the costs of electric power are excluded since these depend on the amount used, and this will be calculated anew in this study.

Costs	**Efficiency Class**	
	High (IE2)	**Premium (IE3)**
Product price (€)	563	675
Maintenance (€)	289	289
Total (€)	**852**	**964**

Based on the total costs in Table 5-2, 1174 IE2- and 1037 IE3-class motors can be afforded with the investment of 1 million Euros.

To calculate the electric power utilized by motors, only losses were quantified since the useful energy produced by the motors must be attributed to the process drawing this power, and not to the motors themselves.

The calculations were as follows:

(Output power / Efficiency)(1-Efficiency)*Load*Hours of operation during lifetime*

This calculation resulted in 46.71MWh used by standard e-motors, 37.48MWh by IE2-class e-motors, and 31.05MWh by IE3-class e-motors. The source of electric power was in each case the current EU-25 grid mix. In order to quantify the electric power *costs* associated with the losses data from the European Energy Portal (www.energy.eu) was retrieved and averaged over the EU27 countries for industrial uses up to 2000 MWh (€0.127/kWh). Adding electricity to the initial and maintenance costs of the e-motors, only 179 high-efficiency and 204 premium efficiency e-motors could be afforded with a million Euros. Since these costs are normally borne by the factory/plant utilizing the useful energy of the motors, calculations were made both excluding and including these costs, and correspond to e-motor scenarios (a) and (b) in the results section.

5.3 Results & Discussion

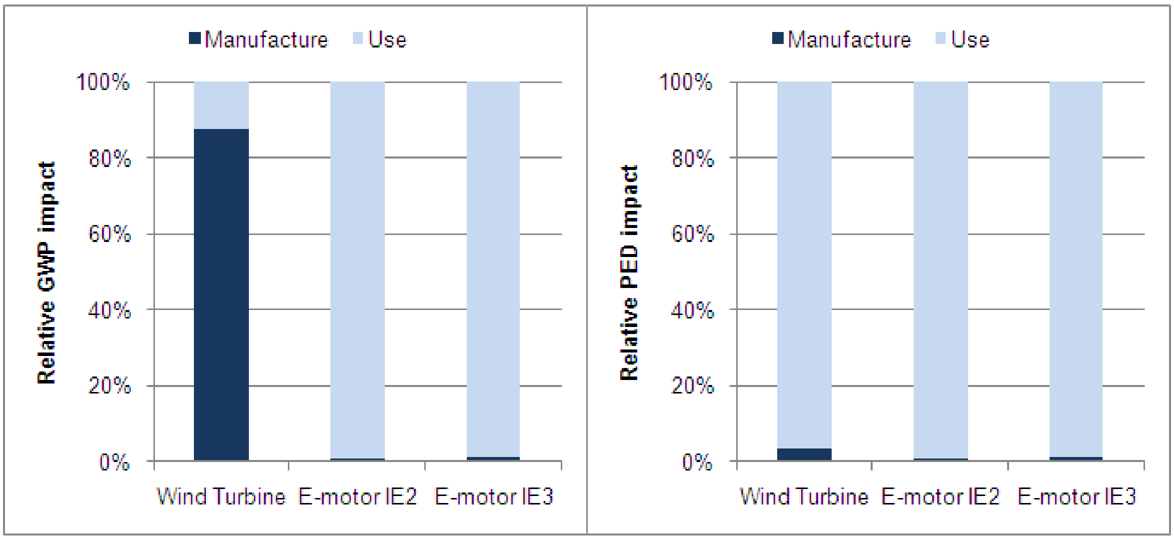

Figure 5-1: Left: Relative GWP (in kg CO_2-equivalents) contributed by the manufacture and use phases of the scenarios considered; Right: Relative PED (net calorific value, MJ) contributed by the manufacture and use phases of the scenarios considered.

Figure 5-1 demonstrates the difference in the wind turbine and the e-motor systems: while the turbines generate electricity, the e-motors use it and convert it; therefore the wind turbine system's impact (GWP) derives predominantly from the manufacture phase due to the material-intensive installation, while the e-motor's use phase is almost exclusively responsible for the impact the motors generate. While the relative contribution of manufacture and use phases of the scenarios looks very similar in case of PED, the difference is that the use-phase PED from the wind turbine derives almost exclusively from wind energy, and is therefore impact-free, while the e-motors' PED is drawn from the grid mix and is associated with emissions burdensome for the environment.

In the section below the reduction/saving potential of the different scenarios will be shown with regards to various environmental aspects. Unlike in other case studies where impacts were compared, the environmental gains are quantified and visualized relative to the baseline scenarios. The baselines are, in case of the wind turbines, the provision of energy from the current EU-25 grid mix, and in case of the e-motors, the standard efficiency (IE1) e-motor. Therefore, in all figures below larger (positive) values mean larger environmental benefit, while negative values mean an environmental impact larger than that of the baseline.

5.3.1 Primary Energy Demand reduction (net calorific value, in MJ): Figure 5-2

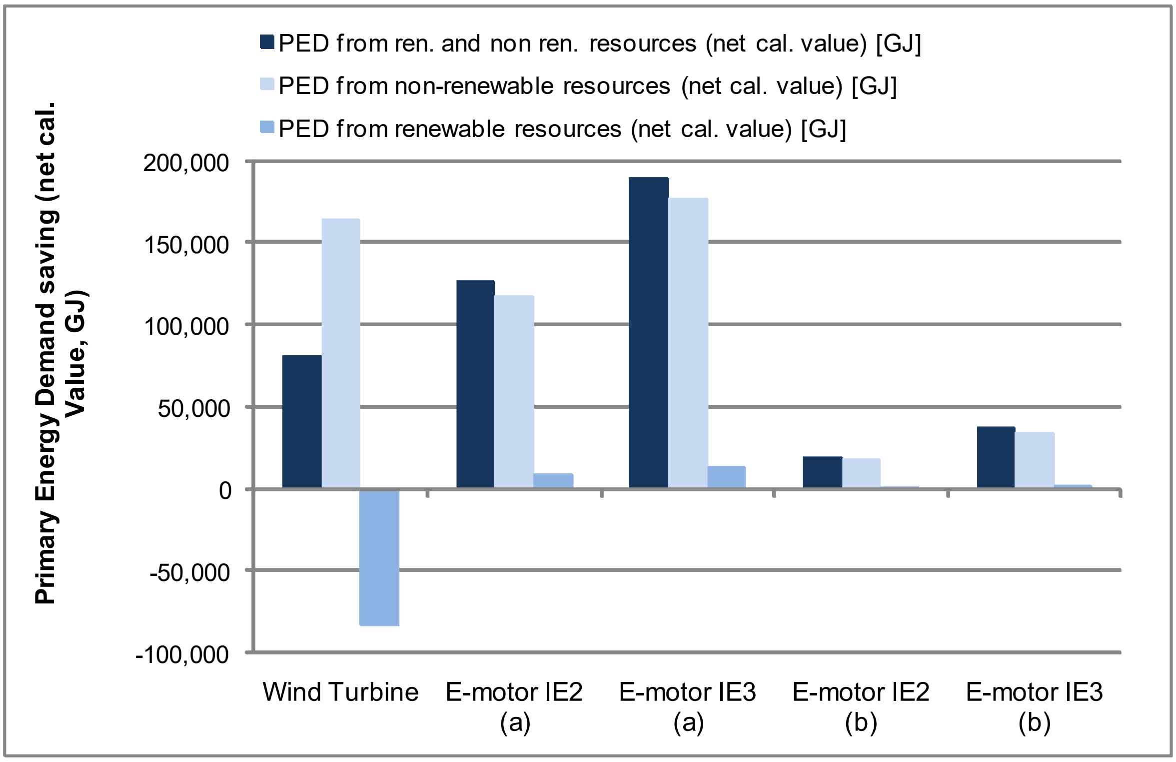

Figure 5-2: Reduction of PED (net calorific value, in GJ) by investment into wind turbine or higher efficiency e-motors. E-motor scenarios (a) exclude costs of electricity for running the motors, scenarios (b) include costs of electricity.

- With regards to PED the Premium efficiency-class (IE3) e-motor shows the largest improvement, when excluding electricity costs of use phase.
- The second rank is debatable since the total PED is lower in case of the high-efficiency e-motor, but taking only non-renewable resources into account the wind turbine shows by far the greatest reduction. Since the increase in non-renewables does not lead to either resource depletion issues or emissions increases, the wind power should be considered more beneficial.
- This pattern is a result of (1) the energy provision by the wind power utilizing almost exclusively renewable energy sources, while (2) the energy use from the power grid mix during manufacture is dwarfed by the use phase energy provision (see Figure 5-1).
- Including the costs of energy provision during the use phase of motors make their reduction potential incomparably small relative to that of the wind power plant.

