Article

Insulation or Smart Temperature Control for Domestic Heating: A Combined Analysis of the Costs, the Eco-Costs, the Customer Perceived Value, and the Rebound Effect of Energy Saving

Arno E. Scheepens [1,2,*] **and Joost G. Vogtländer** [1]

[1] Faculty Industrial Design Engineering, Design for Sustainability, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands; j.g.vogtlander@tudelft.nl

[2] Ernst & Young, Climate Change and Sustainability Services, Boompjes 258, 3011 XZ Rotterdam, The Netherlands

[*] Correspondence: a.e.scheepens@tudelft.nl

Abstract: Calculating the environmental benefits of energy saving systems in dwellings in a life cycle assessment (LCA) has two major issues, namely: how to deal with the customer behaviour and how to deal with rebound effects. Both issues are important for sustainable strategies. From a user-centred design perspective, two fundamentally different strategies are observed, namely: a 'passive' end-user, who invests in insulating the building and maintaining their preferred behaviour routines, versus an 'active' end-user; who must change his or her behaviour in order to save energy. A combined analysis of cost, (market) value, and eco-burden is used to compare and evaluate the two strategies; by applying the methods of eco-costs/value ratio (EVR) and eco-efficient value creation. Simulation software is applied to calculate the results for the active end-user approach (by means of home energy management systems [HEMS]). The energy savings for a passive user approach (applying thermal insulation) are calculated with straightforward heat loss calculations. The rebound effect of energy savings is taken into consideration. From the environmental point of view, the optimal insulation thickness is calculated, by comparing the energy savings with the environmental burden of the insulation materials. This analysis shows that HEMS are effective for poorly insulated houses, but not for well insulated houses. Governmental policies that focus only on insulation, however, lack the urgency of greenhouse gas reduction; the HEMS for existing houses is an indispensable tool for a fast transition to less domestic energy consumption.

Keywords: energy; savings; value; costs; eco-costs; heating; LCA; EVR; eco-efficiency; rebound

1. Introduction

1.1. Insulation or HEMS?

An important step towards a more sustainable society is the reduction of domestic energy use. A major strategy to achieve this reduction is to increase energy efficiency. As is the case with most energy efficiency challenges, residential heating energy savings can be achieved through multiple solutions, such as, in this case, thermal insulation or home energy management systems (HEMS). However, there is often a discrepancy with the potential and actual energy savings achieved through the application of such solutions [1,2], partly because of backslide effects (see Section 1.2.2), and there is a risk of long-term unsustainability through the rebound effects. Besides the physical characteristics of the buildings, the optimal combination of solutions depends to a large extent on user behaviour and the

potential rebound effects on the long term. Hence, decision makers in these processes (home-owners, builders, architects, and policy makers) need to balance many different variables from multiple perspectives, as has been it has elaborated upon in the following sections.

To reduce the complexity of the aforementioned issues, the analyses of this paper are focussed on the following: (a) the energy conservation effects of HEMS and the related consumer behaviour in a free standing two story house with three bedrooms, and (b) the effects of enhanced wall insulation of the outer walls.

The corresponding research questions are as follows: (1) Is a HEMS system an efficient and effective solution for energy savings, and if so under which conditions? (2) Is there an optimum insulation thickness of the outer walls, and if so, what is the optimum for each type of insulation material? (3) What are the implications of combining a high level of thermal insulation with a HEMS system?

To get an answer to the research questions, an integral approach is needed of the system costs, eco-costs, and customer perceived value. The existing model of the eco-costs/value ratio (EVR) and the model of the eco-efficient value creation provides such an integral approach, and is therefore used to tackle the research questions. These two models are explained in Section 2.2.

This paper deals with the research questions on a quite high aggregation level, so neither details on the heating or cooling systems, as such, nor the architectural construction details are dealt with. Only the insulation characteristics of certain insulation materials are part of the study, as they determine the rebound effects.

In Section 1.2 of this paper, a literature review is given, showing the existing knowledge and knowledge gaps. Section 2 provides general information on the two methods that have been used, namely: the simulation model for HEMS (HAMBASE) in Section 2.1, and the EVR and eco-efficient value creation in Section 2.2. The results are given in Section 3, with the simulation of HEMS in HAMBASE and its consequences in the EVR model in Section 3.1, optimisations in insulation thickness for different insulation materials in Section 3.2, and a combination of insulation and HEMS in Section 3.3. Discussions, conclusions, and acknowledgements are given in Sections 4 and 5.

