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Potentials for energy efficiency and renewable energy sources in the Netherlands

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ABSTRACT: In this paper insight is given in the potentials for energy efficiency and renewable energy sources, specifically when applied to the built environment in the Netherlands. To this end, an analysis is presented of the building stock development from now to 2050 and building concepts and scenarios for a mid-century energy-neutral built environment in the Netherlands. The analysis deals with new and existing residential and non-residential buildings and distinguishes different aspects of the energy balance; space heating and cooling, domestic hot water and electricity consumption. An analysis is made of the mix of measures which is needed to reach net energy-neutrality in the built environment in 2050. With the term 'net energy-neutrality', the overall annual energy-usage of the complete building stock, including built environment related systems such as streets within cities is meant, incorporating energy exchange with the industry and transport sectors. For the separate measures the technological feasibility is assessed and set against the current research developments in the Netherlands.

Keywords: energy-neutral, building stock development, technological developments

1. INTRODUCTION

Our world is strongly on the move. The climate changes. More and more uncertainty exists concerning the energy supply. The discussion is no longer about the need to contemplate the future of energy supplies but about the way we can meet the future energy demand in a sustainable way. Both national and international policies are developed in the climate field and people devote themselves to energy transition.

In the Netherlands more than one third of the energy is used in the built environment. Insulation of buildings, more efficient comfort installations and local production of sustainable energy have strongly improved the energy performance of buildings in the previous decades. The potential for even better energy performance however has still not been exhausted. The urgency to bring all measures for improvement of the energy performance into action, and thereby connecting to nationally and internationally pursued policy, increases.

The Dutch research institutes TNO and ECN have started the strategic cooperation *Building Future* (BF) in the field of energy in the built environment in order to jointly give an impulse to this transition. Both institutes believe that by the middle of this century energy neutrality in the Dutch built environment can be reached, provided that the developments to this end are tackled energetically.

2. SCENARIO ANALYSIS

2.1. Traditional approach

Scenario models are a powerful tool to assess the impact of trends and (technological and non-technological) developments on the profile of the future society, with ramifications on specific aspects such as safety, healthcare, energy and economy. For this reason, scenario studies are often carried out to provide insight in the impact of different national or organisational policies and strategies.

On the topic of energy, many scenario studies exist. All of them make use of the projected market development of energy technologies, derived from past technological developments and possible macro-economical developments set against the relative importance of environmental measures stimulated by policies. The outcome of such studies can provide valuable insight in the common results from different developments, indicating what we anyhow should be prepared for. They can also provide warning signs (resulting from distinct differences between the different routes to the future) to act upon if certain possible future outcomes are unwanted. They should however never be seen as a tool to predict the future.

2.2. Building Future approach

In this study a scenario study is performed slightly differently. Not the impact of incremental improvements but the impact of different plausible technological breakthroughs in the built environment on the development of the energy usage in the Dutch built environment in the period from 2000-2050 is assessed. The outcome of this scenario is set against the outcome from existing scenario studies based upon the work of [1]and [2]. This approach has the advantage that its results can serve as a beacon for policy makers and market developers. But it also provides a foundation for a long term R&D agenda.

2.3. The scenario analysis tool

2.3.1. Input

To study the effect of plausible technological breakthroughs, a scenario analysis tool is used. The tool uses two sorts of input:

- The projected development of the number of buildings, resulting from trends in the number of new residential buildings build every year and the number of residential buildings demolished. Two possible scenarios were considered: The Strong Europe (SE) and Global Economy (GE) scenarios [2]. The scenarios have a different outcome with respect to the development of the number of residential buildings as illustrated in Figure 1. In this study the development as depicted by the SE scenario is used as reference in the model, and will in the remainder of this paper be referred to as Business as Usual (BaU).

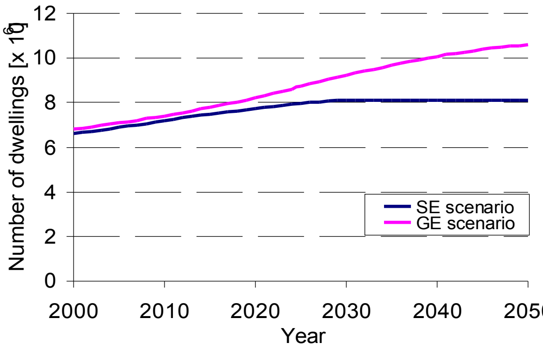


Figure 1. Development of number of residential buildings.

- The energy consumption profile of the Dutch built environment in 2000 as illustrated in Figure 2. The figure illustrates the distinct difference between residential and non-residential buildings: in residential buildings 65% of the total primary energy is used for heat, whereas in the non-residential sector electricity is dominant (52%). It is interesting to note that, although the total primary usage associated with the non-residential sector is lower than that of the residential sector, the average energy per m^2 ground floor area is much higher in the non-residential sector. This is illustrated in Figure 3.

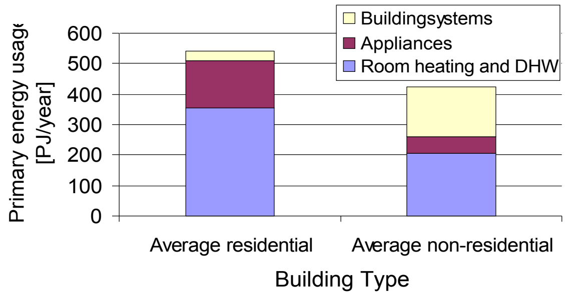


Figure 2. Energy consumption profile for the built environment in 2000

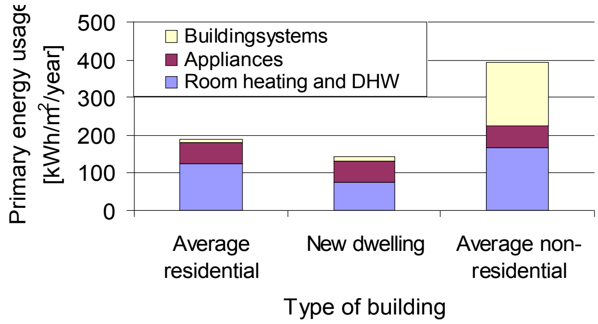


Figure 3. Energy usage of buildings in 2000

Figure 3 shows that in the non-residential sector the higher primary energy usage per m^2 ground floor area is, for the main part, due to the larger amount of energy used for building systems (mainly HVAC and lighting).

