ZERO-ENERGY HOUSES IN THE NETHERLANDS

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ABSTRACT

A zero-energy house is defined as a house where no fossil fuels are consumed, and annual electricity consumption equals annual electricity production. In this paper, simulations of heat demand and supply are used to investigate the feasibility of the zero energy concept in Dutch low-rise row houses. Essential elements are a high energy end-use efficiency, photovoltaic electricity production, and heat supply by an electrical heat pump or by solar collectors. Using present techniques, the concept entails high costs and an extra large south facing roof area. More advanced techniques however may help to overcome these problems.

INTRODUCTION

Energy efficiency in Dutch houses has improved substantially over the past 15 years: natural gas consumption in central heating installations decreased from an average of 3300 m^3/yr/house [1] in 1978 to 1600 m^3/yr/house in 1993. For new houses built in 1995, the figure is expected to be under 1000 m^3/yr/house. Improved insulation has been the main factor in this efficiency improvement. A less spectacular, but nevertheless steady improvement can be reported in the efficiency of lighting and electrical appliances.

The prospects for further efficiency improvements, in combination with emerging new options in solar energy supply, offer the perspective of a zero-energy house. A zero-energy house is defined here as a house in which no fossil fuels are consumed, and annual electricity consumption equals annual electricity production. Unlike in an autarkic situation, the electricity grid acts as a virtual buffer with annually balanced deliveries and returns. This "exchange" version of the zero-energy concept is subject of a government sponsored research program in the Netherlands which aims at demonstrating the concept on a district level before the year 2010.

In this paper, we will investigate the prospects for this zero-energy concept in new Dutch low-rise houses. The main attention will be on lower heat loads for space heating. Furthermore, we will examine the solar resource potential of the roof area, and the possible role of heat storage and electrical heat pumps in using the solar potential. Finally, we will check the feasibility of several zero-energy configurations.

The analysis in this paper relies heavily on simulation of heat demand and heat supply. Simulation is especially needed here, because many of the techniques described are quite new. Heat demand simulations reported in this paper were carried out with the TRNSYS TYPE 56 multi-zone building model (TRNSYS, 1990), with modifications to account for the use of transparent insulation layers (Sick and Kummer, 1992). For the simulation of heat supply, a model based on the TUTSIM simulation language has been used (TUTSIM, 1988; Gilijamse, 1993; Gilijamse and Boonstra, 1995).

THE REFERENCE HOUSE

The reference type for new low-rise houses in the Netherlands is defined in (Novem, 1990) as a three bedroom row house, with a net floor area [2] of 77 m^2 (see figure 1). The house has a central heating system with hot water distribution through radiators, and a controllable mechanical exhaust ventilation system. Average ventilation rates, including infiltration, for this type of houses vary from 0.8 to 1.0 air changes per hour with the lowest values in mid-winter. The average thermostat settings in the living room vary from 17°C (63°F) at night to 19.5°C (67°F) in daytime. Other rooms are heated far less frequently (Boonstra, 1993). Reference heat demand is defined by applying double glazing and 9-10 cm mineral wool insulation

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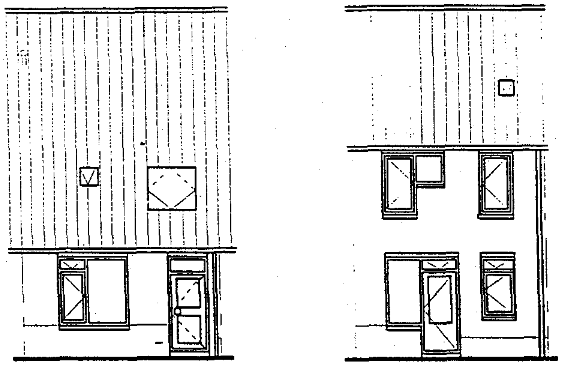
[1] *The most common natural gas quality in the Netherlands has a lower heating value (LHV) of 31.65 MJ/m^3.*

[2] *The net floor area is without outer walls, storerooms, and attic. Gross floor area, including these elements is 141 m^2.*

in walls, roof and ground floor (see table 1 for building specifications).