1.2. General Literature

1.2.1. Improving Insulation

A well-known passive end-user strategy for domestic energy savings is the improvement of the insulation quality of the house. As a result, significant energy savings (meaning the reduction of energy costs and associated environmental impacts) can be achieved (without the need for an 'active' behaviour change from the end-users).

In the European Union (EU), the EU Directive 2010/31 [3] requires that the member states shall set energy performance requirements with regards to the building envelope, either new or under refurbishment, "with a view on achieving cost-optimal levels". (e.g., in the Netherlands, such a cost-optimal level for new residential buildings is currently determined as Rc = 5). Over the last two decades, there has been an increase in research attention for residential heating energy savings, especially with regards to the insulation of dwellings. Research efforts [4,5] are often aimed at answering the question of whether or not improved insulation is an economically viable strategy, commonly executed using, amongst others, life-cycle costing, net present value, internal rate of return, payback methods, and cost-benefit analyses. Life cycle assessment (LCA) studies are mainly aimed at investigating the additional environmental impacts of the insulation, compared to the environmental benefits of decreasing energy use [6–11].

1.2.2. HEMS in Relation to User Behaviour

On the other end of the dyad, another, more recent strategy is to 'empower' end-users to conserve energy, through mechanisms such as awareness rom the feedback on energy use, environmental

impacts and costs [12], advice [13], and social gaming [14]. These product–service systems are generically defined as home energy management systems (HEMS). These usually include 'smart products', sensor networks, and software applications on a (handheld or wall mounted) interface products, and are almost exclusively Information and Communication Technology (ICT)-based. As a result of implementing such a strategy, the end-users should change their behaviour towards lowering and matching their energy-use in order to optimize the utilization of the grid [15]. HEMS are considered as one of the means to change the behaviour of residents.

The most common thermal HEMS are smart thermostats, which require user input to manage the heating system. Usually, the house is equipped with one thermostat controlling the system and therewith the perceived thermal comfort. As consumer perception of thermal comfort is the subject of multiple variables, people tend to have different comfortable temperatures for different areas within the house, at different times [16,17]. This presents a logical further innovation opportunity for thermal HEMS, with regard to energy saving, as it could be programmed and equipped to 'switch off' certain areas within the house when not in use (e.g., bedrooms during the day), or not requiring a high temperature (e.g., the toilet or storage areas). This zoning control HEMS is researched in this paper by including four different scenarios for HEMS control over the heating system.

Research often indicates that if residents are to accept minor losses in thermal comfort, there would be a large potential in energy savings (e.g., [18]). However, important longitudinal research [19] on the consumer use of HEMS products concludes that behavioural changes achieve quite significant energy savings in the first period of use (around 8%), which, on the medium–long term, are not sustained (see Figure 1). In other words, there appears to be a 'behavioural backslide effect': Even the enthusiastic groups that initially achieved energy savings of over 16%, showed a significant decrease in energy savings over a relatively short period of time of 11 months [20].
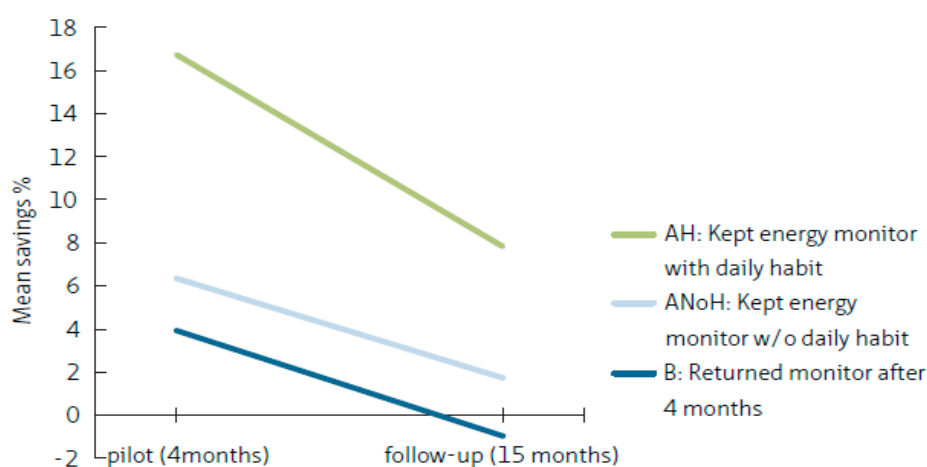

Figure 1. The decrease in achieved energy savings as a result of home energy management systems (HEMS) implementation [20].