2.3.2. Variables

In this study several variables have been used to evaluate the possibilities for energy reduction in the built environment, harnessed by the natural mutation moments. By natural mutation moments the following building related activities are meant: addition of new buildings, demolition of obsolete buildings, building system (HVAC) replacement, large scale maintenance (excluding rigorous facade alterations) and renovation (including rigorous facade alterations).

The possible variables in the scenario tool are the energy reduction intensity resulting from specific building mutations, the speed of market penetration, the rate of renewal of the building stock.

2.3.3. Output

Output of the scenario tool can be presented in terms of the development of energy usage in the built environment and/or CO2 reduction. Also, some economic aspects can be derived, resulting from the application of different energy price scenarios to the different energy development scenarios. The economic aspects are not investigated in this paper.

3. ENERGY IMPACT MEASURES

3.1. Type of variables

In this study the following variables are used:

- Reduction of natural gas demand (for space heating and domestic hot water) resulting from:
  - ➢ improved (energy) quality of new buildings
  - ➢ renovation
  - ➢ large maintenance
  - ➢ (HVAC) building system replacement
- Reduction of final electricity used by building systems usage due to:
  - ➢ renovation
  - ➢ large maintenance
  - ➢ (HVAC) building system replacement
- Speed of market penetration of breakthrough energy-reduction measures.
- Mutation rate of the building stock (rate of renewal, rate of renovation).

3.2. Assumptions

Apart from the previously listed variables the following assumptions have been made:

- The energy-related trends depicted for the SE scenario after 2040 [1], are held constant to construct the extrapolated energy development of the building stock for the BaU scenario towards 2050.
- The energy demand of demolished buildings equals the average energy demand of the building stock in the year of demolishment.
- Energy demand for artificial lighting is part of energy for building systems in case of non-residential buildings, but is *not* part of energy for building systems in case of residential buildings. For the latter, the energy demand for lighting is accounted for in user related energy (appliances).
- The number of residential buildings equals 96.6% of the number of households.
- Market penetration follows a uniform profile, as depicted in Figure 4.

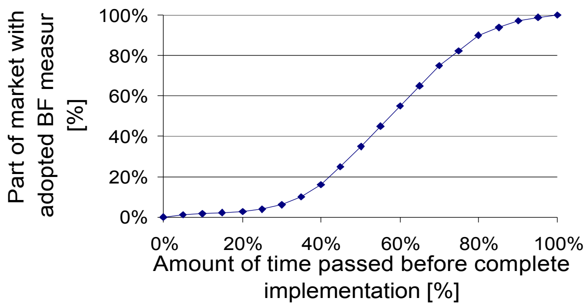


Figure 4. Market penetration profile of new energy measures.

- Primary energy related to electricity usage in the built environment is calculated using the development of the average park efficiency as depicted in Figure 5.

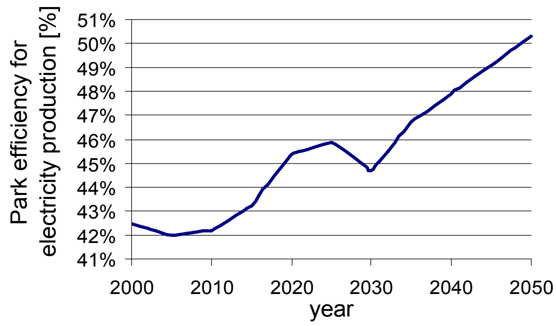


Figure 5. Development of park efficiency for electricity production.

- For CO_2 calculations, it is assumed that 1 GJ of natural gas equals 56,1 kg CO_2. Furthermore this value is multiplied by a factor of 1.01-1.02 to account for losses in the natural gas winning process for natural gas produced and used in the Netherlands. The conversion from final electricity to CO_2 is a combination of (development in the) the park efficiency and the (development in the) product mix for electricity production in the Netherlands. The same assumptions are used for the BaU and the BF scenario.
- The development of energy reduction in the non-residential sector, with respect to total primary energy usage, follows the development in the residential sector.

3.3. Breakthrough technologies

In order to bring about the sought for transition to an energy neutral built environment, implementation of measures are considered which comply with the following philosophy:

1. Maximum demand reduction. With respect to buildings this implies measures such as:

a. optimal insulation of the building skin, minimal infiltration
b. Use of heat recovery on ventilated air and domestic hot water
c. Use of energy efficient appliances (A-label, energy conservation lamps)
d. Avoid standby losses of electrical appliances

2. Optimised use of renewable energy, implying:
   a. Optimal use of passive renewable energy such as solar heat, daylight and natural ventilation
   b. High-efficient renewable energy production, for instance from (high temperature, vacuum) solar collectors (possibly in combination with a μ-Organic Rankine Cycle (μ-ORC), PV(T) panels, (small scale) windmills
   c. Balance demand and supply of renewable energy, both in energy sort (low-temperature heat, high temperature heat or power) and in time
   d. Make use of (compact) energy storage, either local or using grid-connected/community systems
3. Technologies which make efficient use of fossil energy sources such as:
   a. heat pump (compression, absorption, magneto-caloric or thermo-acoustic)
   b. μ-Combined Heat (Cold) and Power Generator (μ-CH(C)P), stirling driven or using fuel cells (SOFC/PEMFC)
   c. Community systems for instance using waste heat from waste processing plants

4. ENERGY IN THE BUILT ENVIRONMENT

4.1. Business as usual

Future energy consumption of the built environment mainly depends on the development of the building stock, but also on global and national developments, such as climate change, national turnover and policy-effectiveness. The building related modifications influencing energy consumption involve construction of new residential buildings, demolition, renovation, extensive maintenance and installation replacement. The change in energy consumption in the housing stock associated with these developments, derived for the BaU scenario, are listed in Table I, along with the expected change in electricity consumption per year associated with use of household appliances (HHA).

Table I: Impact of developments in residential building sector on gas and electricity consumption in % compared to the reference year 2000: 'Business as Usual'.

Mutation	Gas (%)	Electricity (%)
- New buildings[1]	-5/year	+1,5/year[2]
- Renovation	-17	-20[2]
- Maintenance	-8	-20[2]
- Installation replacement	-8	-10[2]
- HHA		+0,8[3]/year
- Renewable Energy (RE):	Implicit	

Taking all these developments into account, future energy consumption according to the 'Business As Usual' scenario can be outlined [1].

Figure 6 illustrates that the expected total primary energy consumption in the building sector remains approximately 1000 PJ_p. Two significant trends contribute to this stabilization. Due to improved building insulation and more efficient comfort installations, gas consumption is expected to decrease. On the other hand, residential electricity consumption increases. Residential electricity consumption is about to increase mainly due to increasing cooling needs and increased use from HHA. A growing number of ICT related applications contribute to increasing electricity consumption in the non-residential sector.