Simulation with these occupancy and building characteristics shows an annual heat demand of 24.5 GJ, mainly in 6 winter months (see figure 2). This heat demand matches an annual natural gas consumption of 870 m^3 if the heat is supplied by a conventional boiler. This natural gas consumption is in accordance with the value found by applying standard Dutch calculation rules (Novem, 1990), and close to the proposed Dutch energy-efficiency standard of 850 m^3 natural gas per house.



front (north side) back (south side)

Figure 1: The reference low-rise row house (Novem, 1990).

Due to the temperate climate, space cooling systems have a penetration of only 1.5% in Dutch houses (van Maanen, 1994). However, overheating can occur in well insulated houses when solar heat accumulates. Effective measures to prevent such overheating are direct cooling ventilation (DCV) and blinds on south facing windows. The simulation shows that with a DCV air change rate of 3 hr^{-1} the number of hours with an indoor temperature exceeding 25°C (77°F) will be less than 100, which is considered acceptable.

'PRESENT BEST' HEAT DEMAND

Several measures to reduce heat demand further have already been demonstrated in Dutch houses. Insulation of walls, roof and ground floor can be improved by increasing mineral wool thickness to about 15 cm. Low emittance double glazing can double the insulation value of windows compared with standard double glazing. Heat recovery from ventilation air in a balanced ventilation system also offers substantial savings. And finally, a passive solar design can be applied which optimizes the area of south facing windows and uses extra mass to store solar heat.

A 'present best' level of heat demand has been defined here incorporating the above-mentioned techniques (see table 1 for building specifications). Simulations, using the same occupancy characteristics as in the reference case, show a substantial heat demand reduction down to a level of 8.0 GJ/yr. Also, the heating season is shortened further (see figure 2). This heat demand matches a natural gas consumption of 280 m^3/yr, somewhat lower than the values measured in demonstration projects realised up to now (Gilijamse, 1993).

The removal of excess heat in the summer requires extra attention here. The simulations show that extra building mass and blinds applied to south facing windows both help to prevent overheating. Additionally, a DCV air change rate of 7 hr^{-1} is necessary to limit the number of hours with a temperature over 25°C under 100. A good strategy for hot days is night storage ventilation: during the day a minimal amount of ventilation via the heat exchanger which then acts as a cooler, and high ventilation rates at night.

'ADVANCED' HEAT DEMAND

An additional reduction of heat demand can be realized using more advanced insulation techniques. Vacuum powder insulation and vacuum aerogel insulation offer insulation values an order of magnitude better than conventional insulation materials like mineral wool or polystyrene. Additional heat demand reduction can be realised by applying translucent insulation material (TIM) that blocks outgoing heat flow, while letting solar heat enter the building construction. An 'advanced' level of heat demand reduction is considered here that makes use of aerogels in vacuum windows, in opaque insulation panels for roofs and north facing walls, and as translucent insulation on south facing walls (specifications from Geuzendam and Gilijamse, 1994, see table 1). Simulations show that with these insulation techniques very low heat demand levels are achievable. With a TIM area that covers 65% of the south facing walls, heat demand for space heating can be reduced to 2.4 GJ/yr, mainly concentrated in 3 winter months (see figure 2).

To prevent overheating, blinding the TIM wall is essential. It is not necessary to use complicated controls: the potential overheating period is in the summer months only, and does not overlap with the heating period. A blinding system therefore has to be switched on only once a year. Because of the smaller window area, and the blinded TIM area, overheating is less problematic than in the 'present best' design. Simulation shows that a DCV air change rate of 3 hr^{-1}, controlled as night storage ventilation in the hottest period of the year, suffices to limit the number of hours with temperatures over 25°C to about 30.