5.3.2 Global Warming and CO_2 emission reduction: Figure 5-3

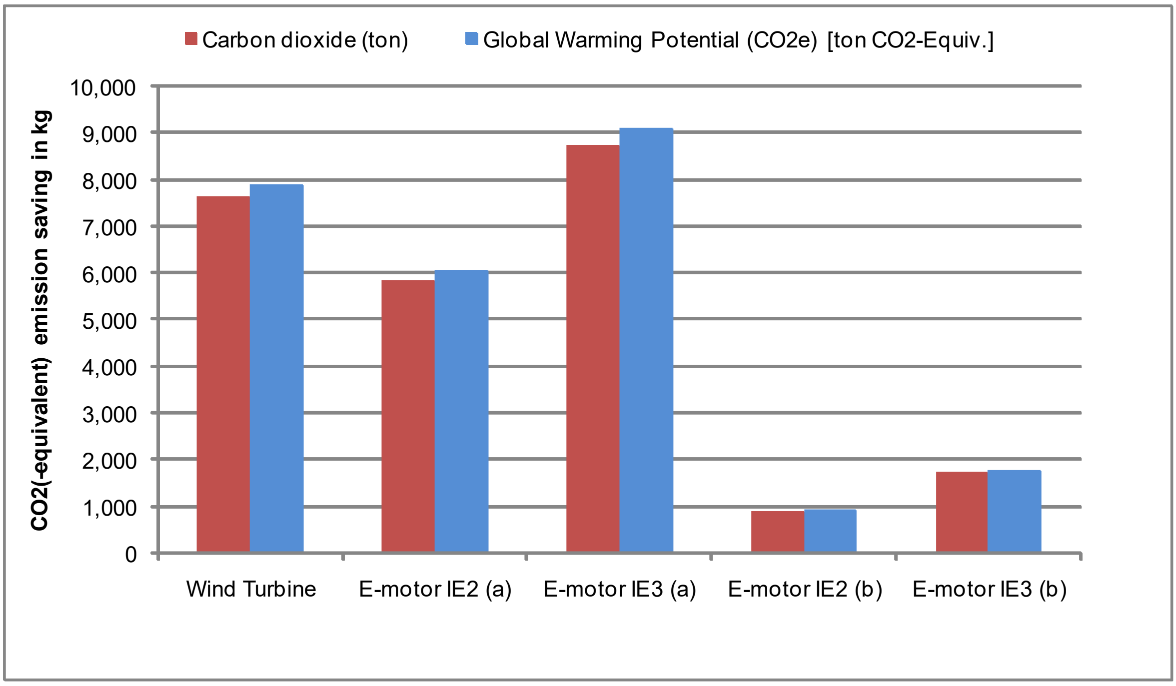

Figure 5-3: Reduction of CO_2(-equivalent) emissions (ton) by investment into wind turbines or higher efficiency e-motors. E-motor scenarios (a) exclude costs of electricity for running the e-motors, scenarios (b) include costs of electricity.

- In case of GWP and CO_2 emissions, the largest reduction takes place by the e-motor with Premium efficiency class (IE3), if electric power costs are excluded. Including these costs on the other hand, makes investment into wind turbine capacity by far the most advantageous solution.

5.3.3 Reduction in selected impact categories: Figure 5-4

- The reduction in selected impact categories paints the same picture as was seen before in GWP: as long as the price of electricity consumed by the e-motors is outside the system boundaries (i.e. assumed to be borne by the factory owner not the investor, scenario (a)), the Premium efficiency (IE3) e-motors have the highest potential to reduce environmental impacts

- If costs of electricity for the losses of the e-motors are borne by the investor, on the other hand (scenario (b)), wind turbines offer a much greater reduction potential in all considered environmental impact categories for the same amount of investment.

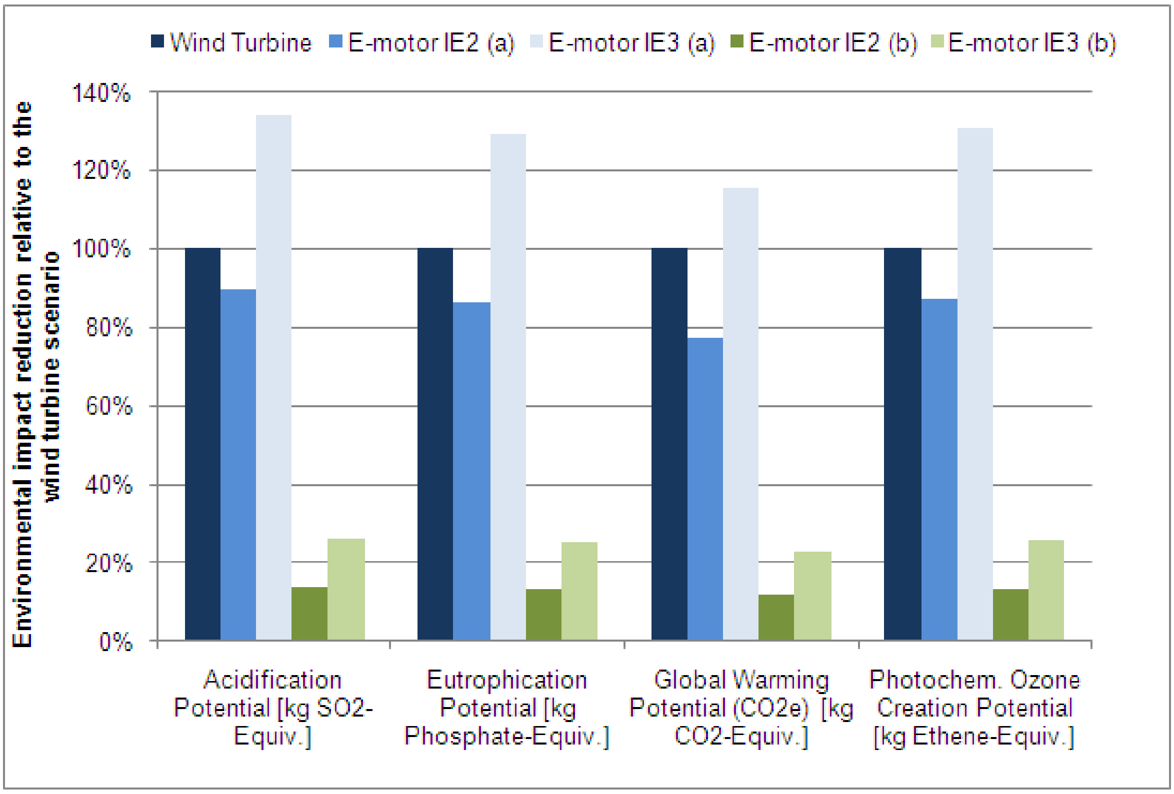

Figure 5-4: **Relative reduction in selected impact categories by investment into wind turbines or higher efficiency e-motors. The reduction by the wind turbine scenario represents 100%.**

5.4 Conclusions

- While the wind power can generate large quantities of practically emission-free energy, the power plant's manufacture phase is both material and energy intensive resulting in large environmental burdens even though these burdens are equally allocated per kWh produced during the lifetime of the plant.
- On the other hand, the impact of e-motors is determined largely by their use phase through the energy consumed by the losses. It becomes clear that the manufacture-phase investment into relatively larger quantities of electric steel and copper (Figure 5-1) pays off quickly during the use phase as efficiency increases (Figure 5-2 - Figure 5-4).
- The cost of electric power for the losses created by the e-motors is a crucial factor in this analysis. Whether this cost is considered along with the investment depends on the situation: if the investor is also the manufacturer using the e-motors, these costs must be taken into account as part of the investment. In this case, a wind turbine capacity affordable with a million Euros would be the straightforward choice for investment. On the other hand, if the cost of electricity lost by the motors is not carried by the investor, then the Premium efficiency (IE3) e-motors' environmental benefits prevail, since more of the same motors can be bought with the same amount of money.
- Many small investments (e.g. e-motors) can outweigh the environmental benefit of a single large-scale investment (wind turbine), if and only if, the considered

scenario accounts for the economic costs of the e-motors only up to enabling their use (i.e. production and maintenance). In costs of electricity is borne by the investor, the number of e-motors affordable become too few to compete with the clean energy provision by the wind turbine. In conclusion, this study has demonstrated that life cycle costing is a necessary tool for making decisions regarding environmental investment.

- It should be noted that, in terms of financing energy efficiency, this is as a worst-case-scenario: a new investment. If we consider motors that failed (or with low running performance), the purchase of a replacement motor would occur anyway but, in this case, the €1 million would only be used to finance the premium – buying a high efficiency motor as opposed to buying a normal efficiency one. For this reason, we would finance many more motors and the environmental impact reduction – the sustainability one could “buy” with €1 million – would be much higher!
- Furthermore, the scrap value of an old motor is considerable and could be re-invested into the new motor purchase, making the business case even more attractive.

6 Case Study 6: building a new house for 1 million Euros

6.1 Introduction

In case studies 3-4 the environmental benefits of a Low-Energy House (LEH) were compared to a Passive House (PH) both equipped with the best available technology to suit the house type (see Case Study 3: Low Energy House versus Passive House and Case Study 4: Primary Energy versus Global Warming). In this case study, the environmental comparison was complemented with an economic assessment of the decision alternatives. This case study can be thought of as a cost-benefit analysis of building a new house with different environmental and economic costs and benefits. Basically, the study aims at analysing the sustainability one can "buy" investing €1 million in different concepts.

Three alternatives for improvement are considered, using a "Standard house" as the baseline (see definition in the Glossary and parameter settings in the Appendix). The LEH with gas condensing heater represents one option, the PH with heat pump another, while the PH with night storage heater a third one. The environmental benefits of the first two options have been discussed before (Case Study 3: Low Energy House versus Passive House) and will only be referred to here. The storage heater benefits have been discussed in the context of the LEH (Case Study 4: Primary Energy versus Global Warming), and so this scenario is expected to show improvement compared to that in Case Study 4. The night storage heater (NSH) scenario will also be investigated using the future grid mix of 2030 with a night tariff system in place.

6.2 System description

The systems considered in this case study are summarized in Table 6-1. More elaborate descriptions of the house types can be found in Case Study 3: Low Energy House versus Passive House and regarding the night storage heater Case Study 4: Primary Energy versus Global Warming can be referred to. In all four scenarios the system boundaries include the manufacture of the house and its use phase including heating and ventilation. The quantification of the benefits of each scenario takes place by calculating the reduction of environmental impacts compared to the standard house. The system analyses the benefits from the perspective of a larger scale housing investment, and quantifies investment into the alternative building types (PH or LEH) relative to an investment into a new standard house. Therefore both financially and environmentally the investment into the standard house is considered the baseline, and this includes its manufacture phase. The lifetime of the houses are in each case 50 years, use phase comparisons are considered over this period in the LEH, the PH and the standard house.