1 Annual improvement of new to build residential buildings
2 Development of building related electricity consumption due to mutation
3 Average value over the period 2000-2050. In the model the trends between several key years as taken from [1] are used.

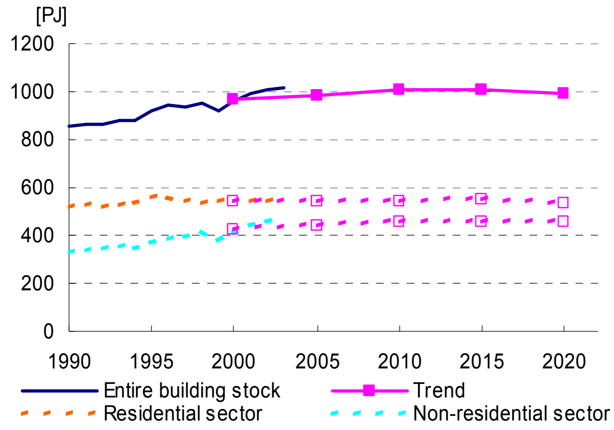


Figure 6. Total primary energy consumption in the building sector according to the 'Business As Usual' scenario.

4.2. Building Future scenario

The research program of *Building Future* (BF) aims at reducing the total net energy usage of the built environment to energy-neutrality around the middle of the century. To this end several technological and non-technological developments have to be undertaken linked to the building stock improvement moments.

To assess the potential of measures, with the model described in paragraph 2.3, first the effect of the measures separately is examined:

- Replacement of heating installations (every 15 years) including compact heat storage and thus reducing the energy for heating and domestic hot water (DHW), by 50% overall through system replacement, will result in a reduction of 130 PJ/year by 2050.
- If from 2015 onwards all new to build residential buildings would be energy-neutral a reduction of 65 PJ would result by 2050.
- Even if from 2015 onwards the introduction of net energy producing residential buildings would be taken on (starting at app. 4.5 GJ/year/building), a maximum reduction of 80 PJ/year could result by 2050.
- On the other hand, when all effort is directed towards renovation, for instance by implementing renovation packages that will reduce the demand for heat and DHW by a factor 4 and additionally integrate Renewable Energy (RE) from the sun in the building, the total reduction will not exceed 145 PJ/year by 2050. With a more modest package, but compared to current best practice still ambitious, consisting of only 50% reduction in demand for heat and DHW, a reduction of approximately 70 PJ/year by 2050 results, which is in the same order as the variant with energy neutral new buildings.
- Reduction of energy used by HHA by 2% per year from 2015 onwards, might result in a total reduction of 145 PJ/year by 2050.

The above findings illustrate that, if an energy neutral built environment is to be reached, focus on only one of the building stock developments will not suffice; all the building stock improvement moments have to be used and a reduction of the user-related energy (HHA) should be accomplished as well. The required combination of measures (which are interrelated) for the residential sector is listed in table II.

Table II: Impact of developments in housing sector on energy consumption [%] compared to the original situation according to BF scenario.

Mutation	Heat (%)	Elec. (%)	RE (kWh/a)
- New buildings	-40/year	-	4000
- Renovation	-75	-20	2000
- Maintenance	-15	-20	-
- Installation replacement	-50	-50	-
- HHA	-	-2	-

On top of these measures, the total energy consumption of the non-residential sector should decrease from 0% in 2010 up to 5% per year in 2025. This decrease in fact implies the same trend in energy consumption as for the residential sector. Most of the targets listed, albeit ambitious, can be achieved with introduction of the required building concepts around 2015, using existing technologies and technologies currently under development.

If all of the abovementioned measures are set in place the resulting development of the net energy usage of the built environment is depicted in Figure 7. Note, that the effect of the separate measures can not simply be added to obtain the result for the combination of measures, since some are interrelated. Table II and Figure 7 illustrate that building related measures (for new to build residential buildings and the existing stock) are not sufficient to reach energy neutrality. Also reduction of user related energy (HHA) and measures on district level (yellow line) should be introduced.

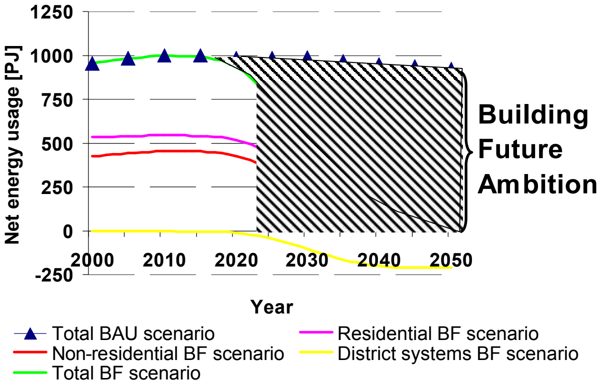


Figure 7. Development of net energy usage.

The effect of the Building Future scenario in terms of CO_2 emission directly related to residential buildings and user related electricity, is a reduction from 31.4 Mton in 2000 to 5.5 Mton in 2050. This implies a 83% reduction of building related energy for the residential sector with respect to the reference year 2000. With respect to Business as Usual in 2050 it implies a 2.5 times higher reduction of Mton CO_2.

Effect of mutation rate

The above mentioned measures may be considered ambitious and call for alternative ways to reach an energy-neutral built environment. If the renewal rate of the building stock is increased or the rate of renovation, the ambition levels for the energy impact measures may be decreased. To assess this effect 3 different scenario's are considered:

- Increased demolition rate: In this scenario the demolition rate between 2010-2030 is doubled (thus increasing from 50.000 houses per year in 2010 to 60.000 in 2030) and the amount of new buildings built is altered to keep the rate of increase of total number of residential buildings equal to the reference scenario. Between 2030-2050 the number of houses demolished per year equals the number of houses newly built at 75000 per year. The resulting effect on the average age is illustrated in Figure 8.

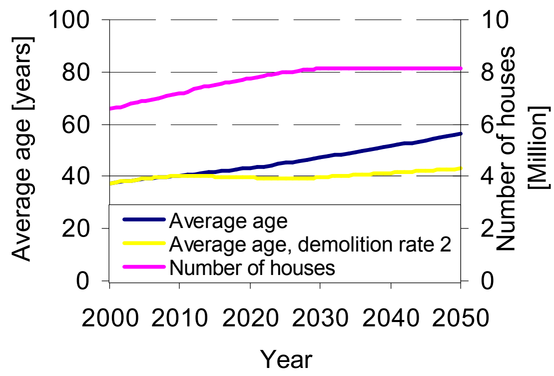


Figure 8. Effect of increased demolition rate on average age of residential buildings.