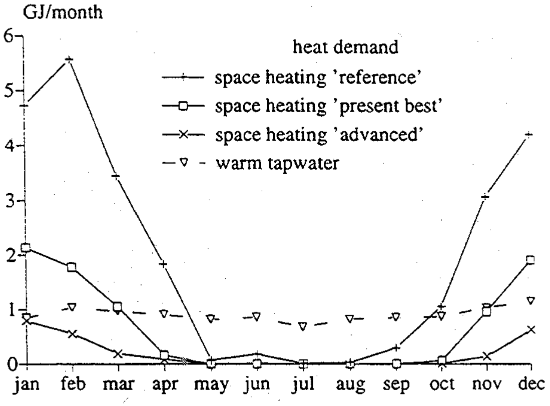


Figure 2: Monthly heat demand for three space heating options and warm tapwater. New low-rise row houses in the Netherlands.

SOLAR HEAT AND ELECTRICITY

Solar irradiation on a south facing 45° slope in the Netherlands is 3.8 GJ/m^2/yr (1060 kWh/m^2/yr). As the reference house has 23 m^2 south facing roof area there is a considerable resource available. We will examine some relevant conversion options.

A first option is the solar water heater, at present the most widespread solar option in the Netherlands. The system consists of a small collector area on the roof and a short term thermal storage (STTS). Simulation with present collector specifications (Gilijamse, 1993) shows that a 4 m^2 system with a 120 litre storage can provide 47% of the reference 10.8 GJ/yr tapwater heat demand [3], in agreement with measured values. More advanced collectors, e.g. based on monolithic silica aerogel (Nordgaard and Beckman, 1992), could increase this contribution to 55%. The potential contribution to space heating is very low, even at larger collector areas, due to the seasonal mismatch of space heating load and solar collector heat production (Gilijamse, 1993).

A solar thermal contribution to space heating requires a long term thermal storage (LTTS). Development of LTTS in the Netherlands concentrates on storage in underground aquifers, which seems to be possible in many Dutch regions. At a storage temperature of about 80°C (176°F), which makes tapwater use possible, the storage efficiency is 70% (van Wees et al, 1994). Aquifer storage cannot be applied on a small scale, so a block heating system is necessary. This entails relatively high distribution losses estimated at 3 GJ/yr/house [4]. The seasonal average collector efficiency is 40% for present collector specifications, and 50% for more advanced collectors (van Wees et al, 1994). These figures imply that the net contribution of the reference roof area to heat demand is 19 GJ/yr for present collector specifications and 26 GJ/yr for advanced collectors, assuming that 50% of tapwater heat demand is provided by STTS.

Solar electricity production considered here is based on photovoltaic cells (PV), again to be installed on the roof. We consider systems based on polycristalline material, with a 'present best' module efficiency of 11.5% (Kelly, 1993), which implies a production of 120 kWh/m2/yr. Future thin film systems could reach the same efficiency at much lower costs (Kelly, 1993). The reference roof area could produce 2800 kWh/yr.

ELECTRICAL HEAT PUMP

For configurations which use (PV) electricity for space heating, the efficiency of heat supply can be boosted by using an electrical heat pump. We will consider a heat pump with ventilation air as a heat source. Ventilation air as a heat source has the advantage of year-round availability at a relatively high temperature, offering a high coefficient of performance (COP). In the system we will consider, the heat pump supplies heat to a stratified hot water storage (Gilijamse, 1993). Cold water from the bottom goes through the condenser and, after heat transfer, back to the top part of the storage.

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[3] *All simulations assume a minimum supply temperature of 60°C (140°F) for warm tapwater and 50°C (122°F) for space heating.*

[4] *Block heating distribution losses are about 3 GJ/yr/house at reference heat demand (Gilijamse, 1993). Heat demand reduction for space heating does not offer a substantial decrease in distribution losses because most of the year the dominating heat flows are for warm tapwater requirements or for the transport of solar heat into the LTTS.*

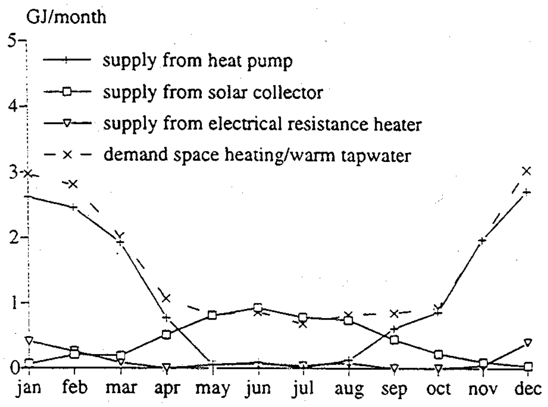

Figure 3: Monthly heat production for a heat supply system with heat pump, solar collector and electrical resistance heater. 'Present best' heat demand and supply system performance.