Table 6-1: Basic settings of the systems considered in case study 6

Scenario name	Heating equipment	Heat demand per year (kWh)	Renewables in grid mix (%)
LEH	Gas condensing heater	4979.8	12.63
PH with heat pump	Heat pump	2168.6	12.63
PH with NSH today	Night storage heater	2168.6	12.63
PH with NSH 2030	Night storage heater	2168.6	50

6.3 Life Cycle Costing (LCC) of the LEH and the PH

6.3.1 Construction costs

Costs are averages and are rounded based on figures from http://www.energiesparen-im-haushalt.de. The costs sum up the **initial** investment relative to the investment cost of a standard house (Table 6-2), and as such exclude maintenance costs and cost of electricity over the lifetime of the buildings. Taking the cost difference for the alternative building types as shown in Table 6-2, €1 million allows investing into improving roughly 33 houses from Standard to LEHs or 17 Standard to PHs Therefore the results presented in section 6.4.2 will in fact reflect:

1. **LEH with gas condensing heater**: ∆ Impact [{(33 X manufacture of standard house) + (33 X use phase of standard house)} – {(33 X manufacture of LEH with gas condensing heater) + (33 X use phase of LEH with gas condensing heater)}]
2. **PH with heat pump**: ∆ Impact [{(17 X manufacture of standard house) + (17 X use phase of standard house)} – {(17 X manufacture of PH with heat pump) + (17 X use phase of PH with heat pump)}]
3. **PH with storage heater today**: ∆ Impact [{(17 X manufacture of standard house) + (17 X use phase of standard house} – {(17 X manufacture of PH with storage heater) + (17 X use phase of PH with storage heater)}]
4. **PH with storage heater in 2030**: ∆ Impact [{(17 X manufacture of standard house) + (17 X use phase of standard house} – {(17 X manufacture of PH with storage heater) + (17 X use phase of PH with storage heater and 2030 night tariff)}]

Table 6-2: Construction costs of the two housing types considered.

Costs	**LEH**	**PH**	**Standard House**
Price per m^2 (€)	1600	1850	1380
Total cost of house (130m^2) (€)	**Ca. 210,000**	**Ca. 240,000**	**Ca. 180,000**
Cost difference from Standard House	**30,000**	**60,000**	**NA**

6.3.2 Use phase costs

In addition to examining the buying power of €1 million regarding construction of new houses only, it was deemed valuable to estimate the use phase costs of each house, and calculate the potential savings of the alternative houses. Table 6-3 summarizes these costs for all the houses considered as well as the savings made during the lifetime of the alternative houses relative to the standard house.

Table 6-3: Use phase costs of the various building types, each 130m^2. Key: LEH – LEH with gas condensing boiler; PH – PH with heat pump; PH (NSH) – PH with night storage heater; Standard – standard house with conventional gas boiler.

House type	**Gas consumption (kWh)**	**Gas consumption costs* (€)**	**Power consumption (kWh)**	**Power consumption costs* (€)**	**Total use phase costs (€)**	**Total savings (€)**
LEH	344849	25,236	48492	8,612	**33,848**	**65,381**
PH	0.00	-	99565	17,682	**17,682**	**81,547**
PH (NSH)	0.00	-	167765	29,794	**29,794**	**69,435**
Standard	1302250	95,299	22131	3,930	**99,299**	**-**

*Gas and electricity prices were taken from the European Energy Portal (www.energy.eu) and averaged over EU countries in 2009. The average gas price was 0.07€/kWh for domestic use under 500m^3 consumption. The average electricity price was 0.18€/kWh for domestic use under 3500kWh/year consumption.

6.4 Results & Discussion

In the section below each environmental impact category will be evaluated from two different aspects. First, the impact of the single houses (standard house along with the various alternatives) will be shown in absolute numbers. Then the reduction/saving potential of the four different alternative scenarios will be presented.

6.4.1 Comparison of single houses

In the figures below, one single house of each type is compared with the others in terms of their environmental impact. The standard house (1) as the baseline option is shown along with the LEH (2), the PH with heat pump (3), the PH with NSH today (4) and using the grid mix of 2030 with night tariff system (5).

6.4.1.1 Primary Energy Demand (PED) (net calorific value, in GJ): Figure 6-1

- The PED of the standard house is about twice as high as any of the alternative housing options
- Among the alternative housing options, the PH with the heat pump has the lowest total PED; considering, however, only the PED from non-renewable resources, the PH with NSH and the 2030 grid mix has an even lower impact. As described in Case study 1: environmental impact of the electricity mix, the 2030 grid mix has a very high share of renewables, which is clearly visible in the figure.
- The PH with the NSH and today's grid mix is the most energy intensive alternative to the standard house. With over 4 times lower efficiency than the heat pump, combined with the inherent losses through the grid mix, this solution has the least to offer in environmental terms (see also Case Study 4: Primary Energy versus Global Warming).

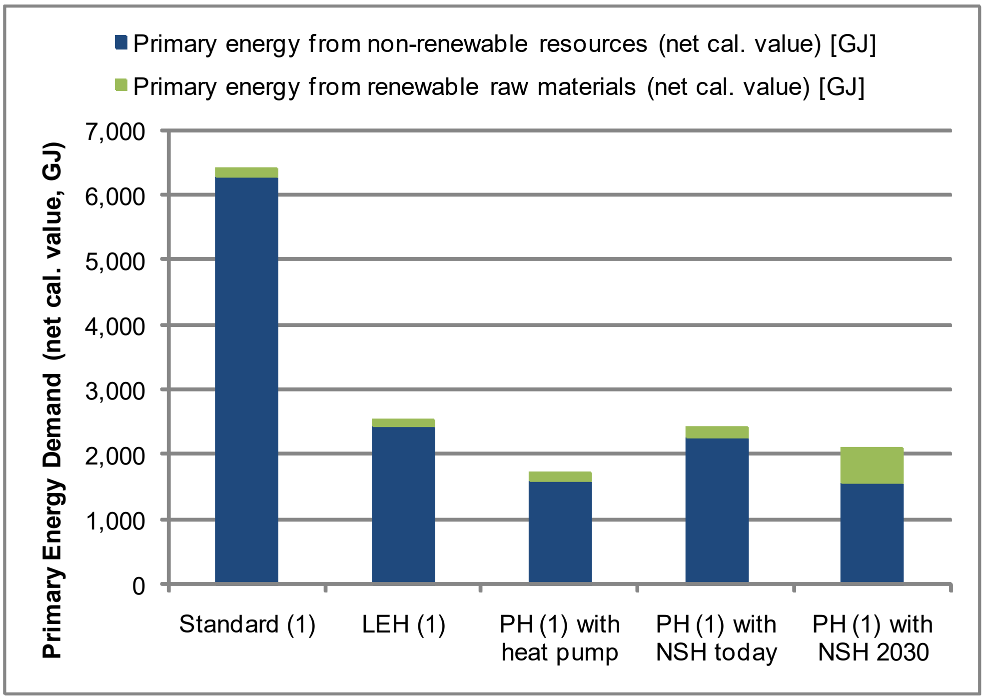

Figure 6-1: Primary Energy Demand (GJ, net calorific value) of the various housing options.

6.4.1.2 Global Warming Potential (GWP) and CO_2 emissions (tonnes): Figure 6-2

- As seen in case of PED, the standard house has the highest contribution to GWP and CO_2 emissions.
- The pattern seen here follows that of PED from non-renewable resources. Since fossil-based non-renewable resources are carbon chains that emit CO_2 when burnt, GWP is directly linked to this impact. The PH with the future grid mix of 2030 containing 50% renewables, as well as a night tariff system in which even fewer emissions are generated (see Case Study 4: Primary Energy versus Global Warming), has by far the lowest impact in these categories.

- Considering only today’s alternatives, the PH with heat pump stands out as the most environmentally friendly option in this category.
- As in case of PED, the PH with the NSH has the highest impact among the alternatives to the standard house, but as we move towards an energy mix (2030 scenario) with lower CO2 content, this situation inverts.