By itself this increased demolition rate, increases the energy reduction with 20 PJ in 2050, compared to Business as Usual. To reach the same energy reduction as in the BF scenario, the energy reduction level for building related measures can be diminished from 75% to 50%.

- Increased renovation rate: In this scenario the renovation rate is increased from once every 45 years to once every 30 years. To reach the same energy reduction as in the BF scenario, the energy reduction level for building related measures can in this case be diminished from 75% to 63%.
- Combination of above mentioned increased demolition rate and renovation rate: To reach the same energy reduction as in the BF scenario, the energy reduction level for building related measures now can be diminished from 75% to 50%.

5. RESEARCH ACTIVITIES FOR KEY TECHNOLOGIES

At the R&D institutes forming Building Future, TNO and ECN, there are various technologies under development that will play a crucial role in the built environment the coming decades, when striving to enable the Building Future scenario. Important examples are Building skin optimisation, Ventilation, Photovoltaic's (PV), fuel cell, heat pump, (compact) heat storage and Stirling micro-CHP (Combined Heat and Power). The following paragraphs provide more details on the related R&D at TNO and ECN.

5.1. Demand reduction

5.1.1. Building skin improvement

Even with the current standards for buildings, still a lot of energy can be saved through improved design of building skins. Obviously, this is especially true for the existing building stock. To minimise heat losses, the concept of PassivHaus should be applied. In short, this implies for the building skin:

1. The insulation levels of walls, floor and roof are bought to R_c=7.5 m^2.K/W.
2. Windows are installed with triple glazing U=0.6 W/m^2.K.
3. The air tightness is brought down to 0.6 air changes/hour at 50 Pa.

Such measures will reduce the energy for heating in new buildings by a factor of 2 and can result in a reduction by a factor of 5-9 for existing buildings. ECN and TNO actively participate in promoting these techniques and the associated concepts, amongst others in the participation in the scientific committee of the Dutch Passive House organisation: Passiefbouwen.nl. Furthermore ECN leads the EU-EIE project PEP, which stands for Promotion of European Passive houses (www.europeanpassivehouses.org).

5.1.2 Natural ventilation with HRU

Ventilation is an important topic in energy saving in the build environment. Insulation measures do not affect the ventilation energy losses. In the Netherlands heat recovery ventilation systems have let to comfort related complaints mainly due to faulty design, installation and maintenance. Also the effectiveness in practice in an actual building is in many cases lower than the sum of effectiveness of the apparatus. For instance a component efficiency of 95% can in practice result in a lower overall ventilation heat recovery efficiency. This is due to: air leakage of the building, overheating during moderate outside conditions, frost protection and flow demands and temperature differences from the test conditions of the heat recovery system.

Therefore it is an important challenge to combine energy saving, thermal comfort and wellbeing in new ventilation systems to deal with these issues. Therefore different innovations are being developed. Thereby we try to improve overall ventilation heat recovery efficiency, combined with a more comfortable and healthy indoor air environment.

An important development direction is the development of demand controlled ventilation systems, with only 1 sensor unit and control unit. This results in a more cost effective system.

A second development direction is a building integrated ventilation system which uses the air leakages in the building envelope as air intake. In this way it prevents surplus ventilation due to wind loads on the building envelop and prevents cross ventilation. Calculation shows that it is possible to reduce ventilation leakage flow up to 30%.

5.1.2. Domestic hot water heat recovery

With increased effort on insulation and infiltration improvements, the domestic hot water, becomes the next major building-related energy demand. Currently heat recovery units exist that can be integrated in new buildings to substantially reduce the amount of energy used in the bathroom.

Another interesting element is the heating demand by electrical appliances such as dishwashers and washing machines. At ECN research is carried out to develop a heat recovery unit which can harvest the waste heat at the end of the (dish)washing cycle and stored it for re-use in the next cycle.

5.1.3. Energy Management systems

Recent research has shown that he technical savings potential of advanced control systems in the whole Dutch built environment is estimated to be of the order of 170 PJp of primary energy per annum (30% of the total energy usage of the Dutch built environment) and 11 Mton CO_2 emission reduction per annum. In the residential sector automated user adaptive and user educating control each represent about half of the estimated savings potential. In the service sector the majority of the potential is covered by improved operation and maintenance through on going monitoring.

In addition to the use of advanced control systems for the reduction of primary energy use, it is also possible introduce demand response in the built environment. This does not directly lead to the reduction of the primary energy use, but it will be necessary in future electricity grids with a high penetration of intermittent, renewable energy sources. In the residential sector there is a significant potential for demand response by shifting the electricity demand of various appliances: 34 PJe demand response per year.

These figures indicate the great energy saving potential of energy management systems. At TNO and ECN, research is focussed on developing energy management systems, ranging from environment-adaptive, user-adaptive up to user-educational. First experiences in the latter category have been acquired in the EU-FP5 project EBOB (Energy Efficient Behaviour in Office Buildings), see Figure 9. The effect of the system in an office building situated in Sweden, showed that more than 50% energy saving could be realised on indoor climate systems, with the major part on the heating system.

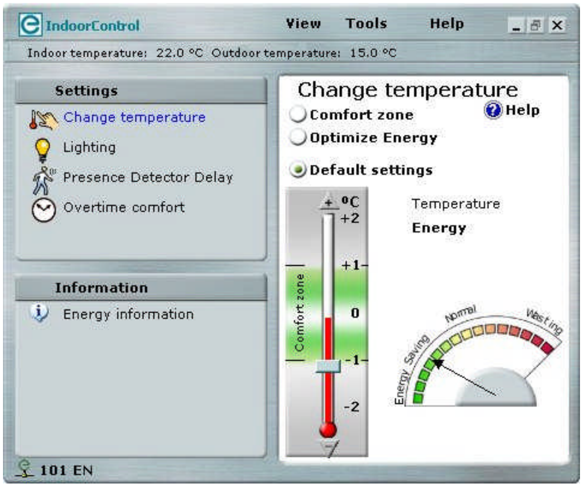


Figure 9. User Interface, providing feedback on comfort and energy.