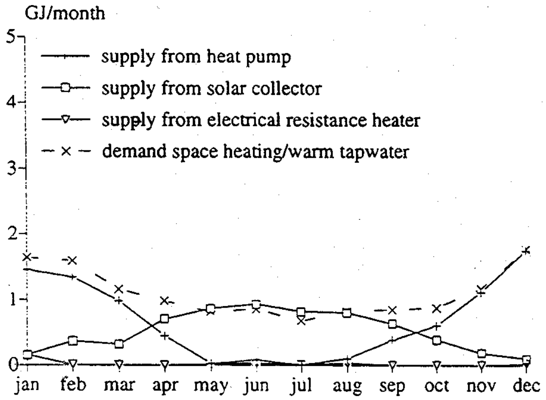

Figure 4: Monthly heat production for a heat supply system with heat pump, solar collector and electrical resistance heater. 'Advanced' heat demand and supply system performance.

'Present best' heat pumps offer a COP of 3.0 for an average condenser temperature of 60 °C (140°F) (Gilijamse, 1993). Simulations have been used to optimize system performance, especially regarding the maximum inlet temperature and the temperature drop over the condenser. Table 2 shows optimized values for these control parameters and storage volume. The simulations show that the heat pump can supply 93% of the heat demand for the 'present best' heat demand level defined above, including the warm tapwater part. The rest of the heat demand is supplied by an electrical resistance back-up heater. The seasonal average COP, including back-up heating and storage losses is 2.8. For more advanced systems, COP at a condenser temperature of 60 °C is assumed to be 4.0 (van Wees et al, 1994). Applied at the 'advanced' heat demand level defined above, an advanced heat pump would provide 98% of total heat demand with a seasonal average COP of 3.9.

In this heat pump configuration with a stratified storage, a small solar thermal system that uses the same storage can offer additional electricity savings during a large part of the year. Figures 3 and 4 show simulation results for a system with a 4 m^2 collector addition. Like in the system without a solar collector, electrical resistance back-up is minimal. The solar collector provides 27% of total heat load in the 'present best' situation and 42% in case of advanced heat demand reduction and supply specifications.

ZERO-ENERGY CONFIGURATIONS

We now return to the question whether a zero-energy house is a feasible option for low-rise houses in the Netherlands. Table 3 summarizes the simulation results for the heat demand reduction options discussed above. Additional estimates of efficiency improvements for cooking, lighting and appliances are also given in table 3. Table 4 shows annual energy flows for three zero-energy configurations, based on the solar supply and conversion options discussed above. Results are shown for both 'present best' and 'advanced' energy demand level and energy supply specifications.

All three configurations are based on PV electricity for cooking, lighting and appliances. Configurations differ in the way the solar resource is used to supply heat for space heating and warm tapwater. The first configuration is based on heat supply by solar collectors in combination with LTTS. The second configuration is based on heat supply by a heat pump and additional PV area to provide the necessary electricity. The third configuration differs from the second because a 4 m^2 collector area provides heat to a common STTS.

Total roof area for PV and solar collectors in 'present best' configurations ranges from 36 m^2 to 40 m^2. This exceeds reference south facing roof area, but can be realized with some modifications of building design, e.g. extending the sloped part of the roof to the first floor of the house. Total roof area for PV and solar collectors in 'advanced' configurations ranges from 21 m^2 to 24 m^2, approximately the available south facing roof area of the reference house.