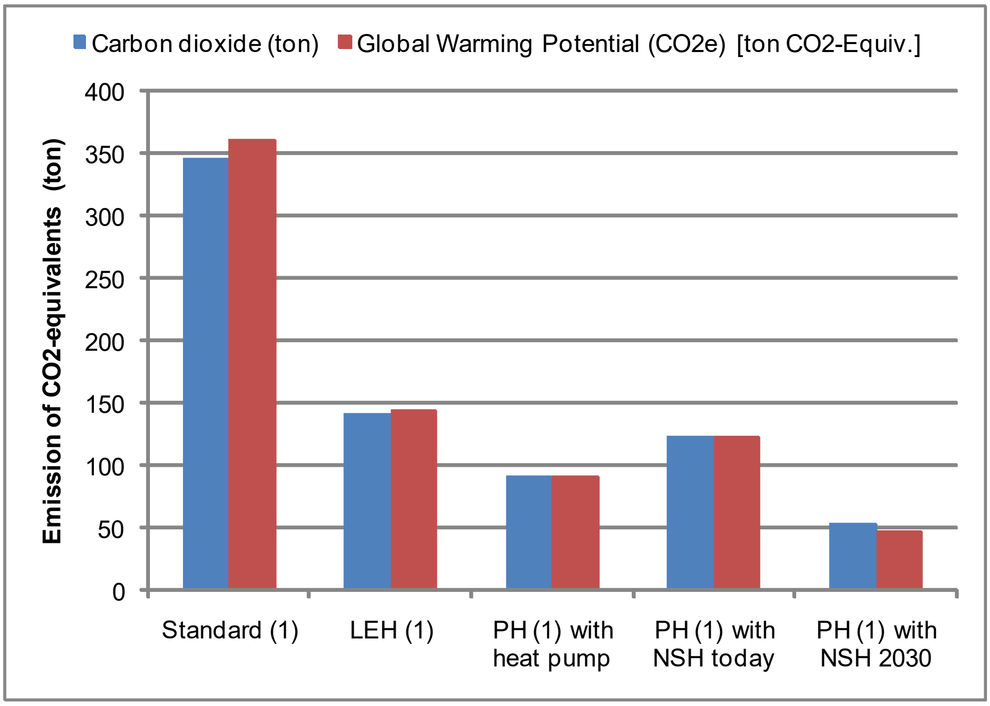

Figure 6-2: **Global Warming Potential (ton CO_2-eq.) and CO_2 emissions (both in tonnes)**

6.4.1.3 Selected impact categories: Figure 6-3

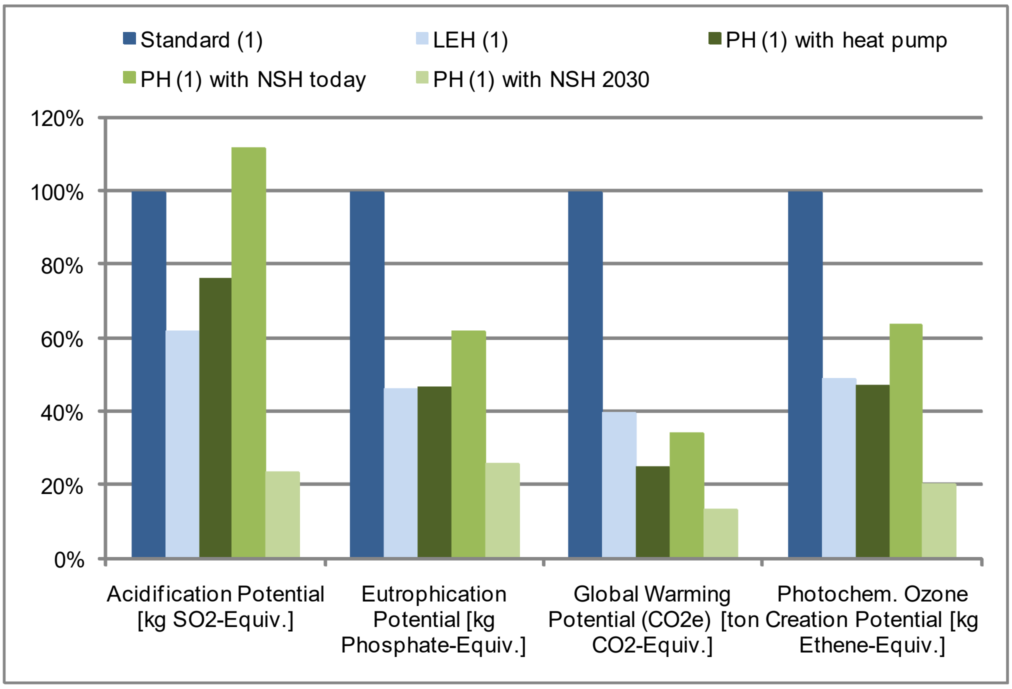

Figure 6-3: **Contribution of the five housing types to selected impact categories.**

- In the selected impact categories somewhat different patterns emerge from what we have seen so far
- While GWP closely follows the PED from non-renewable resources, Acidification Potential (AP) differs significantly. This can be attributed to the fact that GWP is

influenced by burning all fuels including natural gas used for the boiler of the LEH. On the other hand, natural gas burning results in far lower NO_x and SO_2 emissions than some other fuel sources (oil, hard coal etc.) which are present in the power grid mix providing the energy for the PH. SO_2 emissions influence AP directly, while NO_x emissions influence Eutrophication Potential directly. Therefore the electric (power grid-based) heating systems suffer from this effect.

- With higher efficiency (see PH with heat pump) and lower reliance on fossil fuels (see PH with 2030 grid mix), this effect can be diminished and even overcompensated.

6.4.2 Investment power of 1 million Euros

In the figures below, the environmental gains are quantified and visualized *relative to* the baseline scenario of the standard house – meaning we look only at the investment premium for the more efficient house types and to the impact reduction these return. Therefore, in these figures positive values mean larger environmental benefit, while negative values mean an environmental impact larger than that of the baseline (due to the construction of the house). The results shown are for the €1 million investment equivalent, meaning LEH refers to the 33 LEHs and PH refers to the 17 PHs one can finance with €1 million, and not to an individual house. The data is then compared with the same number of Standard houses.

6.4.2.1 Reduction in Primary Energy Demand (PED) (net calorific value, in GJ):

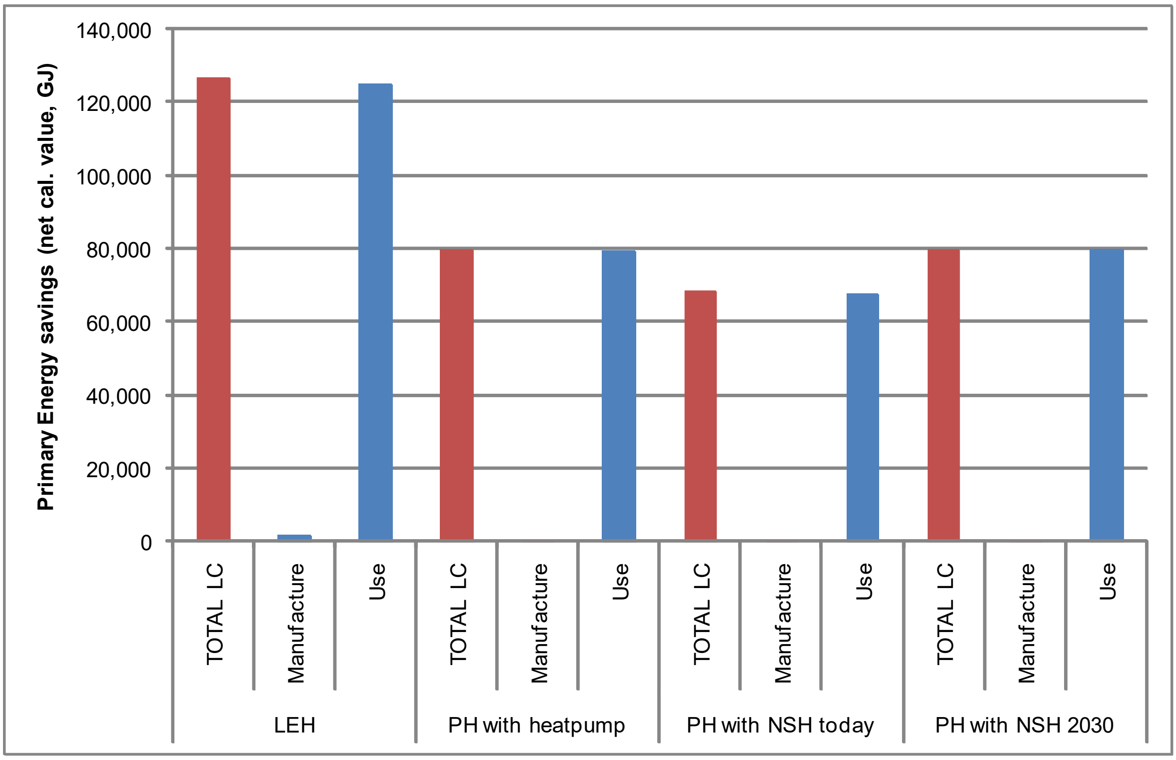

Figure 6-4: Primary Energy (net calorific value, in GJ) reduction in the various investment scenarios and their life cycle phases (total life cycle impacts are shown in red).

- In Figure 6-4 it becomes clear that the contribution of the use phase is the dominant phase of the life cycle of the houses. Even though the manufacture phase is a costly investment in environmental and economical terms, relative to the baseline of the standard house's manufacture, there is little (in case of the LEH) or no gain from this phase. .

- In both Figure 6-4 and Figure 6-5 it is evident that the LEH scenario has the highest reduction potential, with twice as many houses affordable as in case of the PH scenarios. While the single LEH could not compete with the energy efficiency of the PH with the heat pump, twice as many LEHs become more environmentally friendly than the PH alternative.

- The PH with the heat pump and the futuristic scenario of PH with night storage heater and the 2030 grid mix and night tariff system, are a close match in terms of environmental gain. The night storage heater in the PH results in a lower PED given the futuristic energy provision scenario of 2030 than using today's grid mix. This is due to the increased share of renewables (see Case study 1: environmental impact of the electricity mix).

- In Figure 6-5 one can also note that while the total PED is reduced greatly compared to the standard house in all scenarios, the share of renewables increases in the three PH options (see negative increase). This is due to the fact the energy required for heating comes from the power grid mix which also contains renewable energy sources, unlike the gas-dependent boiler of the LEH. This effect is most notable in the futuristic scenario where half of the energy derives from renewables.