5.2. Renewable Energy

5.2.1. PV

Major developments in the field of PV technology are achieved at ECN and partners within the EU FP6 Integrated Project CrystalClear (see www.ipcrystalclear.info, and references on that site). The CrystalClear project is a research and development project dedicated primarily to cost reduction of solar (photovoltaic, PV) modules, which form the heart of any solar energy system and which account for some 60% of the turn-key price of roof-top installations. The objective of the CrystalClear project is to enable a price reduction *on a system level* to approximately 3 €/Wp, which roughly corresponds to electricity generation costs of 15 to 40 eurocents per kWh, depending on location in the EU. At the same time CrystalClear aims at improving the environmental quality of solar modules by the reduction of material consumption, replacement of materials and designing for recycling. Last but not least CrystalClear wants to enhance the applicability of solar modules by tailoring to customer needs and improving product lifetime and reliability.

Highlights of the progress in this project are:

- Several types of new solar grade silicon feedstock (the starting material for solar cell fabrication) have been successfully tested. Since feedstock production capacity has not followed the strong growth of the PV sector in recent years, a shortage and resulting high silicon prices have limited market development and PV module price reduction. New feedstock production capacity is now in the pilot or preproduction phase and will soon allow the sector to catch up again. Additional advantages of the new feedstock materials are lower manufacturing costs and lower energy consumption.
- By using a thin (0.1 mm) ribbon of silicon as starting material for cell fabrication, researchers have been able to demonstrate (on a lab scale) a record low silicon consumption per unit of solar cell power: 3 grams per watt-peak (to be compared with typically 10 grams for commercial production today). By using ribbons instead of cut wafers cutting losses are avoided and by using *thin* ribbons even more efficient use of silicon can be obtained.
- The CrystalClear consortium has reached a record high efficiency of 18.1% for a large area multicrystalline silicon solar cell, by using advanced processing and cell design.
- With the aim to enable the use of large, ultra-thin cells in high-throughput, high-yield module assembly, new cell and module concepts are under development. Key words are rear-side contacting and conductive adhesives for electrical interconnection of cells. CrystalClear has shown the potential of conductive adhesives as an alternative for soldering, allowing "single shot" module manufacturing.
- Using Life Cycle Inventory data of actual manufacturing practices as basis for Life Cycle Analysis it was revealed that the energy pay-back time of solar modules and systems is unexpectedly short. The data have also been made available for the public

domain (www.ecn.nl/solar). The energy pay-back times of PV systems were calculated to be in the range of 1.7 to 2.1 years (Southern Europe), as illustrated in Figure 10. These results are considerably lower than previously published estimates, and they have the great advantage that they are now based on real production data. In an outlook towards near-future silicon technology it was estimated that an energy pay-back time around *one year* can be achieved for multi- and ribbon silicon technology, if new solar grade silicon technology can be applied successfully, wafer thickness in production can be halved and module efficiency can be increased to 15-16%.

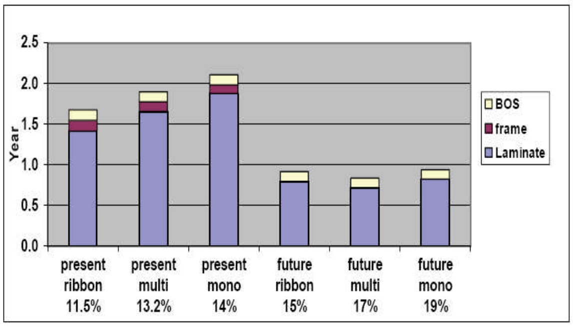
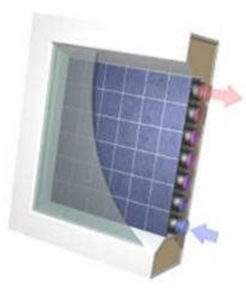


Figure 10. Energy Pay-Back Time for Southern Europe of PV systems based on today's wafer-based silicon technology, compared with near-term future technology. The numbers below the X-axis give the respective module efficiencies

5.2.2.PVT

Apart from 'main stream' solar collectors and PV-panels, the last couple of years ECN has put a considerable R&D effort in the development of the PVT-technology. This technology combines solar thermal, for space heating and/or domestic hot water, and PV in one system.



In line with the first steps along the PVT-roadmap[4] [3], this has resulted in the market introduction of the first commercial PVT panels in the Netherlands through the spin-off company PVTWins. The coming years R&D effort will be focussed on system integration, optimising the complete system (the building) into a net energy producing residential building. This work is carried out within the WAELS project, which is partially funded through the Dutch Energy Agency SenterNovem.

5.2.3.Heat pump

Heat pumps provide the built environment with a technology that can efficiently upgrade low-temperature renewable energy, such as ambient energy, to useful levels for space heating or domestic hot water. Besides efficient heating, a heat pump can in principle also provide efficient cooling, a demand that is clearly growing in The Netherlands. R&D at TNO focuses on making efficient heat pumps able to deliver heat at higher temperatures, fit to be introduced in older residential buildings, and finding replacements for environmental unfriendly coolants. Beside the research on aspects of compression heat pumps, new heat pumps based on alternative principles such as ab(d)sorption and magneto-caloric effects are developed at TNO. R&D at ECN focuses on heat pumps using the principle of thermally driven sorption and of thermo-acoustic compression.

The internal cycle of a **sorption heat pump** resembles the 'standard' compression cycle, with the major difference that the mechanical compression is replaced by thermal compression. Advantages are the lack of HCFC's and of a mechanical compressor (moving parts, noise etc). And because they're thermally driven, sorption chillers do not cause peak demands on the electricity grid. Ongoing research at ECN concerns the development of a silicagel-water adsorption chiller [4], for small-scale (<10kW$_{th}$) cooling applications. Besides automotive applications, this power range is also very well suited for residential applications. Figure 11 shows the system layout of the ECN sorption chiller. The system includes two sorbent reactors, which operate in counter-phase to obtain continuous cold production.

[4] The PVT Roadmap is one of the main deliverables of the European Co-ordination Action PV Catapult.

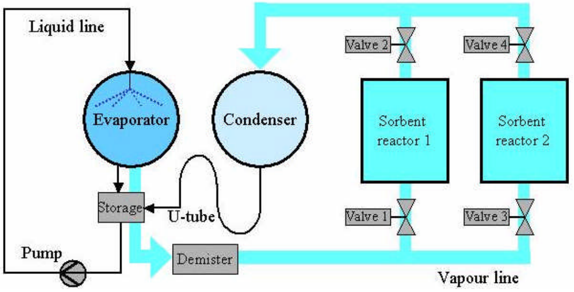


Figure 11. Basic system layout of the sorption cooling system.