Tables 3 and 4 also show cost estimations for efficiency improvement, solar supply and conversion. Costs of 'present best' systems are based on estimates of present costs or, in case of on-going cost reductions (e.g. in heat pumps and PV systems), expected costs for 1995/1996. Costs of 'advanced' systems are based on various estimates for the first decades of the next century. Not surprisingly, it appears that for 'present best' systems the investments of zero-energy configurations are very high: about Dfl 29,000 (1 Dfl = $ 0.55) per house. Compared with a present annual energy bill of about Dfl 1,300 zero-energy options are clearly not cost effective. For 'advanced' systems cost-effectivity seems to improve considerably because of lower costs: about Dfl 13,000 - 16,000, with the lowest costs for the configurations with heat pumps.

Some final remarks on the zero-energy concept should be made here. Minimizing the macro effects of energy use requires optimization on a higher system level than the house level considered here. A more comprehensive analysis should include the effects of exchange with the electricity grid, the energy incorporated in insulation materials and installations, and the energy requirements of other household activities like transportation. Zero-energy configurations as proposed here are therefore certainly not the only way, and possibly not the best way, to move towards an energy future based on solar energy. But still, zero-energy configurations show us on a micro scale level what could be achieved on a macro scale level as well.

CONCLUSIONS

The zero-energy concept is feasible for Dutch low-rise houses. Energy for space heating, warm tapwater, cooking, lighting and electrical appliances can be provided by rooftop solar thermal and solar electric systems, assuming that exchange of electricity with the grid is possible.

Application of the concept requires substantial end-use efficiency improvement. The most important end-use is heat demand for space heating. Heavy conventional insulation and passive solar concepts can reduce this heat demand substantially. More advanced vacuum insulation techniques may reduce heat demand to even lower levels. Compressor cooling can be prevented by applying blinds and direct cooling ventilation. Improved efficiency in lighting and electrical appliances is a second important development.

Several zero-energy configurations are conceivable. All configurations considered here rely on photovoltaic electricity production for cooking, lighting and electrical appliances. Configurations differ in the way the solar resource is used to supply heat for space heating and warm tapwater: either by solar collectors in combination with seasonal heat storage or by additional photovoltaic cells and an electrical heat pump. Configurations with an electrical heat pump for space heating have the disadvantage of more exchange with the electricity grid but require less total roof area, do not require a block heating system, and seem to be less costly.

Using 'present best' techniques, all zero-energy configurations require a building design adapted to make extra roof area available for solar systems. Also the systems are not cost-effective now or in the near future. The same configurations, but using more advanced techniques, require less roof area and can be expected to become cost-effective in the next century.

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Table 1: Design features for the three space heating demand options.

	reference	present best	advanced
R_c for walls/roof/ground floor ([m^2.K]/W)	3.0	4.0	10.9
k-value windows (W/[m^2.K])	3.0	1.4	0.37
R_c for TIM south wall ([m^2.K]/W)	-	-	5.9
average heat gain for TIM south wall (-)	-	-	0.65
window percentage south wall (%)	35%	70%	35%
TIM percentage south wall (%)	-	-	65%
building mass inside insulation (MJ/K)	80	110	110
efficiency heat recovery (%)	-	.7	.7
DCV ventilation rate (air changes per hour)	3	7	3

Table 2: Design features for heat supply systems with solar collectors and electrical heat pumps.

	present best	advanced
heat pump system:		
COP at condenser temperature 35°C/60°C	4.0/3.0	5.0/4.0
capacity (W) [a]	300	200
temperature drop over condenser (°C)	30	40
switch off inlet temperature (°C)	35	30
storage tank volume (m^3)	360	240
solar thermal supply system:		
$F_R(\tau\alpha)$ collector	0.75	0.74
F_RU_L collector	3.0	1.43
collector outlet temperature (°C)	70	70
LTTS (aquifer) efficiency (%)	70	70

[a] Capacity depends on COP: the maximum extractable heat from the ventilation air is 600 W.