Other studies around thermal energy also indicate that initially, quite significant energy savings are likely to be achievable through altering user behaviour, however, over time, only small energy savings are obtainable [17,21,22], due to, for example, a decline in interest.

Within the context of thermal comfort in dwellings, many solutions that are currently available in the market can be defined as product–service systems (PSS). In order to enable the determination of the optimal energy saving solutions, an integrated approach for the design of such PSS and their business models is required, which includes their (long-term) effects on user behaviour and the avoidance of backslide effects, putting the user at the centre of the analysis.

1.2.3. Customer Perceived Value of Thermal Comfort

The general solution developed to cope with the multiple variables influencing perceived thermal comfort is the adaptive heating energy system, which gives users control over the set-point temperature at which they feel comfortable in different states of outdoor temperature, activity, clothing, et cetera.

An interesting study on the relationship between customer perceived value and energy saving measures concerns the consumer willingness to pay (WTP) for passive energy saving measures, such as insulation [23]. Rather than considering the economic and environmental pay-back time (cost-benefit) only, this study shows that consumers also consider other values of insulation, such as high thermal comfort and noise protection. The increased WTP for such measures increases the potential for future market share. Hence, it is concluded that an insulation strategy has the potential for achieving extra customer perceived value.

It is clear that many different variables influence energy saving behaviour [24]. These include costs and environmental impacts, but also customer perceived value. This customer perceived value is defined as all of the factors contributing to the perception of consumers, such as thermal comfort, noise reduction, as well as image and other social values. Most importantly, it is unlikely that consumers are willing to accept a lower customer perceived value. Within the context of domestic energy use, this behaviour is underlined in the studies (such as [25]), where it has been demonstrated that consumers are willing to save energy, wherever it does not compromise convenience. Hence, in order to design systems for domestic thermal energy savings, the customer perceived value has to be taken into account as an important variable. The method of the EVR is well-equipped to do so, as will be set out in Section 2.2.

1.2.4. The Rebound Effect

An important aspect of consumer behaviour within the context of energy use is the rebound effect, first described in relation to the efficiency of coal machinery by Jevons [26]. The rebound effect is described as the expected increase in the consumption of energy, following energy-efficiency improvements. It explains the measured differences between real-life and calculated energy savings. The rebound-effect (also take-back effect) have been widely acknowledged, however, the extent to which they actually take place continues to be the subject of studies and discussions in energy-economics literature [27–30].

In general, three different types of the rebound-effect are distinguished, namely:

a.　The direct rebound effect. The direct rebound effect is the spending of saved money from energy efficiency on the increase of energy use in other (or even the same) applications. An example is the tendency that people have to place more lights in their homes and gardens, when the lamps achieve a better efficiency. More on the subject of direct rebound in households can be found in the literature [31–33].

b.　The indirect rebound effect. The indirect rebound effect is described as the spending of saved money from energy efficiency on other offerings than energy, with their own respective environmental impacts [34]. As an example, one can think of people spending the saved money on flight tickets.

c.　The economy-wide rebound effect. This type of rebound differs from the previous types, by the idea that energy savings on a product level by technical innovation could lead to a sharp increase in the sales of that product, resulting in an increase of energy use by the sum of all of the products. This is the most discussed rebound effect, also referred to as the 'Jevons Paradox' [35,36]. Although it is the essence of the case of Jevons (1866), it is hard to prove in reality [30]. However, when, for instance, the driving of cars would become extremely energy efficient (and cheap), it would trigger that more people would buy a car. This could lead to the extra use of energy on a national or global scale.

For insulation improvements, any form of direct rebound (type a) is expected to be low, as consumers are not likely to 'superheat' their homes. Therefore, the main issue in this paper is the indirect rebound (type b). This rebound only starts when there are net savings (i.e., the savings in energy are more than the investment in extra insulation), which will be explained in the next section. The economy-wide rebound (type c) is unlikely to occur, as most residences in the Western world are already equipped with a heating system.

1.2.5. Environmental Impacts over the Full Life-Cycle

Where the insulation of a house reduces the use of heating energy, the insulation, as such, adds to the environmental impacts of the building itself. The added environmental impacts through the increased use of insulation materials (often plastics), requires a significant amount of extra energy savings in order to generate lower environmental impacts over the full life-cycle of the house. The production of HEMS equipment has environmental impacts as well. The obvious advantage of HEMS is that it is relatively easy to install in existing houses, as opposed to insulation.