The silicagel-water chiller can be driven by temperatures around 80°C. This means that solar thermal energy can be used to provide cooling to a building, reducing primary energy consumption for cooling to almost zero (there is only electricity needed for pumps and controls).

The first prototype built has 5 kW thermal output. After successful lab experiments this prototype has been placed in a field test in Italy. Currently the second prototype is being designed, aiming at a higher power density and a thermal output of 2.5 kW.

A **thermoacoustic heat pump** is based on the principle that a temperature difference can amplify an acoustic wave and, vice versa, an acoustic wave can create a temperature difference. The system consists of a thermoacoustic motor (creating an acoustic wave) and a thermoacoustic heat pump (transforming acoustic wave into a temperature difference), coupled via a resonator (transporting the acoustic wave from motor to heat pump). The internal cycle of this heat pump strongly resembles the Stirling cycle.

Figure 12 Linear motor driven thermoacoustic cooler.

ECN is developing thermoacoustic (TA) heat pump technology for upgrading industrial waste heat to useful temperature levels [5], with spin-off opportunities to the built environment. Besides no moving parts and HCFC's, the advantages of TA heat pumps are the relatively large temperature lift that can be accomplished and the use of relatively simple (and common) materials for the construction of the heat pump.

5.2.4. Compact Heat storage

Heat storage technologies are supporting technologies that improve the performance of renewable energy systems (e.g. solar collectors, biomass boilers) and systems rationalising use of energy (heat pumps, micro cogeneration). The following three principles can be used for heat storage, with increased storage density (and hence capacity):

- using sensible heat (for instance in water tanks)
- using latent heat of Phase Change Materials (PCM)
- using heat associated with chemical reactions from Thermo-Chemical Materials (TCM)

Sensible heat

Modern solar storage vessels combine several specific features that improve the overall efficiency of storing solar heat:

- Few thermal bridges.
- Enhanced insulation, even vacuum insulation in the future.
- Improved bottom insulation.
- Siphon introductions of pipes to avoid natural convection losses.
- Reduced number of connections to avoid thermal bridges.
- Stratification enhancers to increase the exergetic value of the content of the store.
- Internal devices to reduce speed of inlet water not to disturb stratification.
- Large heat exchangers or mantle heat exchanger.

Based on these principles, at ECN, a new compact water-based heat storage vessel will be developed which will increase the storage density by 35%, with respect to a convential system.

Phase Change Materials

Using latent heat of Phase Change Materials (PCM): The idea of using PCM in a storage tank has been investigated in the 80s with paraffin. Although it works, the advantage is nowadays not strategic since the solar collectors have been much improved and are less dependant of the operating temperature in the range 50 to 80 °C than they were. Paraffin has also a major drawback, its flammability. At ECN, the possibilities of using PCM's in household appliances, using electrically generated heat, such as washing machines and dishwashers, are investigated.

Thermo-Chemical Materials (TCM)

In principle, high storage densities can be achieved by means of chemical reactions. Many ways exist to convert solar energy (in what form so ever) into thermal energy. Quite obvious is the photo thermal route as utilized in current solar hot water and space heating systems. Many chemical reactions are not suitable for storage of solar energy in residential areas. In addition to common conditions for a residential thermal energy store like reasonable costs and safe and reliable operation, chemical storages need to satisfy the following criteria:

1) High storage density (> 2 GJ/m^3).
2) The chemical reactions need to be:
   - Controllable and reversible at a rate sufficient to cover DHW and space heating and/or cooling loads, direct or indirect via a small intermediate buffer.
   - Take place at safe (low < say 10 bar) pressures and temperature levels within the range of domestic solar collectors (< 250 °C).
3) In addition, the components involved in the chemical reactions need to be:
   - Chemically stable.
   - Safe and easy to handle.
   - Recyclable and environmentally benign (non toxic).
   - Inflammable.

Especially the temperature level restriction and the power density (reaction kinetic) conditions pose severe limits to the chemical reactions known. In general, chemical reactions take place at acceptable power levels at elevated temperatures (say >500 °C). There are a few reactions that will be presented that could provide solutions for moderate collector temperatures (< 250 °C).

In an extensive study for medium temperature thermo chemical storage materials, ECN and Utrecht University, The Netherlands, identified many candidate materials that were all selected with respect to criteria similar as outlined above. An indicator was defined in the study, called the realisation potential. This was calculated based on criteria similar to those of the above list together with weighting factors, in order to have a single figure for comparing the suitability of the different reactions for the aims of the project. The reaction of magnesium sulphate with water and the reaction of silicon with oxygen or nitrogen, came out as promising reaction candidates.

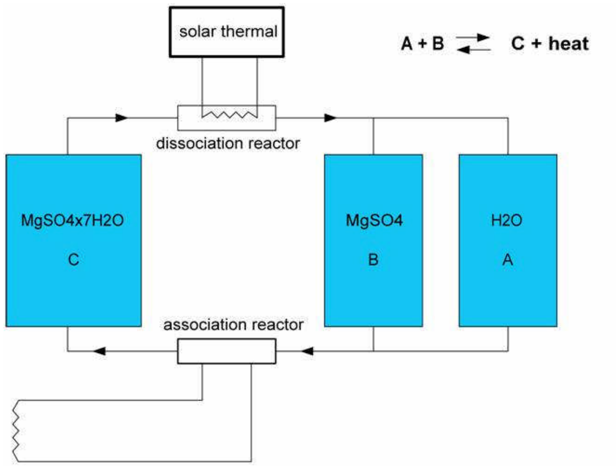


Figure 13. Reaction principle for magnesium sulphate and water

Although in principle attractive materials exists, further research is needed to determine practical aspects like reaction kinetics and mass transfer rates. This will be the focus of the R&D effort at ECN on this subject.

At TNO work is concentrated to develop the first prototype of a thermo-chemical reactor based on slurry-sorption reactions.

5.3. Energy Effieciency

5.3.1. Micro-CHP

Stirling driven micro-CHP

The cogeneration of heat and power (CHP) can lead to a significant reduction of primary energy use. To avoid transport and distribution of heat, the size of the CHP unit is often designed in such a way that it can meet the local heat and electricity demand. For residential applications, the electric power is in the range of 1-5 kWe (micro CHP). Natural gas is the most often used fuel for residential CHP, but propane and kerosene (Japan) are used as well. For commercial applications, such as office buildings and hospitals, the system size is in the range of 200 kWe and even larger (mini CHP).