Table 3: Energy end-use for new low-rise houses in the Netherlands.

	reference	present best	advanced
heat demand (GJ/yr):			
space heating	24.5	8.0	2.4
warm tapwater	10.8	10.8	10.8
total	35.3	18.8	13.2
electricity demand (kWh/yr):			
ventilators/pumps in heating/ventilation installations [a]	310	310	180
cooking [b]	570	570	400
lighting [c]	510	200	110
food cooling/freezing [d]	430	340	100
clothes washing/drying [d]	440	350	150
audio/video/communication [e]	380	300	300
miscellaneous [e]	490	390	300
total	3130	2460	1540
investment costs of heat and electricity demand reduction (Dfl)		5000 [f]	7000 [g]

[a] Figures from (Geuzendam and Gilijamse, 1994), advanced is based on a balanced ventilation system.

[b] Assuming all electric cooking. Figures for present consumption are from (van Maanen, 1994), advanced is based on an estimated 30% reduction (Geuzendam and Gilijamse, 1994).

[c] The figure for present consumption is from (van Maanen, 1994). The 'present best' level assumes 80% of present incandescent lighting replaced by compact fluorescent lamps (CFL's). The advanced level is based on future improvements of CFL's (Geuzendam and Gilijamse, 1994).

[d] The figures for present consumption are for new appliances, assuming a 50% penetration rate for freezers and a 15% penetration rate for clothes dryers (van Maanen, 1994). The 'present best' level is assumed to be 20% more efficient. The advanced consumption level is based on 100% penetration of freezers and clothes dryers, and consumption data from (Geuzendam and Gilijamse, 1994).

[e] Figures for present consumption are from (van Maanen, 1994). The 'present best' level is assumed to be 20% more efficient. Future efficiency improvements in audio/video/communication appliances are assumed to be offset by extending demands. In the category miscellaneous, advances in the efficiency of electric motors are assumed to offer additional reductions.

[f] Cost estimate based on the following specific extra costs: additional insulation 10 Dfl/m^2; LE glazing 60 Dfl/m^2; balanced ventilation system with heat recovery Dfl 1600; CFL's Dfl 500; appliances Dfl 1000.

[g] Cost estimate based on the following specific extra costs (Geuzendam and Gilijamse, 1994): additional insulation 0 Dfl/m^2; vacuum aerogel windows 150 Dfl/m^2; TIM wall 100 Dfl/m^2; heat recovery, lighting and appliances: as for present best level.

Table 4: Zero-energy supply configurations.

	present best	advanced
zero-energy configuration 1:		
solar collector area (m^2)	19	11
PV area (m^2)	21	13
energy supply totals:		
solar collector production (GJ/yr)	28.8	20.8
PV production (kWh/yr)	2460	1540
heat storage and distribution losses (GJ/yr)	10.0	7.6
investment costs (Dfl) [a]	23,000	9,000
zero-energy configuration 2:		
PV area (m^2)	36	21
energy supply totals:		
PV production (kWh/yr)	4320	2490
heat pump plus back-up production (GJ/yr)	20.6	14.8
heat pump plus back-up consumption (kWh/yr)	1860	950
heat storage losses (GJ/yr)	1.8	1.6
investment costs (Dfl) [a]	24,000	6,000
zero-energy configuration 3:		
solar collector area (m^2)	4	4
PV area (m^2)	33	18
energy supply totals:		
solar collector production (GJ/yr)	5.0	6.2
PV production (kWh/yr)	3940	2120
heat pump plus back-up production (GJ/yr)	15.6	8.6
heat pump plus back-up consumption (kWh/yr)	1480	580
heat storage losses (GJ/yr)	1.8	1.6
investment costs (Dfl) [a]	24,000	6,000

[a] Cost estimates based on ('present best' resp. 'advanced'): solar collectors 400 Dfl/m^2 resp. 240 Dfl/m^2 (van Wees et al, 1994); PV modules 590 Dfl/m^2 resp. 250 Dfl/m^2 (Kelly, 1993); heat distribution Dfl 3000/house (van Wees et al, 1993); aquifer storage 25 Dfl/GJ resp. 20 Dfl/GJ (van Wees et al, 1993); electrical heat pump, additional costs over natural gas boiler Dfl 2500 resp. Dfl 1000 (van Wees et al, 1993).