The environmental data, which have been used in the calculations, are from the Ecoinvent and Idemat LCI databases. The calculations have been made by means of Simapro software. Apart from the CO_2 emissions of the house, all of the data are from so called background processes. More information on the background systems and their boundary limits (from cradle-to-gate, gate-to-gate-and gate-to-grave, and grave-to-cradle) can be found at www.ecocostsvalue.com and www.ecoinvent.com (both assessed in August 2018)

1.2.6. The Combined Approach of Costs and Eco-Burden

Figure 2 depicts an analysis of an energy conservation system, where the costs (x-axis) and the eco-burden (y-axis) of a life cycle are combined. The base case is an energy consumption line that ends up in point A, for the case that there is neither extra insulation nor a HEMS system. Then, an investment is made, and the effect on eco-costs and value (price) is shown by lines A–B (this is the 'production phase' in LCA). Note that the slope of the investment line is much lower than the slope of the energy consumption line.
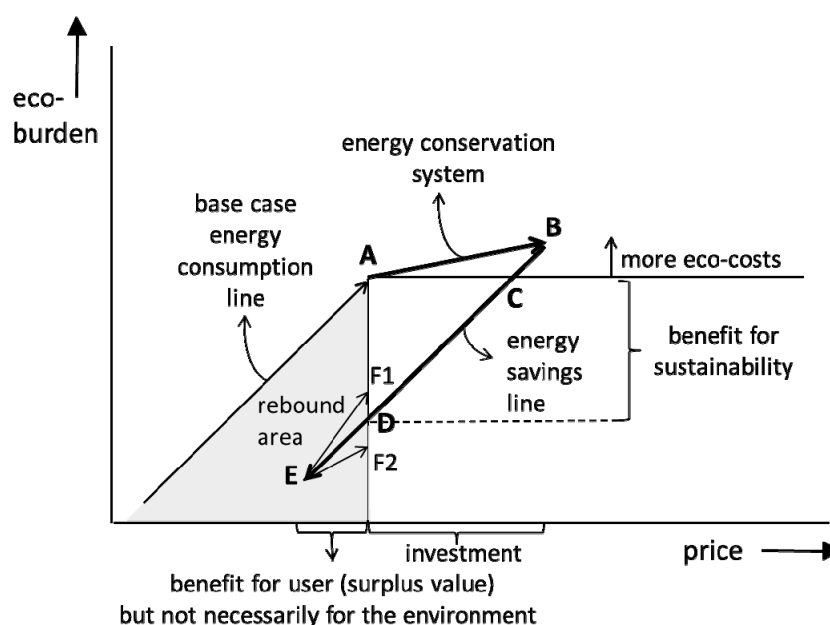

Figure 2. A combined analysis of price and eco-burden of an energy conservation system [37].

The energy savings are depicted by lines B–E (this is the 'use phase' of the LCA), which is in parallel to the 'base case energy consumption line'. This line crosses the 'more eco-costs' lines at

point C, which is likely to happen in practice. Point D is the pay-back point of the investment, with a corresponding reduction in the eco-burden from point A to point D. Then, however, the 'energy savings line' enters the 'rebound area'. From point D to E, the owner has a financial benefit (i.e., the owner is saving more money than the investment). That money, however, is likely to be spent on something else [38,39], such as travel, investment in the house, et cetera, which causes a rebound (lines E–F1 for travelling, and lines E–F2 for the renovation or refurbishing a house). The slope of the line for, for example, diesel, is higher than the slope of the energy savings line, causing a severe rebound effect. The slope of the line for renovation and refurbishing is lower than the line of the energy savings, resulting in a small rebound effect. Such a calculation differs for each country, as the (energy) tax level varies from country to country, the climate conditions are different, and the source of the energy may vary as well. The rebound depends also from case to case, but it is safe to assume that the average rebound effect is 100% on eco-costs. That means that lines D–E are a benefit for the user (the user saves money that will be spent on something that the user prefers), but is not a benefit for the environment. In practice, that means that only the first few years (the pay-out period) have a positive impact on the environment; long economic pay-out times eliminate the risk of short-term rebound effects. In practice, consumers will accept long pay-out times as long as they expect extra comfort and convenience.

2. Materials and Methods

To analyse the net efficiency of the two domestic heating energy conservation systems (i.e., HEMS and thermal insulation), two methods are applied, namely:

1.　The HAMBASE computer simulation software to analyse the effect of variable room temperatures on energy savings in combination with comfort.
2.　The method of the eco-costs/value ratio (EVR) for the combined analysis of costs, customer perceived value, and eco-costs (a monetised single indicator for LCA, based on the marginal prevention costs of eco-burden).

