Renovation concepts for saving 75% on total domestic energy consumption

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Abstract

In the RIGOUREUS project, ECN, TNO, TU Delft end DHV cooperate to develop innovative and affordable renovation concepts for terrace dwellings in The Netherlands, aiming at reducing their total (primary) energy consumption by 75%. A key aspect in the realisation of this target is minimisation of heat losses and maximisation of using solar heat. The basis for the concepts to be developed therefore is the Passive House concept and a solar collector in combination with additional measures.

The potential of integral renovation concepts based on maximising the amount of passive and active solar energy is explored, addressing the reduction of space heating and DHW as well as the reduction of domestic electricity consumption. A number of additional measures are presented, in particular aimed at decreasing electricity consumption in order to achieve the energy target.

Keywords: Renovation, 75% reduction primary energy, integral concept.

1. Introduction

The energy consumption in the built environment accounts for approximately one third of the total energy consumption in The Netherlands. The introduction of the Energy Performance Coefficient EPC in The Netherlands in 1998 as a mandatory requirement for new buildings has contributed considerably to the reduction of the energy consumption of new dwellings. However, little effort has been undertaken so far for existing buildings in this respect.

In the RIGOUREUS project, ECN, TNO, TU Delft and DHV develop innovative renovation concepts aiming at a reduction of 75% of the total (primary) energy consumption for Dutch terrace dwellings. A key aspect in the realisation of this target is minimisation of heat losses and maximisation of the solar contribution, while reducing the building related and user related electricity demand. The basis for the concepts to be developed is the Passive House concept [1], minimising the energy demand for space heating, in combination with a solar thermal collector to reduce the energy demand for DHW. Even though these concepts are well known in German speaking countries, several factors have prevented widespread application in the Netherlands, such as: fear of the unfamiliar, the typical Dutch building practice and economical considerations. Nevertheless, it is regarded as a necessary starting point for energy ambitious renovation concepts.

2. Energy consumption of a Dutch terrace dwelling

An analysis of the building stock [2] shows that the category ‘terrace dwellings’ built between 1945 and 1975 makes up a major part of the total building stock, both in respect to number of dwellings and energy consumption. In the next decade, these dwellings will be in need of renovation. For these reasons, this type of dwelling is selected as the object for the renovation concepts.

The annual energy consumption of such a dwelling consists of approx. 2.000 m^3 of natural gas (for space heating, DHW and cooking) and approx. 3350 kWh of electricity. It is assumed that there is no need for cooling in these dwellings in their current state nor will there be after renovation. In terms of primary energy (denoted with the index p), the total energy consumption adds up to 260 kWh_p/m^2a, shown by the left bar in the graph in figure 1.

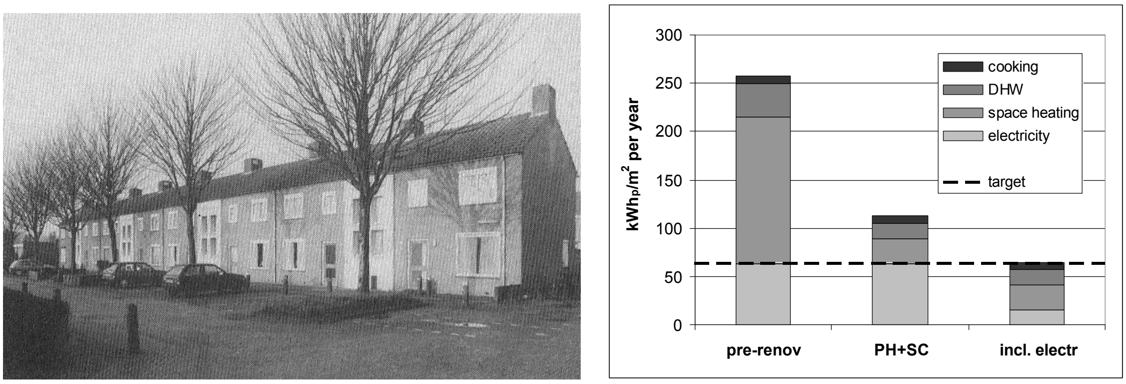

Fig. 1. Post war Dutch terrace dwelling and breakdown of primary energy demand per m^2 of floor area.