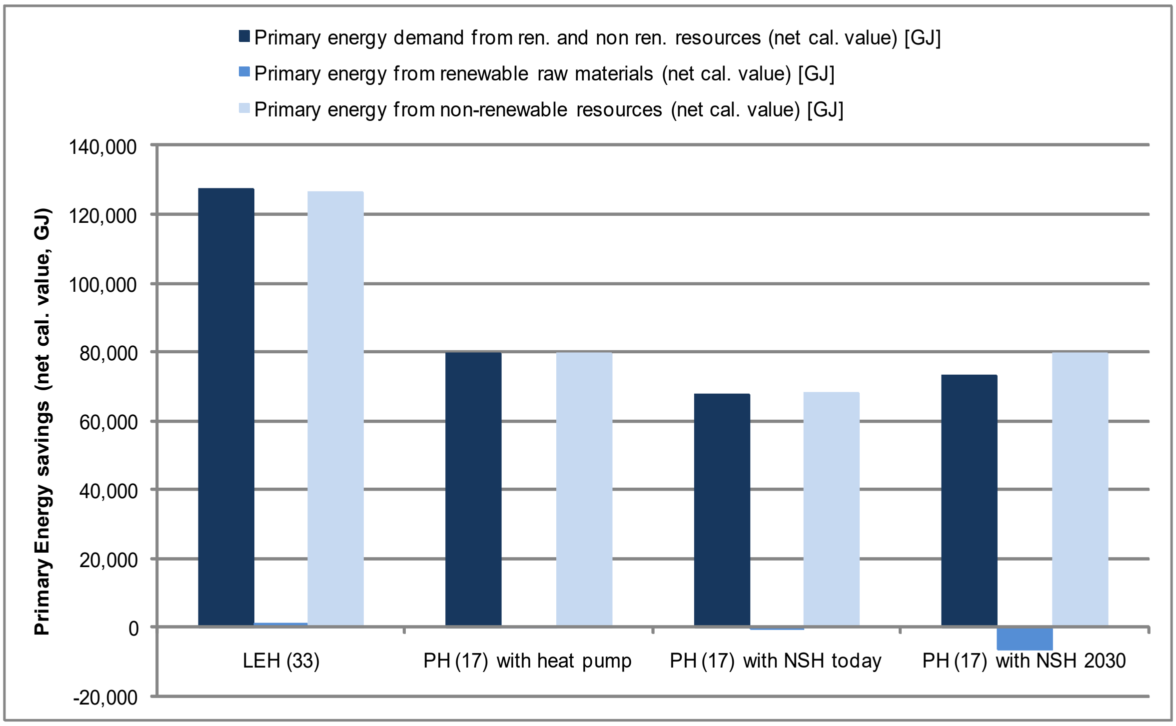

Figure 6-5: Primary Energy Demand (net calorific value, in GJ) reduction in the various investment scenarios, showing the total PED as well as the share of renewable and non-renewable resources. PED from renewable resources shows a "negative reduction" to be interpreted as an increase compared to the baseline scenario. NSH - night storage heater

- Figure 6-6 allows the consideration of all three aspects of the investment decision: cost, reduction potential and housing space. One can read off what decision alternatives are available with a certain amount of money, as well as the alternatives capable of reaching a given goal of reduction, or the financial and environmental consequences of a residential project.
- Interestingly, while a single LEH is environmentally far less favourable than the PH with heat pump (ca. 1.3 times in GWP), due to the cost differences existing today (ca. 2 times costlier PH than LEH), the investment will always favour the LEH. This means that the cost difference has to reduce to below the factor of environmental dominance (i.e. ca. 1.3), in order for the PH alternative to become the more optimal investment alternative.

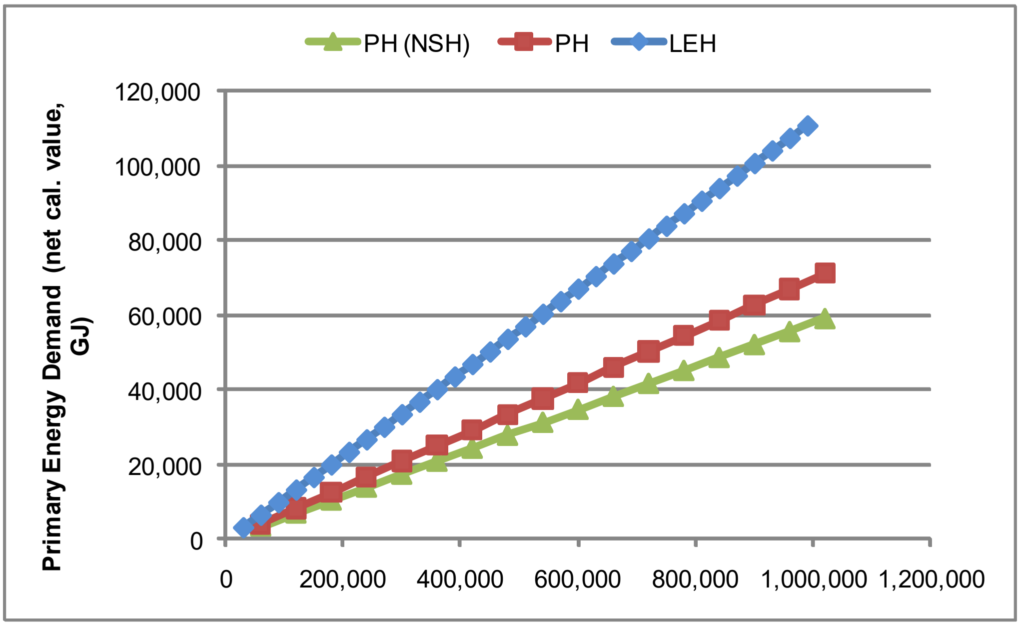

Figure 6-6: **Net reduction of Primary Energy Demand (net calorific value, in GJ) affordable with given expenditure. Key: Blue diamonds – LEH; Red squares – PH with heat pump; Green triangles – PH with night storage heater (NSH).**

6.4.2.2 Global Warming and CO_2 emission reduction: Figure 6-7 and Figure 6-8

- The pattern of Global Warming Potential (GWP) looks slightly different from the pattern in total PED, although it follows the pattern of PED from non-renewables. The supremacy of the LEH alternative remains unbeatable due to the number of houses affordable (33 vs. 17 PHs).
- While in terms of the total PED the PH with heat pump could not be distinguished from the PH with NSH with the 2030 grid mix, in terms of GWP and CO_2 emissions the latter has a clearly greater reduction potential. With the 50% renewable share in the 2030 grid mix, not only does the total PED decrease but also the associated emissions decline drastically, enabling an enormous reduction in CO_2 and GWP.

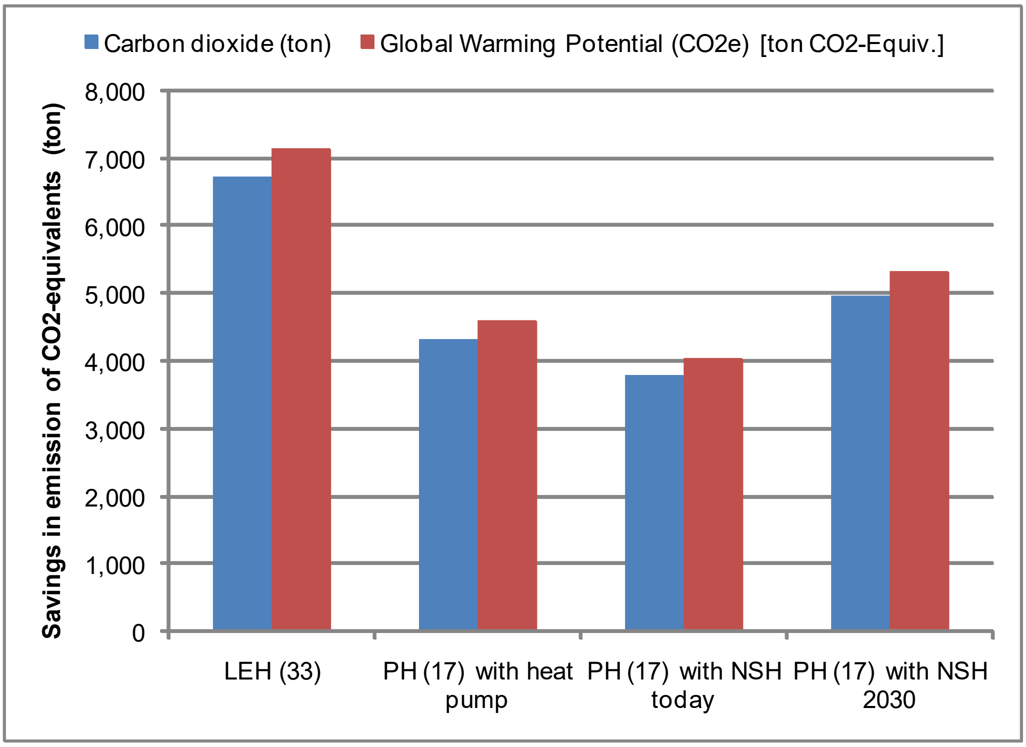

Figure 6-7: Reduction of CO_2(-equivalent) emissions (tonnes) under the various investment scenarios. NSH – night storage heater.

- Figure 6-8 allows the consideration of all three aspects of the investment decision: cost, reduction potential and housing space. One can read off what decision alternatives are available with a certain amount of money, as well as the alternatives capable of reaching a given goal of reduction, or the financial and environmental consequences of a residential project.
- As seen already in Figure 6-6, due to the cost differences the PH alternatives cannot compete with the LEH. Prices must reduce to allow a cost difference of no more than 1.3 times in order to make the PH scenario the alternative with a higher reduction potential.