The calculations on the effect on energy savings resulting from extra insulation are based on the reduction of the thermal resistance (the R-value) of the walls, floors, and roofs. For clarity and simplicity, the influences of heat losses via construction elements are kept outside the system boundaries of the calculations.

2.1. HAMBASE

In order to explore the net efficiency of the zoning control strategy, a typical residence, see Figure 3, is simulated in HAMBASE modelling software [40], and is subjected to different heating system control strategies. The main objective is to obtain an idea of the relative magnitudes of energy savings and thermal comfort when applying a zoning control strategy: answering the question to what extent zoning control achieves energy savings combined with comfort.

The HAMBASE modelling software has been selected because it allows for the modelling of buildings, zoning strategies, and climate conditions for calculating energy consumption as well as the predicted mean vote (PMV) and predictive percentage dissatisfied (PPD) from the Fanger Model for thermal comfort. This allows for a comparison between energy consumption in MJ and the modelled average customer perceived value in terms of the average score for thermal comfort (PMV) as well as the percentage of residents experiencing thermal discomfort (PPD).

The following four different scenarios have been simulated:

(1)　Single thermostat, continuous temperature setting of 21 °C (representing the worst-case scenario).
(2)　Single thermostat, day temperature setting of 21 °C, night set-back temperature of 15.5 °C.
(3)　One thermostat per floor (2), day temperature setting of 21 °C, zoning (only heating when floor is occupied), day and night set-back temperature of 15.5 °C.

(4)　One thermostat per room, day temperature setting of 21 °C, zoning (only heating when room is occupied), day and night set-back temperature of 15.5 °C (representing the hypothetically optimal scenario).

The zoning strategy is based on the following division of different types of rooms in a typical residential building: Zone 1—living room and Kitchen; Zone 2—office/study; Zone 3—bedrooms; Zone 4—bathroom; Zone 5—entrance and hallways; and Zone 6—storage and toilets.

In each scenario, the energy demand for the radiators and the floor-heating systems are calculated. Further details regarding the HAMBASE simulation can be found in Appendix A (the simulation of scenarios for building energy use). Also, in the Appendix A, the modelling scenario for the simulation of a typical Dutch apartment can be found.
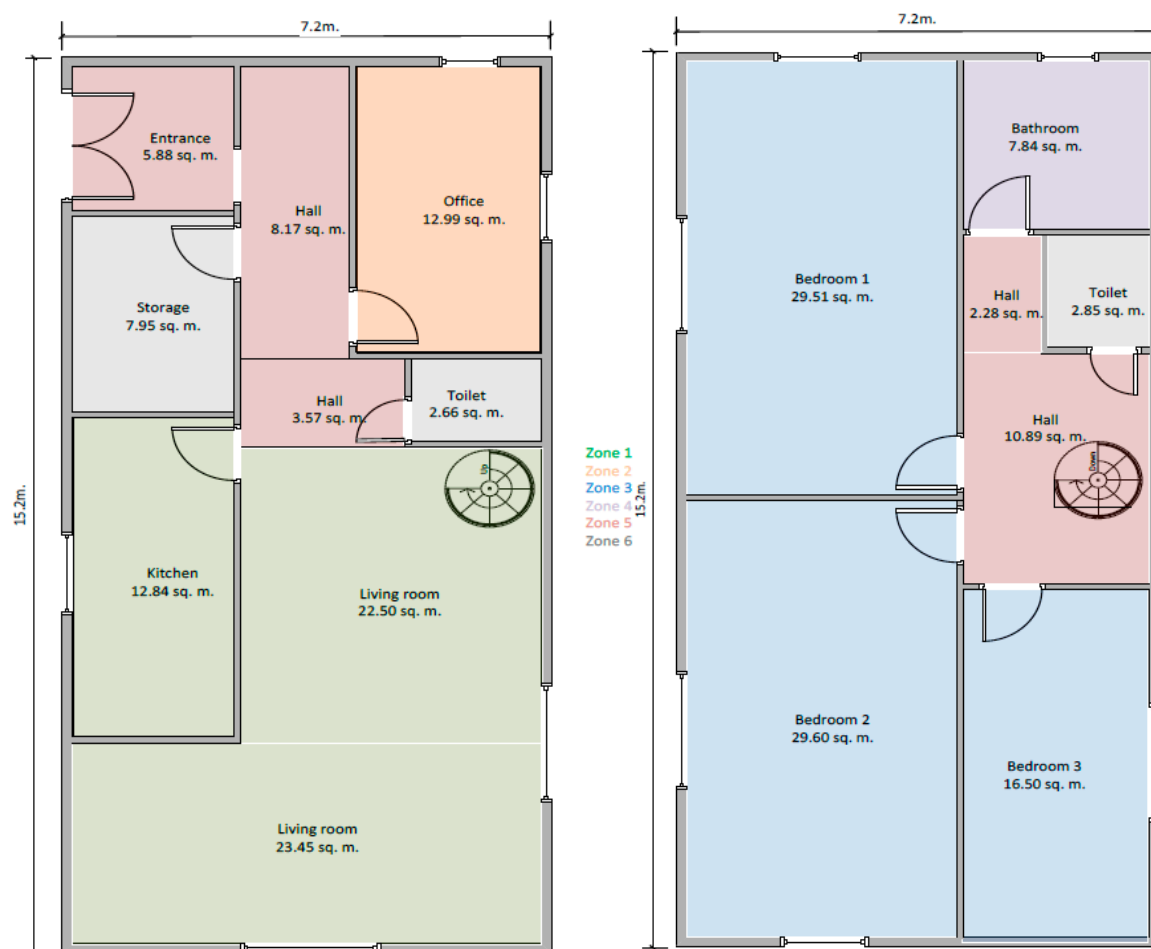