The target of the RIGOUREUS project is to reduce this figure by 75% down to 65 kWh_p/m^2a. To put this into perspective, in order to obtain the Passive House quality mark, the primary energy consumption of a Passive House must be less than 120 kWh_p/m^2a. The ambition of the RIGOUREUS project therefore is almost twice as high as the Passive House quality mark.

The middle bar in figure 1 shows the energy demand of a terrace dwelling after the energy demand for space heating has been reduced to 25 kWh/m^2a by the application of the Passive House concept and the energy demand for DHW has been reduced by a factor of two by the use of a solar collector. As figure 1 shows, these measures do not suffice to reach the target. The remaining energy consumption is now dominated by the domestic electricity consumption. This too should be reduced by approx. a factor of 4 in order to reach the target of 65 kWh_p/m^2a, as shown by the right bar in figure 1. In fact, the issue of reducing the domestic electricity consumption is all the more important because in The Netherlands, as in the EU, electricity consumption shows an increasing trend of approx. 2% per year between 1990 and 2006 [3] and it is expected to further increase in the future.

3. Measures to reach the target of 75% energy reduction

Starting from the middle bar in figure 1, the question is how to further reduce the primary energy consumption of a dwelling, in particular the (net) electricity consumption. Following the Kyoto pyramid, the three steps to reduce energy consumption are (in this order): 1) reducing energy demand, 2) application of renewable energy and 3) efficient use of fossil energy. Let’s explore how far we can go in each step. In relation to the renovation concepts, building related measures are of particular interest.

3.1. Reduction of domestic electricity

On the basis of the Basic Survey Electricity Consumption of Small Users [4] a list was composed of electrical appliances in a typical Dutch household. In this survey the degree of penetration, being the percentage of households that owns a particular appliance is also listed. In the present list, common appliances (with penetration > 50%) are assumed to be present, while less common appliances (with penetration < 50%) are left off the list. So we did not examine a household with 60% of tumble dryer and 2% of Jacuzzi hot tub. The resulting list is shown in table 1.

Table 1. Appliances and their electricity consumption in a Dutch household after two steps to save energy.

Appliance group	**electricity consumption [kWh/a]**	***saved in step 1 [kWh/a]***	**remaining after step 1 [kWh/a]**	***saved in step 2 [kWh/a]***	**remaining after step 2 [kWh/a]**
oven, microwave etc.	96	*27*	69		69
cooking utensils	136	*22*	114	*66*	48
Hobby	8	*2*	6		6
personal care	16	*4*	12		12
audio/ video/ communication	629	*189*	440	*51*	389
heating / DHW	271	*50*	221		221
fans etc.	26	*0*	26		26
refrigerator, freezer	589	*6*	583	*359*	224
Cleaning	1213	*0*	1213	*174*	1039
lights (mainly incandescent lamps)	642	*90*	552	*366*	186
Other	46	*10*	36		36
Total	**3672**	***400***	**3272**	***1016***	**2256**

The electricity consumption of the remaining appliances adds up to 3670 kWh/a, which is somewhat higher than the average electricity consumption of the Dutch dwelling (3350 kWh/a). How can we reduce this electricity consumption? A number of steps are discussed below.

Step 1: Elimination of standby electricity

In an average household, electricity consumption of standby modus makes up approx. 10% of the total consumption, which can be significantly reduced by application of so called ‘stand-by killers’. Different types of stand-by killers are available on the market. However, a more structural approach on the level of building related measures would entail the implementation of a series of wall outlets of a different colour (e.g. green) that can be switched off during the night or in absence of the occupants. By eliminating all standby electricity the annual electricity consumption of the appliances on our list can be reduced by approx. 400 kWh/a (11%). This is perhaps an optimistic figure to achieve in practice as not all appliances lend themselves to standby killers (in particular those with a clock or a timer). Also some appliances’ standby consumption will only be reduced during the night.

Step 2: Replacement of appliances by the most energy efficient variant (A-label)
This step shows the potential of reducing electricity consumption with the state of the art technology. Table 1 shows that the largest gains in terms of kWh/a are achieved by application of low-energy light bulbs and replacing the refrigerator and the freezer with an A-label combined refrigerator-freezer. With these and a number of other small replacements, the average Dutch tenant can save another 1016 kWh/a (28%).