At present most cogeneration systems are based on gas engines and Stirling engines. Stirling engines are starting to be deployed for residential applications, and are available in the 1 kW range. Their Heat to Power ration is typically 9:1, making them especially suitable for houses with a relatively high heat demand (the building stock older than 2004). Gas engines are available in a wide power range, but are especially successful in the power range of 0.5 MW and larger, in the horticulture and in hospitals. The latter as a combination of power generation and back up power supply. For these larger units, natural gas as well as biogas are the fuels being used. The electric efficiency of these large systems can be as high as 40%.

In cooperation with international industrial partners, ECN is developing a Stirling micro-CHP unit for residential applications. The free-piston Stirling Engine has a nominal electrical output of 1 kW and is fuelled with natural gas. The ratio between thermal and electrical output makes this Stirling Engine especially suited for the existing building stock, the majority of which is already connected to the natural gas network. In combination with a storage tank the Stirling can provide both space heating and domestic hot water to a house. Configurations of Stirling plus peak burner are also possible. Because system volume is always an issue in existing buildings, ECN has developed a 'high density water storage' with a 30% lower volume compared to traditional water tanks. This volume reduction is achieved by improving the heat exchange with the storage (focusing on Stirling micro-CHP) and by minimizing the losses, using vacuum insulated panels.

In a recently started European project called PolySMART, ECN is combining Stirling technology and sorption technology into tri-generation, or so-called micro-CHCP (Combined Heating Cooling and Power). The ECN sorption chiller is connected to a Stirling, using the thermal output to provide cooling in summer. The strength of this micro-CHCP system compared to separate production of heating, cooling and power is a higher fuel utilisation rate, leading to financial and environmental benefits. After developing the concept, the micro-CHCP system will be built and tested in one the ECN research houses.

Fuel Cell systems

Fuel Cell systems can be seen as the future generation systems for CHP. Their high electrical efficiency and low noise levels make them especially suitable for residential use. Low temperature fuel cells, operated at 70 °C, (Proton Exchange Membrane, PEMFC or PEFC) and high temperature fuel cells, operated between 750 – 950 °C, (Solid Oxide, SOFC) are in development for stationary use [6].

Fuel cell systems for stationary use are becoming available for demonstration. In Japan, around 700 PEM fuel cell systems of 1 kWe are being installed this year. The electric efficiency of the present generation is around 31 % (LHV), and demonstrated system life time exceeding 10,000 hours.

R&D is aimed at increasing the electrical to at least 35% and total efficiency to 90%, extending the lifetime to 90,000 hours, increasing the robustness and lowering the cost. The system cost at which the fuel cell system can become profitable differs largely per country, depending on the local gas and electricity prices, and on whether the system will be owned by the consumer or by an Energy Service Company. The target used by many developers is around $1000 per kWe.

Systems analysis by ECN has shown that for the Dutch market the system should cost less than €1450 per kWe on top of the heating boiler system cost to become profitable. Both for PEMFC as well as for SOFC, ECN is developing cell, stack and system technology for small stationary applications.

In our PEMFC R&D, PEMFC stationary systems have been developed with partners in national and EU projects in the range of 1 to 50 kWe. The systems, running at 70 °C and atmospheric pressure, comprise natural gas reformers which produce hydrogen which is fed to the fuel cell stacks. A 2 kWe proof of concept system comprising an ECN PEMFC stack, a Johnson Matthey Hot Spot reformer and an Exendis DC/AC inverter was operated in 2002 with an electric efficiency between 25 and 28% and a total efficiency of 81% [7].

At present, a national project in cooperation with Nedstack, Hygear and Exendis is aiming at a PEMFC system which can be operated at temperatures between150 - 180°C. This increase in temperature leads to a more simple system layout, as well as to a more useable heat for tap water and space heating. A barrier at this moment is the fact that the cell and stack technology for this high temperature operation is immature.

In our SOFC R&D, cell and stack developments are aimed at cost reduction by applying cheap materials and increasing robustness by developing electrodes which are more tolerant towards temperature cycles and air/fuel cycles. In cooperation with HC Starck, cell development has been done to meet the specifications of customers with respect to cost, performance and mechanical properties.

An industrially developed SOFC system, the Sulzer Hexis 1000 Premiere, has been tested in 2002 by ECN [7]. The electric efficiency of the system was between 25 and 32%, the total efficiency 85%. The lifetime of that stack was limited, and could only be maintained by avoiding dynamic operation of the system .

ECN is at present participating in the EU FP6 project FLAME SOFC, aiming at a 2 kWe SOFC system which can be operated on fuels ranging from natural gas to LPG and liquid fuels, a system electrical efficiency exceeding 35% and total efficiency exceeding 90%.

6. SYSTEM INTEGRATION

6.1. Where to begin

Insight in development of new and existing residential and non-residential buildings is essential to aim for an energy-neutral built environment. From trends [1] on the increase of buildings in the housing stock, the amount of newly developed houses each year and the demolition rate, a development of the composition of the housing stock can be extrapolated. The result of such a development, stemming from the BaU scenario, from 2004 (red bars) to 2050 (green bars) is shown in Figure 14.

In this SE scenario, the average age of the housing stock as a whole will increase from approximately 40 years now to 60 years in 2050. Figure 14 implicates that the major part of the energy consumption will come from new residential buildings built between 2005-2050 and the residential buildings constructed in the period 1945-1974, which is the segment currently up for renovation.

The current distribution of types of residential buildings in the housing stock is illustrated in Figure 15.

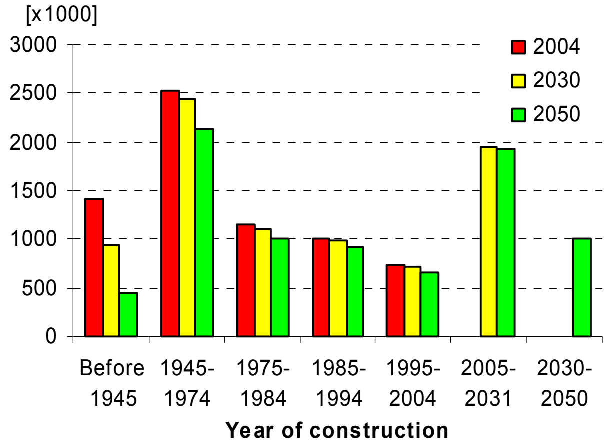


Figure 14. Development of the composition of the Dutch housing stock.