Figure 3. Blueprint of the free standing two story house, modelled in the simulation model for home energy management systems (HEMS) (HAMBASE).

2.2. The EVR and Eco-Efficient Value Creation

The method of the eco-costs/value ratio (EVR) is a combined analysis of the costs, the (market) value, and the eco-costs of a product or product service system. It is LCA based, and is developed for eco-efficient value creation in (product-, service-, and product–service-system) design and innovation. It resolves a basic shortcoming of the LCA benchmarking of two (or more) product or services; LCA benchmarking requires that the products or services in the comparative study have the same functionality and quality (tangible as well as intangible). In innovation, this is never the case, as innovations add either functionality or quality to the benchmark, otherwise the innovation does not make sense. Keeping costs, market value, and eco-costs strictly separate in the analysis has the advantage that the aspects of the production costs and market value are not ignored in the

decision-making process for achieving better environmental sustainability. The system can also be applied to analyse and develop business solutions in the circular economy (e.g., cradle-to-cradle systems) [37,41].

Eco-costs are a so-called 'single indicator' in LCA. It is a measure to express the amount of environmental burden of a product on the basis of the prevention of that burden; the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level that is in line with the carrying capacity of our earth (the 'no effect level'). The eco-costs should be regarded as hidden obligations, also called 'external costs' in environmental economics.

The eco-costs have been introduced in the Journal of Cleaner Production [42] and in the International Journal of LCA [43], and have been updated in 2007, 2012, and 2017 (see, for a short description, http://en.wikipedia.org/wiki/Eco-costs, accessed August 2018).

The market value equals the price in this EVR analysis for existing products. When a product or service is not yet available on the market, the value equals the willingness to pay (WTP). The costs are defined in the model as the production costs (or life cycle costs), and must not be confused with the price (which is the costs for the consumer). In this paper, the price is used to conduct the analysis, as the focus is on the costs of the consumer. With regard to the value, we have to zoom in to the level of the consumer, revealing a more complex issue, the perception of the individual buyer, see Figure 4. For definitions, see Table 1.
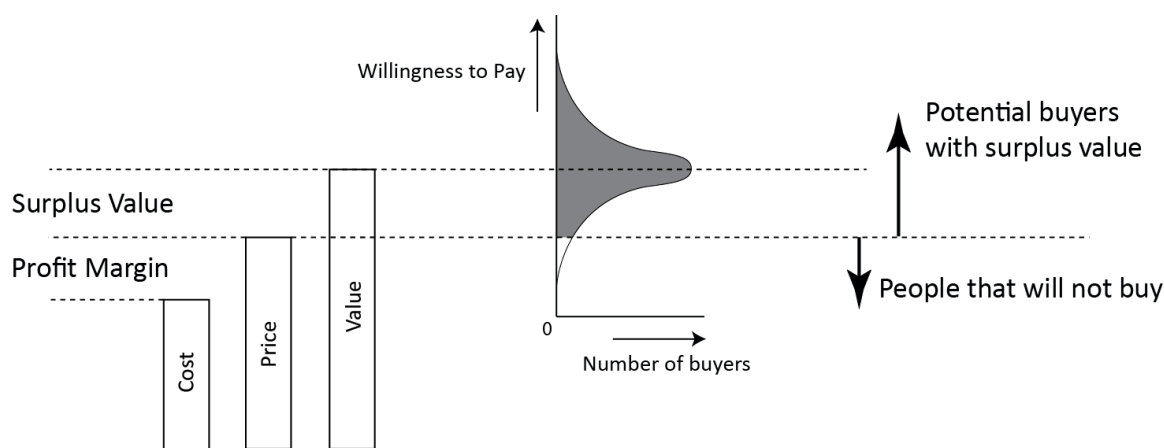

Figure 4. The relation between the costs of production, the price at point of sale, and the customer perceived value of a successful offering. Only buyers that perceive surplus value will consider buying the offering [37].