Step 3: Low energy or renewable energy appliances

When considering the appliances remaining after step 2, a number of these require heat that is supplied in the form of electricity, such as the dishwasher or the washing machine. Offering heat from a boiler, a micro Combined Heat and Power plant (CHP) means that we avoid the heat losses in the electricity plant (50%) where the electricity is being generated. An even more desirable option is to use solar heat from a solar collector. This option is further discussed in chapter 3.2.2. Of course, care must be taken to reduce as much as possible any heat losses from the piping between the heat source and the dishwasher / washing machine.

Another major consumer of electricity in dwellings is the tumble dryer. Gas fired dryers are a good alternative or, more ambitiously, a drying room fed with waste heat from e.g. the refrigerator.

Further reductions are possible: research is being carried out on dishwashers that require no more than a single cup of water. Using the right soaps/enzymes, washing could be carried out at much lower temperatures, saving on the need for water heating. Drying at low temperatures, using a fan rather than a heater also lowers the heating demand.

Refrigeration is also a major electricity consumer. This could be done more efficiently using a cool room or cool cupboard in the house, that is efficiently cooled with ground heat exchangers or - in wintertime - by the evaporator side of the heat pump. Implementation of a top lid on the refrigerator avoids losses when opening the door. A carousel system can provide easy access to all wares stored.

A bonus for all these savings is a reduction in internal gains, which will reduce the risk of overheating of the dwelling during the summer.

It is doubtful whether we will achieve a factor of 4 in the reduction of domestic electricity consumption with the three steps described above. That means that in order to reach our target of 65 kWh_p/m^2a, additional measures will be necessary. This is the next step in the Kyoto Pyramid.

3.2. Application of renewables

Renewables can be introduced with locally installed PhotoVoltaic (PV) cells or solar collectors or by importing ‘green electricity’ e.g. from an off shore wind park. The latter however is not accepted within this project. The precondition we set for ourselves is that the investment for the installation generating renewable energy must stem from the renovation budget.

3.2.1. Application of Photo Voltaic

One option to reach the target is the application of PhotoVoltaic (PV) cells. Starting again from the middle bar in figure 1, the target can be reached by mounting 30-35 m^2 of PV-modules of optimum orientation on the roof. However, for technical or architectural reasons this may not always be possible or feasible in renovation. In addition, it may not be very economical, which for Dutch builders is an important criterion. Financing constructions, e.g. leasing the PV cells from an energy supplier or an Energy Service Company (ESC) can help to overcome this barrier.

ECN is cooperating with 15 partners in the European 'Crystal Clear' Integrated Project aiming to reduce the cost of PV on a system level down to 3€/W_p, which roughly corresponds to an electricity price of €0.15 - €0.40 per kWh - depending on the location in the EU.

Assuming that any PV electricity not consumed can be fed into the grid, the application of PV does not interfere with other measures. The amount of PV, required to reach our target is therefore used as a measure of the success of other measures. This will be discussed in chapter 5 below.

3.2.2. Increased size of the solar collector system

As mentioned before, main consumers of electricity in a typical Dutch household are appliances such as a washing machine and a dishwasher, that can also be fed with (solar) heat (hot fill). However, solar heat is not always available when needed, especially in wintertime. There are two ways to maximise the contribution of solar heat: 1) to store the solar heat in a storage vessel until the time that it is needed and 2) to shift the moment of heat demand to the moment that solar heat is available. The latter could be achieved using smart control systems that would automatically switch on appliances like a washing machine, when sufficient solar heat is stored in the vessel.

The Dutch practice is to apply (if at all) a rather small solar collector, usually in the order of 3 m^2 and a storage vessel of typically 150 l. These are rather modest sizes compared to the practice in e.g. German speaking countries, where collector areas are found of up to 15 m^2 and storage vessels of up to 2m^3 [5].

It is therefore interesting to see how much a larger solar collector system can contribute to the target of reducing the energy consumption by 75%. The scope of the simulations carried out is broader than just saving on electricity consumption; it includes savings on energy demand for space heating and DHW as well as the solar contribution to hot fill. The results of the simulations depend on the assumptions for the different parameters describing the system. These are briefly discussed in the following chapter.

3.2.3 Model of the solar collector and storage vessel

The solar collector and the storage vessel were modelled in Matlab. A collector heats the water in the primary loop, shown on the left in figure 2, allowing a temperature stratification within the storage vessel. Water at the top of the vessel is extracted for space heating, DHW and hot fill and simultaneously cold water (10°C) is fed to the bottom of the vessel. If the temperature of the extracted water is too low, the boiler will heat it to the desired level: 40 °C for space heating, 55°C for DHW and 60°C for hot fill. The latter values are relatively high in order to prevent Legionella contamination. The water at 55°C is mixed with cold water to obtain the desired temperature level of the DHW tapings.