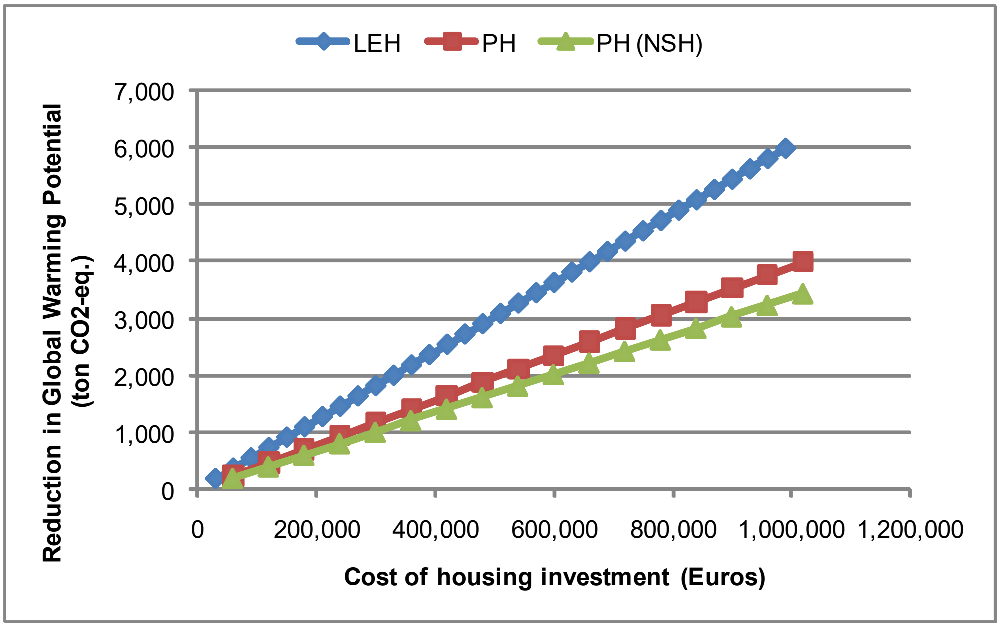

Figure 6-8: **Net reduction of Global Warming Potential (in ton CO_2-equivalents) affordable with given expenditure. Key: Blue diamonds – LEH; Red squares – PH with heat pump; Green triangles – PH with night storage heater (NSH).**

6.4.3 Reduction in selected impact categories: Figure 6-9

- As in the case of GWP, other impact categories also demonstrate that the highest environmental benefits today can be reaped from the LEH investment scenario given current conditions.
- As regards to the future, electric heating through the 2030 grid mix (especially with the night tariff system) has a higher reduction potential in terms of Acidification Potential, since the grid mix composition in this theoretical scenario does not rely on any fossil fuels.
- Under current conditions, the PH with the night storage heater is the least worthwhile investment. Not only is the reduction potential the lowest in all impact categories, but in fact its Acidification Potential (AP) is higher than that of the standard house. This is because the current grid mix contains fossil fuels (Coal, Oil, Lignite) that have much higher sulphur content than does natural gas (the fuel burnt in the standard house), thus result in high SO_2 emissions upon burning. This and the inefficiency of the grid means that the impact becomes very high.

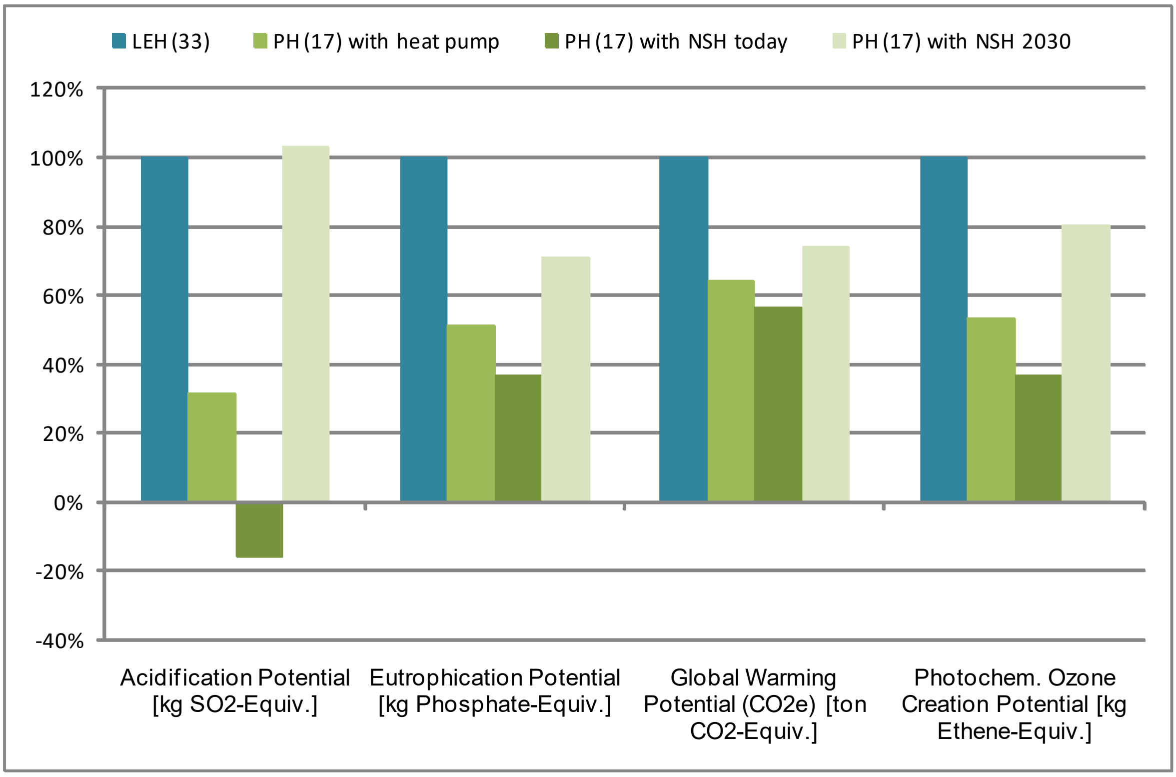

Figure 6-9: Reduction in selected impact categories by the various investment scenarios. Reduction by the LEH scenario is considered as 100% in each of the impact categories, reduction by the other scenarios is given in percentages relative to this scenario. NSH – night storage heater.

6.5 Conclusions

- Long-term and all-inclusive life cycle costing is imperative to making sound judgements in investment scenarios.
- The power is in numbers: investing into buying 33 LEHs outcompetes the alternative of 17 PHs in all environmental categories, given current grid mix conditions. Taking the example of GWP, a single PH with heat pump offers a 1.3 times higher reduction than a single LEH with gas condensing boiler:

  $\Delta GW_{PH} = 1.3 * \Delta GWP_{LEH}$

  But 17 times this reduction is still smaller than the reduction by 33 LEHs:

  $17*\Delta GW_{PH} = 22 * \Delta GWP_{LEH}$

- If the (premium) construction costs of the PH reduce to 1.5 times that of the LEH, the two housing alternatives would become equivalent in environmental as well as economic terms. This trend is predictable with the spreading of these new housing types and the expansion of the construction industry in this direction. Not only is there more and more supply and demand for these houses but technologies are still improving and diversifying. With the concurrently growing interest in renewable energy supplies, the focus of development in both the energy and the construction sector is likely to turn more and more towards optimization of electric heating systems (as in the PH).

- The presented comparative assessment is not applicable to investment scenarios when living space is the first priority
- In the results section the use phase savings were not considered since the savings over the lifetime of both the LEH and the PH with heat pump would have resulted in a net financial gain (ca. 65,000 Euros saved overcompensate the 30,000 invested in a single LEH, while ca. 81,000 Euros saved overcompensate the 60,000 invested in the PH). It is noteworthy, however, that considering the absolute investment costs, the LEH would compensate for the initial building costs in a little over 3 years, while the investment into the PH would already be returned before the end of the 3rd year!

7 Case Study 7: renovating/improving a standard house for 1 million Euros

7.1 Introduction

In Case Study 6: building a new house for 1 million Euros the investment costs and environmental payoffs of newly built houses were compared. In this case study, the renovation options of a standard house (see Glossary and parameter settings in Appendix) will be compared both in terms of the environmental benefits obtainable with the investment of 1 million Euros in each case. Two alternatives are considered: in scenario (1) the standard house will simply be equipped with a gas condensing heater, the Best Available Technology among fossil fuel-based heating systems; in scenario (2) the standard house will be renovated with additional insulation and equipped with gas condensing heater. While one option represents a very economical but short-sighted approach, the alternative represents a financially more burdensome, yet far-sighted approach. The question addressed here is whether the lower investment costs can compensate for the higher consumption in the use phase of the standard house versus the newly insulated house.

7.2 System description

The systems considered in this case study are summarized in Table 7-1. In both scenarios the baseline system is a standard house (see definition in the Glossary and parameter settings in the Appendix) that should undergo improvements from an energetic point of view. The manufacture phase includes the renovation in the second scenario, while excluding the manufacture of the house itself since it is assumed to have existed for about 30 years at the time of the investment. The use phase consists of the manufacture of the new boilers as well as the heating of the house by a gas condensing boiler with hot water storage (virtual efficiency 106%). Some electric power is utilized for the operation of the boiler and the pump circulating the hot water. Mechanical ventilation is not installed in either the standard or the renovated house. The lifetime of the house is 20 years, considering that the house was built about 30 years earlier. The quantification of the benefits of each scenario takes place by calculating the reduction of environmental impacts compared to the use phase of a standard house with a lower-efficiency *conventional* gas boiler (efficiency 93.5%).

Table 7-1: Basic parameters of the scenarios of case study 7.