Table 1. A summary of important concepts used in this paper.

EVR	The eco-costs/value ratio
Eco-costs	A prevention based single indicator for environmental impacts (€)
Value	The sum of the perceived product- and service-quality, and the image (€)
Price	The price at which these offerings are sold in the current market (€)
WTP	Willingness to pay (€)
Customer Perceived Value	The expected use and fun of a product and/or service after the purchase (€)
Surplus Value	The difference between the price and the customer perceived value (€)
Eco-efficient Value Creation	The overall aim of application of the EVR Model (the double objective)
Double Objective	Lowering of the eco-burden of a product and/or service and at the same time enhancing the value

In Figure 4, the difference between the costs and the price is the profit margin for the seller, and the difference between the price and the (customer perceived) value constitutes the 'surplus value'. The higher the surplus value, the more desirable the offering is.

The eco-costs/value ratio (EVR) is basically an indicator of the sustainable buying behaviour of consumers. It is also related to the rebound effect, as depicted in Figure 2.

As most people are inclined to almost spend in their life all of what they earn, the ratio of eco-burden per euro spent is an important indicator for sustainability. It matters what people buy, for example, do they spend their money on diesel or on their health. The EVR of products in the EU are provided in the literature [44] (in the eco-costs tables; accessed in 2017). The current average EVR is 0.4 in the EU, so we should aim at a considerable reduction of the EVR, say less than 0.04.

An important issue is that manufacturers cannot improve the EVR of their products just by increasing the price. Figure 4 shows that when the price is more than the value, there is no surplus value, and the product will not be bought.

On a product level, this leads to a 'double objective' of the 'eco-efficient value creation' in innovation, namely:

- 　　create lower eco-costs, and at the same time
- 　　create higher value

The higher value enables a higher price, which creates the opportunity to pay the extra costs that are required to lower the eco-costs.

Recent papers [45–47] show how such a double objective can be achieved in product design. The consequences for business models in the circular economy are provided in the literature [37,41,48]. Case studies with the consequences for governmental policies are given in the literature [48,49].

3. Results

3.1. The HEMS Strategy in HAMBASE

Table 2 shows the findings of the application of the HAMBASE model for the two-story house as well as the four scenarios, as described in Section 2.1. Insulation is assumed with an R value of two for the outside walls and an R value of five for the roof.

Table 2. Modelled annual heating energy and savings for four different scenarios [50] for a free standing two story house with R = 2 (m^2 K/W) for the outside walls.

	Baseline Case	Single Zone Thermostat Control, Day Distinction and Night Setback		Two Floor Zones Thermostat Control, Day Distinction and Night Setback		Six Room Zones Thermostat Control, Day Distinction and Night Setback	
	Energy Use (GJ)	Energy Use (GJ)	Change Respective to Baseline	Energy Use (GJ)	Change Respective to Baseline	Energy Use (GJ)	Change Respective to Baseline
Radiators	36.15	30.90	−14.5%	28.80	−20.3%	27.61	−23.6%
Floor heating	37.31	31.81	−14.7%	28.77	−22.9%	22.34	−40%

Note: the R value, the heat resistance, (m^2 K/W) is the reciprocal of the U value, the thermal transmittance coefficient (W/m^2 K).

It is clear that, as expected, the energy use is lower for the scenarios where certain zones are not heated during certain periods of time. The best savings are achieved in the third scenario (six room zones), with up to 40% savings of heating energy.

However, in order to fulfil the double objective of the eco-efficient value creation, this should not go hand-in-hand with a lower perceived value, in this case, mainly thermal comfort. As shown in Table 3, the HAMBASE modelling indicates that the double objective is not achieved; the predicted percentage dissatisfied of the users is significantly higher for the individual zones scenario compared to the baseline scenario. The lack of comfort is probably the main reason for the reported evading success of HEMS [21,22,51]. Modern people seem to want maximum comfort when they can afford it.