The type of collector is a vacuum collector[1] of varying size, oriented towards the south with a tilt of 45 degrees. The storage vessel is modelled as a cylindrical vessel of varying size which is thermally insulated with a U-value of 0.1-0.2 W/m^2K. The temperature stratification in the vessel is modelled as 8 isothermal segments of water.

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[1] The collector was modeled after the CPC Star azzurro from Ritter GmbH & Co. KG with the following coefficients: η_0= 0.675, k_1=0.697, k_2=0.003.

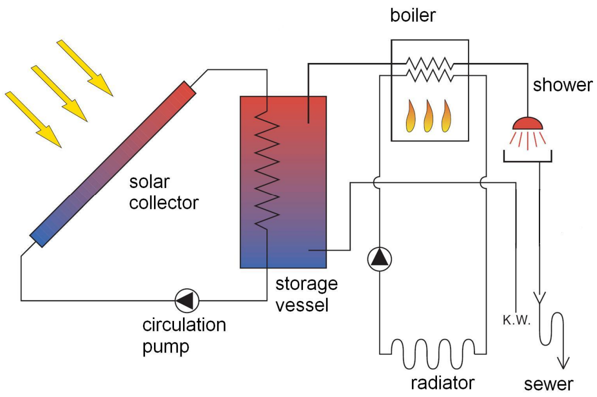

Fig. 2 Schematic of the model of solar collector integrated in the heating system. The shower is the symbol for all DHW demand including hot fill of dishwasher and washing machine.

In the base case scenario, the DHW pattern is modelled after that in the Dutch Energy Performance Norm EPN [6], which entails approx. 20 short and longer tapings of a particular temperature level including a long taping of 50 l every morning and every evening for showering. The pattern for the hot fill of dishwasher is a daily taping of 14 l at 60°C and that for the washing machine two tapings of 13 l on Saturday and Sunday each and another on Monday. This pattern and a number of variants (see chapter 3.2.5) were simulated and the contribution to the saving of primary energy was calculated.

3.2.4 Results of the simulations of solar collector and storage vessel

The area of the collector is varied between 2 and 16 m^2, and for each, the volume of the storage vessel is varied between 0.15 and 10 m^3. Although the latter value is perhaps a little high for a single family house, the simulations are carried out to show the potential and limitations of the system. The results are compared to those of the base case, where a 3 m^2 vacuum collector with a 150 l storage vessel is used solely for DHW production. The added savings on primary energy demand for space heating, DHW and hot fill are shown in fig 3.

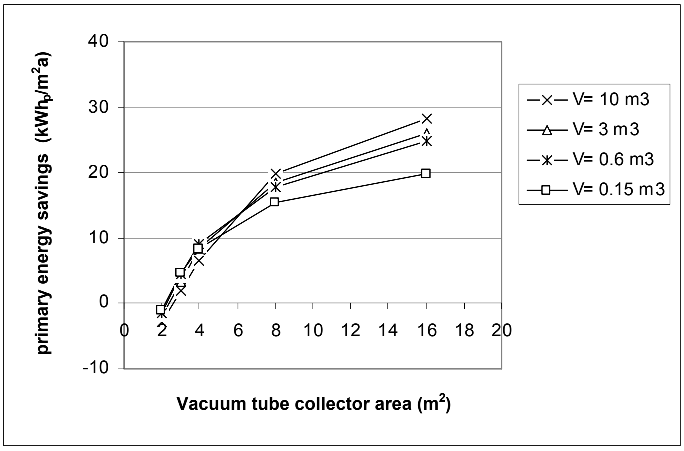

Fig. 3. Savings on primary energy – compared to base case - as a result of the solar collector contributing to space heating, DHW and hot fill as a function of collector area and at different storage vessel sizes

The solar contribution to the total primary energy savings for *space heating* is calculated assuming that in the absence of a solar collector, the heat has to be generated with a boiler with an efficiency of 95% (on lower heating value). Similarly, for *DHW* the efficiency of the boiler is assumed to be 75%. For the hot fill the savings are calculated assuming that in the absence of the solar collector, the electricity has to be generated in a power plant with a primary energy efficiency of 50%. When the solar collector cannot supply enough heat for the hot fill, there is still a gain in primary energy because the heat is then generated by the boiler with an efficiency of 75% rather than in the electricity plant at 50%.