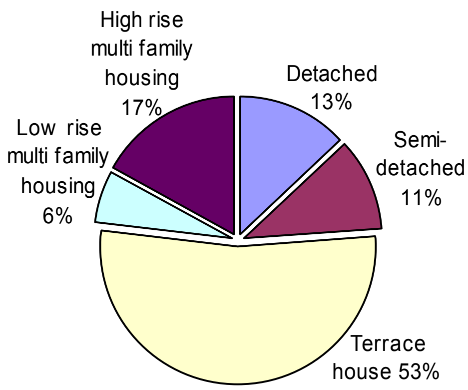


Figure 15. Distribution of types of residential buildings in Dutch housing stock.

The number of houses in which renovation (now approximately 150.000 a year), large maintenance (now approximately 300,000 a year) and installation replacement (now approximately 450,000 a year) will take place, will increase slightly during the coming years with up to 20 %.

6.2. Building concepts

In the previous sections it is shown that in order to reach an energy-neutral built environment in the Netherlands around mid-century, there is a demand for building concepts with a higher (energy) ambition level than currently available. These ambition levels are the set point for a number of building concepts for residential buildings and non-residential buildings and are based on expected availability of technology in the year 2010, with estimated payback times of the complete concepts of approximately 15 years. A short description is given of two residential buildings and one office building concept. In all concepts a strategy is used in which as a first step the energy demand is reduced as much as possible, in line with PassivHaus targets [8]. The second step is to fulfil the need for energy wherever possible with renewable energy sources and, thirdly, using fossil fuels if still needed in an energy efficient way. Both residential building concepts discussed below have the following measures in common:

1. Increasing the insulation levels of walls, floor and roof to R_c=7.5 m2.K/W. Windows are replaced by triple glazing U=0.6 W/m2.K.
2. Improving the air tightness to 0.6 air changes/hour at 50 Pa.
3. Heat recovery from ventilation air by using either a central balanced system or decentralised solutions like a facade integrated HVAC or a window-frame integrated system (new development)
4. Application of external shading to prevent overheating.

6.3. Residential renovation concept

As a reference case a typical Dutch terraced house of the late sixties is selected, since the major part of the housing stock currently up for renovation resembles the building characteristics of this type (see Figure 14 and Figure 15). The aim is to bring back the total energy demand for gas and electricity 'on the meter' to one quarter of the existing energy end-use before renovation. This means that besides building related energy (heating, domestic hot water, ventilation, lighting, etc.) also building related measures to reduce energy consumption of HHA have to be taken into account. In addition to the reduction of the energy demand for space heating, described above, the following measures are incorporated:

- Heat recovery for DHW from the (renewed) shower
- Installation of intelligent sockets designed to minimise standby losses of HHA
- Heat recovery and storage connected to water distribution system of dish water and washing machine
- Replacement of standard boiler by a micro-Combined-Heating-Cooling-Power-generator micro-CHCP operating in combination with a solar collector.

The energy usage of this concept before and after renovation are illustrated in Figure 16.

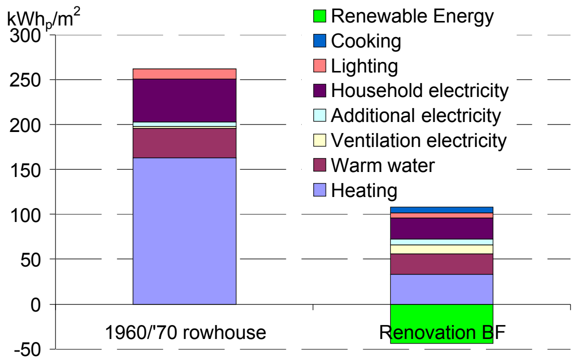


Figure 16. Energy usage before and after renovation.

6.4. Concept for newly built residential buildings

A general feature of the generated concepts for new buildings is that they are at least energy-neutral on a yearly base and net energy producing on a larger district level. This means the buildings themselves will serve as energy-generators, in line with the ambition levels presented in the previous paragraph. Here, a short description is given of the measures to transform a standard (new to built) residential building into an energy-generating residential building in addition to the PassivHaus measures, described above:

1. Active (top)cooling is available with a reversible small size heat pump
2. Compact chemical heat storage techniques are used for storage of DHW as well as space heating
3. Solar PVT collectors are used for heat and electricity generation. Alternatively, vacuum tube collectors can be used, that produce electricity in a second step, using an organic rankine cycle machine connected to a (low temperature) district heating system.

In Figure 17 the energy needs of a standard Dutch (new) residential building [9] and the residential building of the Building Future concept are compared. For this case the installation of 4000 kWh renewable energy is assumed, corresponding to about 90 kWh/(m^2 year).

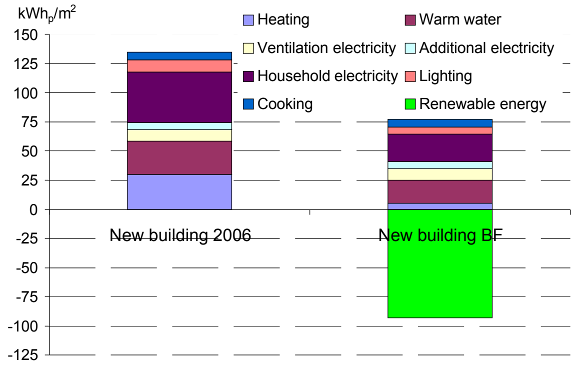


Figure 17. Energy needs of a standard new residential building and a BF concept residential building.

6.5. Thermal comfort

Simulations with TRNSYS show that for both presented new and renovated buildings the temperatures in summer and winter are very comfortable. In summer external shading and night cooling should be used to avoid overheating. The amount of overheating hours (> 25 ^{0}C) can thus be reduced to very acceptable levels.

6.6. Costs and financing

The building concepts are based on payback times of approximately 15 years. The aim is to have an equal burden of living costs before and after renovation. Therefore extra costs for building measures and energy generation should in principle be paid from the lower energy-bills and the improved comfort level. Taking into account a moderate increase of the energy prices, the estimated savings amount to more than € 1,400.- /year for the renovation concept. Since costs and savings do not take place at the same moment in time, new financing schemes are called for, for instance based on integral living expenses.

7. CONCLUSIONS

The developments concerning the built environment indicate that in a business as usual scenario, the energy usage will not decrease although a great potential for reduction exists. This potential can only be achieved by bringing about a transition to a sustainable energy system in the built environment, borne by all responsible parties.

From the Building Future scenario, associated with this transition, it can be deduced that all available measures for improvement should be used. This implies making best practice (such as Passivhaus measures), common practice and developing necessary technologies for essential concepts such as energy producing new to build residential buildings and factor 4 renovation concepts.

Potentially successful concepts incorporate technologies for building related and user related energy reduction as well as integration of renewable energy technology.

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