Scenario name	Heating equipment	Insulation (U-value)			Heat demand per year (kWh)
		Exterior wall	Roof	Window	
New boiler only	Gas condensing heater, virtual efficiency factor 106%	0.43191	0.4	3	27216
Full renovation	Gas condensing heater, virtual efficiency factor 106%	0.06159	0.3	1.2	18884

7.3 Life Cycle Costing (LCC) of the scenarios

7.3.1 LCC for construction only

As in Case Study 6: building a new house for 1 million Euros, the base case considers only the construction/realization costs of the two alternative improvement scenarios. These costs are summarized in Table 7-2. Based on these costs 167 standard houses can be equipped with the gas boiler, while only 28 houses can be fully renovated, given the financial limit of 1 million Euros. As in Case Study 6, the calculation of the environmental improvement was done by taking the 20-year use phase of the standard house and subtracting the environmental burdens of the alternative systems (including renovation). The gains over a single house were then multiplied by the number of affordable solutions, i.e. 167 for the “new boiler only” scenario and by 28 for the “full renovation” scenario. This means almost six times as many of the former as of the latter types of improvements.

Table 7-2: Costs of construction of the improvement options

Alternatives	Improvement	Cost (€)
New boiler only	Equipment with gas condensing boiler	6,000*
Full renovation	Renovation including insulation, new windows, gas condensing boiler	35,644**

*http://www.buderus.de/Online_Anwendungen/Heizsystemberater-2229947.html

** Costs of a single family house were taken from http://www.energiesparen-im-haushalt.de/energie/bauen-und-modernisieren/modernisierung-haus/modernisierung-kosten-haus.html. Taking into account the reduced material costs of a row house, 67% of those costs was used here.

7.3.2 LCC for construction plus use phase

Table 7-3 summarizes the costs associated with the use phase of the scenarios considered. It becomes clear that compared to the unimproved standard house with conventional gas heater both improvement scenarios demonstrate considerable savings, financially speaking. While the total savings are over fourfold in case of the renovated house’s use phase, the sum gained would suffice to cover only 0.45 more renovations, compared with 0.57 new boilers affordable with the gain from the scenario “new boiler only”. This means that if we deduct the savings of the use phase from the construction costs, the available number of new boilers amount to 383, and the number of full renovations to 51, that is, about 7.5 more new boilers than full renovations.

Table 7-3: Costs and savings of the use phase of improvement options

	Consumption (kWh) over 20 years		**Energy costs over 20 years (€)**		
	gas	**electricity**	**renovation**	**standard house**	**savings (€)**
New boiler only	474,158.94	9015.28	36300	39,691.58	**3,391.58**
Full renovation	313,619.56	8651.67	23565		**16,126.31**

7.4 Results & Discussion

In the section below the reduction/saving potential of the different scenarios will be shown with regards to various environmental aspects. Unlike in other case studies where impacts were compared, the environmental gains are quantified and visualized relative to the baseline scenario of the standard house. Therefore, in all figures below, positive values mean larger environmental benefit, while negative values mean an environmental impact larger than that of the baseline. In order to quantify environmental benefits of the scenarios, the gains of each scenario were multiplied by the number of affordable improvements. Therefore:

Considering only the construction costs (henceforth “construction only”):

New boiler only: [environmental benefit compared to standard house] * 167

Full renovation: [environmental benefit compared to standard house] * 28

Considering the construction costs and use phase savings (henceforth “construction plus use”):

New boiler only: [environmental benefit compared to standard house] * 383

Full renovation: [environmental benefit compared to standard house] * 51

7.4.1 Primary Energy Demand (PED) reduction (net calorific value, in MJ): Figure 7-1

- PED reduction is by far the highest when considering the use phase in the life cycle costing. Due to the large savings during the use phase many more improvements can be made with 1 million Euros of investment (see section 7.3.2).
- Whether or not the use phase savings are taken into account, the ranking of scenarios does not change. The new boilers with increased efficiency may not result in as high a reduction as the reduction when insulation is also provided, but multiplied by the number of affordable improvements, the total savings become significantly higher. This effect only multiplies when use phase savings are considered.

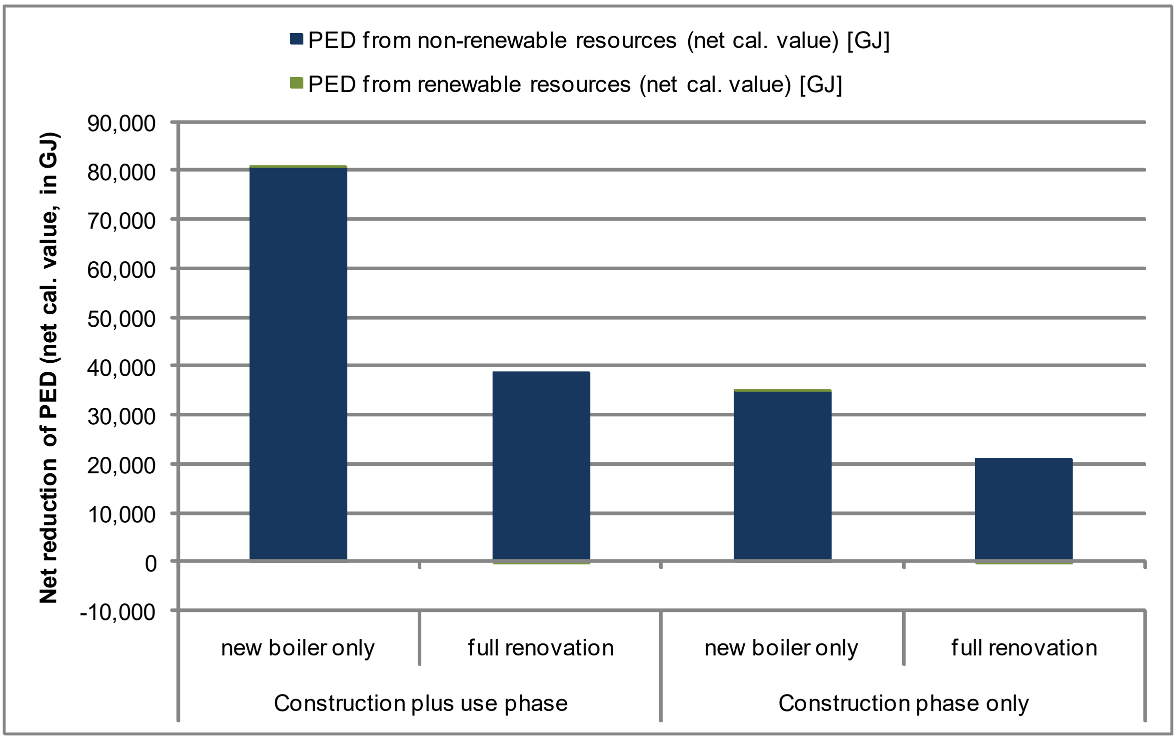

Figure 7-1: **Reduction of the Primary Energy Demand (net calorific value, GJ) of the standard house's use phase under various scenarios.**

7.4.2 Global Warming and CO_2 emission reduction: Figure 7-2

- The pattern visible with the reduction of CO_2(-equivalent) emissions is very much like the patterns discernable in PED because unlike in Case Study 6: building a new house for 1 million Euros, the same grid mix conditions apply.
- Construction and use phase costs considered all scenarios benefit from the use phase savings that allow for further houses to be equipped with gas boiler or renovated.
- Even when construction phase costs are considered alone, the new boiler only scenario takes the lead by about 1.5 as much reduction as result from the full renovation. In simple words the much fewer affordable full renovations cannot compete with the multiplied effect of installing a new boiler.

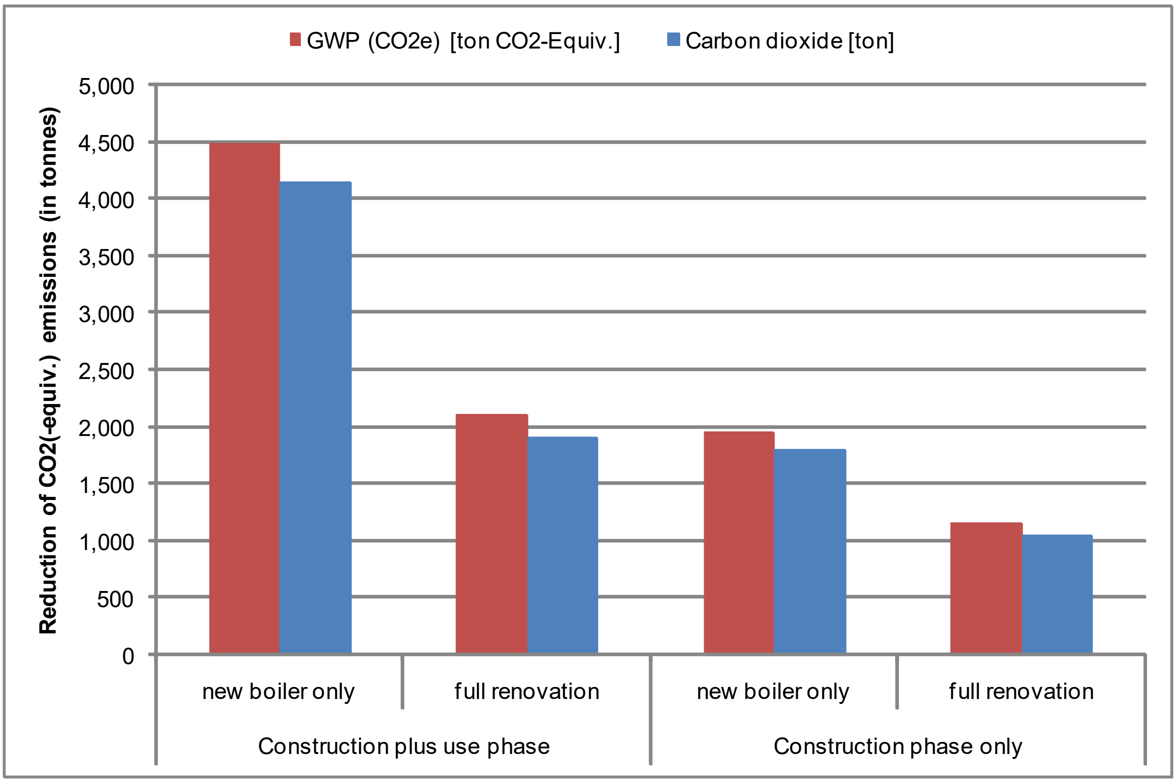

Figure 7-2: Reduction of CO_2(-equivalent) emissions (in tonnes) under the various investment scenarios.