From Figure 3 it appears that even with rather modest collector sizes in the order of 8 m^2, there is a substantial saving on primary energy of 15-20 kWh/m^2a over the base case. This corresponds to a solar fraction of about 45% of the total heating demand for space heating, DHW and hot fill. It also appears that at this collector area, the size of the vessel is of secondary importance, as long as it is at least 0.6 m^3.

3.2.5. Matching the heat demand to the availability of solar heat

An alternative to using a storage vessel to maximise the use of solar heat is to match the heat demand to the availability of solar heat. This can be achieved by allowing appliances like the dish washer or the washing machine to start operating only when sufficient solar heat is available. Instead of setting the start of the washing program, the latest allowable time of stop of the program can be set.

Simulations are carried out for the base case, which includes a 3 m^2 vacuum collector and a 150 l vessel. Different DHW and hot fill patterns are compared, including the one described in chapter 3.2.3, a pattern with heating demand only during the day time, one with heating demand only during the night time and one where the daily heating demand for DHW and hot fill is 'smeared out' over 24 hrs.

The results show a difference in primary energy savings between the different patterns in the order of 1%. This small figure is due to the fact that even a rather small 150 l storage vessel is an efficient way to match the heating demand to the availability of solar heat. The results suggest that rather than implementing complicated control devices, that may result in delays and therefore annoyance on the part of the occupant, the use of a storage vessel is a better way to maximise the use of solar heat.

4. Efficient use of fossil fuels

Two of the most promising technologies for efficient use of fossil energy are the Combined Heat and Power plant (CHP) and the high performance heat pump. In The Netherlands, several small (micro) CHP plants are available for application in dwellings. In analogy to high efficiency boilers, a so called HRE quality mark is being introduced for units with a Primary Energy Ration (PER) of 140% or more.

Alternatively, state of the art heat pumps achieve a Seasonal Performance Factor (SPF) of 2.5-3 for DHW and 4-5 for space heating. Assuming an electrical efficiency of 50% in the electricity plant, this translates to a PER of 140% for DHW and 220% for space heating. Application of such a unit with a thermal output in the 2-5 kW_{th}-range would save an additional 15-20 kWh/m^2a in our terrace dwelling.

5. Summary

Table 2 below summarizes the effect of the different scenarios. The first scenario is the base case consisting of the Passive House concept plus a 3 m^2 vacuum tube solar collector and a 150 l storage vessel. Additionally, in case 2 domestic electricity is reduced by 39% using standby killers and A-label appliances. Here, innovative measures such as low energy coolers are not yet included. Most of the measures in scenario 2 fall under the first step of the Kyoto pyramid. The target of 75% reduction can be reached by adding 16 m^2 of PV modules in optimum orientation.

In scenario 3, the area of the solar collector is increased from 3 to 8 m^3 and the storage vessel from 0.15 to 0.6 m^3. In this scenario, the target is nearly reached and only 4 m^2 of PV are needed to reach it. Of academic interest is that a 16 m^2 collector will reach the target without the need to install any PV.

Finally, replacing the boiler with a high efficiency heat pump will help reach the target without the need for additional PV cells.

Table 2. Results of different scenarios for saving energy. The last column shows the amount of PV that is needed to reach the target of 75% reduction on total domestic energy consumption.

Scenario	Description of measures	Primary energy demand [kWh_p/m^2a]	PV to reach target [m^2]
1	Passive House + 3 m^2 solar collector+150 l storage vessel for DHW	113	32
2	As scenario 1 plus step1+2 in electricity reduction (-39%)	88	16
3	As scenario 2 plus 8 m^2 solar collector+600 l storage vessel, for DHW, space heating and hot fill	70	4
4	As scenario 3, heat pump instead of boiler	52	-

6. Conclusion

A reduction of 75% of the total (primary) energy consumption in a Dutch terrace dwelling appears very well possible with an integral approach based on the Passive House concept in combination with a solar collector to maximise the amount of passive and active solar energy. In addition, standby killers and application of label A appliances are applied to substantially reduce the electricity consumption. As a final touch, the application of either 4 m^2 of PV cells or the application of a high efficiency heat pump will help reach the target. More innovative measures are being studied, but their effect is not included in these results.

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