7.4.3 Reduction in selected impact categories: Figure 7-3

- Acidification Potential (AP), Eutrophication Potential (EP) and Photochemical Ozone Creation Potential (POCP) behave very differently from the previously shown environmental impacts.
- In the full renovation scenarios the abovementioned impact categories do not show as much reduction as does GWP. This can be attributed to the fact that GWP is influenced by burning all fuels, i.e. in this case natural gas. Due to the increased insulation and increased boiler efficiency considerably less gas is burnt, and proportionally less CO2-equivalents enter the atmosphere. On the other hand, natural gas burning results in far lower NOx and SO2 emissions than some other fuel sources (oil, hard coal etc.) which are present in the power grid mix. Therefore decreasing the amount of gas consumption reduces the amount of SO2 and NOx, and associated impact categories, i.e. AP and EP, only moderately.
- By contrast to the new boiler only, the full renovation option also has environmental impacts associated with the renovation itself. The renovation phase largely depends on the power grid mix and fossil fuels other than natural gas for material production, and these are associated with a significant, although small in relative terms, amount of emissions that contribute to AP and EP, as well as partially to POCP. This is why the reduction of the renovation option is considerably smaller than that of the new boiler only.

- Although not shown here, the impacts of the newly built PH and LEH can be expected to behave similarly as the renovation option, only more dramatically, since the construction itself has an impact that is also dependent on the current grid mix including high sulphur content fossil fuels.

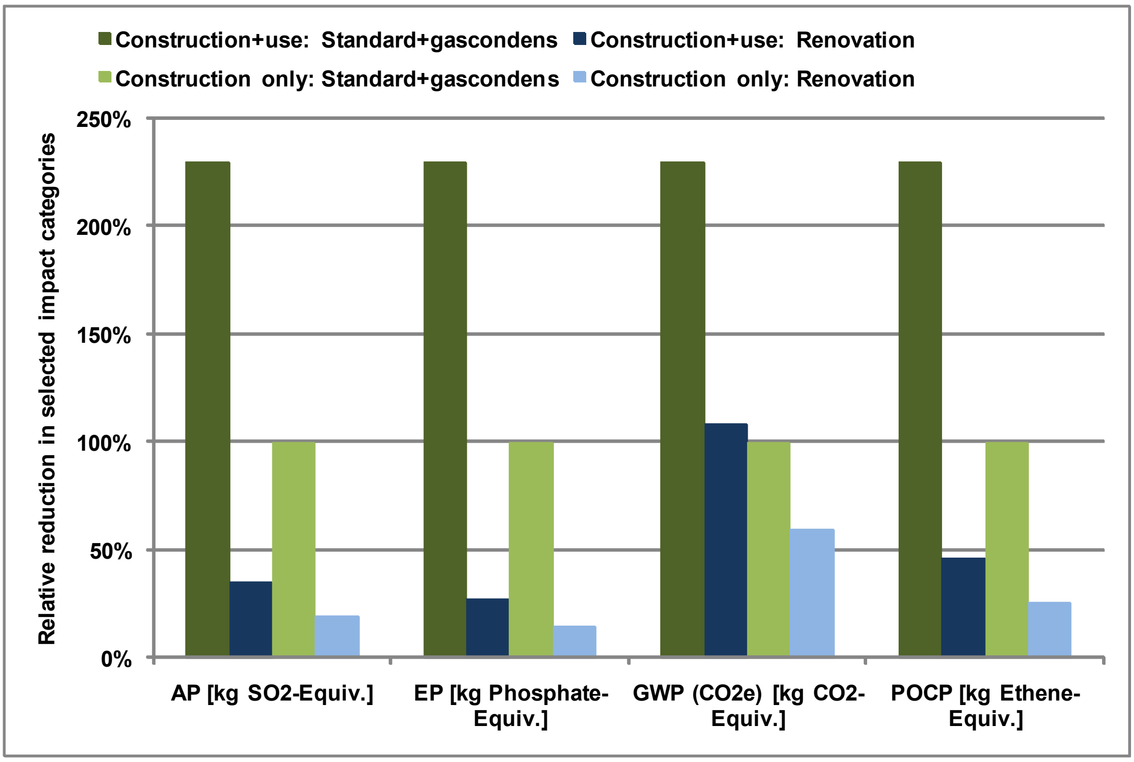

Figure 7-3: Reduction in selected impact categories by the various investment scenarios. Reduction by the "Standard plus gas condens" scenario with investment in construction phase only is considered as 100% in each of the impact categories. Reduction by the other scenarios is given in percentages relative to this scenario.

7.5 Conclusions

- As was demonstrated already in Case Study 6: building a new house for 1 million Euros, power is in numbers. With current cost prices, the number of affordable small-scale solutions has a much more powerful potential to reduce environmental impacts.
- Even though it could have been presumed that considering use phase savings in costs could improve the position of the full renovation scenario, the savings *relative to the cost of the improvement* still favoured the new boiler only scenario. This means that the multiplication effect of the new boiler only scenario was even higher than that of the full renovation scenario.
- While in PED and GWP reduction, the new boiler only scenario was about 1.5 to 2 times more successful than the full renovation scenario, in the impact categories AP, EP and to a lesser degree POCP, the new boiler only scenario was about 5-8 times more successful. This can be attributed to the fact that the renovation phase also has environmental impacts, in relative terms higher in AP and EP than in GWP, due to the higher dependence on fossil fuels other than natural gas.

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Supplement A Parameter settings of the 3 housing types (all row houses with buildings on either sides)

	standard house	low energy house	passive house
Base parameters			
lifetime of building	50	50	50
new building or renovation	new house	new house	new house
Building settings			
Building geometry			
length (m)	7.22	7.22	7.22
width (m)	9	9	9
storey height (m)	2.7	2.7	2.7
storey number	2	2	2
flap tile height (m)	0	0	0
selection of basement (on or off)	off	off	off
window (south) (m2)	6	16	22
window (west & east) (m2)	0	0	0
window (north) (m2)	5	4	4
Building material			
Selection and definition of exterior wall			
Selection of exterior wall (brick, sand-lime brick, aerated concrete wooden wallboard)	brick	sand-lime brick	sand-lime brick
Selection of u-value exterior wall (calculated or typed in)	typed in	typed in	typed in
U-value exrerior wall typed in (W/(m2*K))	0.431907	0.06159	0.035736
Definition of wall types			
Vertically perforated brick wall			
Thickness of layers			
Bricks (m)	0.2359		
Density of materials			
Bricks (kg/m3)	1000		
Sand lime brick wall			
Thickness of layers			
EPS insulation (m)		0.0439	0.067544
Bricks (m)		0.1131	0.11114
Roof			
Thickness of materials			
Mineral wool for insulation (m)	0.1	0.2	0.3
Thickness of materials			
Concrete (m)	0.16	0.16	0.16
EPS (m)	0.04	0.2	0.3
Tubes and cable			
cable (kg)	100	100	100

Tubes for AC and ventilation			
Typed in amount of ventilation ducts (m)	0	0	0
Weight of air duct (kg/m)			
Window			
Selection of u-value typed in (W/(m2*K))	3	1.2	0.7
Building energy balance			
Climate parameters			
Heating			
Heating degree day (HDD)	3433	3433	3433
Heating period	185	185	185
Ventilation			
Exchange rate infiltration	0.5	0.07	0.07
Exchange rate window	0.2	0.1	0.1
Selection mechanical ventilation	off	on	on
Efficiency mechanical ventilation		75	85
Exchange rate		0.4	0.4
Additional use parameters			
Persons	3	3	3
Night reduction	off	off	off
Weekend reduction	off	off	off
Heating equipment			
Selection of heating equipment	Gas conventional	Gas condensing	Heat Pump
Use phase of boiler			
4-25kW			
Gas conventional			
Capacity	20		
Efficiency factor	93.5		
Average boiler temperature	60		
Gas condensing			
Capacity		5	
Efficiency factor		106	
Average boiler temperature		41	
Oil conventional			
Oil condensing			
Power consuming equipment			
Selection of equipemt			
Circulating pump	1	1	1
Radiator	0	0	0
Measurement & control system	0	0	0
Free Modul 1	0	0	0
Free Modul 2	0	0	0

Use phase			
Circulating Pump			
Power demand for application	266	266	266
Power demand for loss	0	0	0
Room air conditioner			
Cooling on or off	off	off	off
SEER of cooling			
Electric radiator			
Heat pump			
COP of heat pump			4
Power Supply			
Hardcoal	19.45	19.45	19.45
Lignite	11	11	11
Natural gas	17.7	17.7	17.7
Fuel oil	6.22	6.22	6.22
Nuclear	33	33	33
Hydro power	11.3	11.3	11.3
Solar	0.1	0.1	0.1
Wind	1.23	1.23	1.23