The data are summarized in the EVR chart of Figure 5. It shows the degree of eco-efficient value creation for the zoning control strategy.
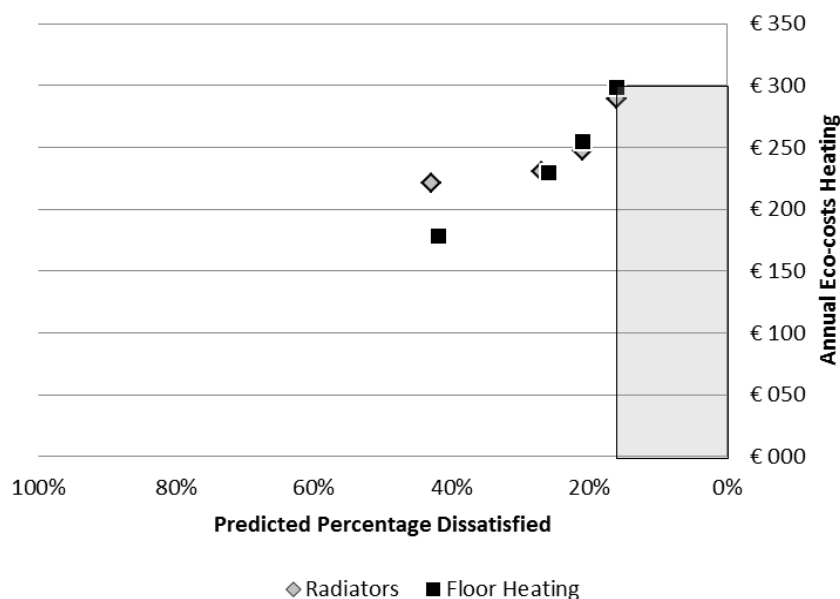
Figure 5. The eco-costs/value ratio (EVR) chart expressed in eco-costs for energy use and the predicted percentage dissatisfied (the grey area represents the target area for eco-efficient value creation).

Table 3. The predicted percentage dissatisfied (PPD) for the four scenarios (two-story free-standing house with radiators) [50].

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Average
Baseline scenario	20%	20%	20%	18%	10%	9%	16%
Single-zone scenario	26%	26%	28%	22%	15%	11%	21%
Two floor-zones scenario	27%	27%	44%	37%	16%	13%	27%
Six zones scenario	29%	34%	45%	45%	55%	52%	43%

The main finding is that quite significant energy savings can be achieved (up to 40%), however, a lower perceived thermal comfort (increased PPD) is unavoidable. This means that the zoning control strategy has little chance of contributing to a transition towards a more sustainable society, because only a very small percentage of consumers are expected to accept lower thermal comfort in their house for the sake of the environment; zoning control is not able to achieve the double-objective of eco-efficient value creation.

Even if the more intelligent thermostats are considered, which are designed to diminish the hassle of programming and adjusting the settings by 'sensing/learning' the user's behaviour, the physical heating system will require a 'heat-up time', resulting in thermal discomfort if the occupants deviate from their usual behaviour. This will eventually lead to users overriding the automatic programming, and decreasing the energy savings.

After a while, only a mild form of temperature setback is applied by users at night and when they are away (e.g., two to max three degrees C lower temperature at periods when people are always at sleep and normally at work). Although many smart thermostats are accompanied by high claims for energy savings, a seemingly more reliable figure is measured by a producer of a popular smart thermostat, who stated that the average savings of 175,000 devices are approximately 5% (https://www.duurzaambedrijfsleven.nl/energie/10903/175000-toon-thermostaten-besparen-5-procent-energie). The potential of 14.5% savings, in Table 1, will not last, because of the fact that the corresponding extra 5% loss of comfort (21–16% of Table 3) is not accepted; the user reverts to a higher setback temperature and a smaller setback time. Independent studies on the heating energy savings of smart thermostats report achieved savings in the range of 3–5% [52,53]. This paper assumes slightly higher achievable energy savings of 6.5%, accounting for future innovations as well as user behaviour.

Thermal HEMS systems can be bought in a price range of approximately €600–800 for systems that can control the six zones, and approximately €160–240 for single zone systems, without installation (both types can be programmed to handle time dependent settings, e.g., night setback). We did not include the fact that many HEMS nowadays also require a monthly subscription fee.

The estimated eco-cost of single zone HEMS is €49 [51] from cradle-to-grave. The eco-costs of a six-zone system is estimated to be €170. The assumption is made that the life span of a central-heating boiler is 15 years, and that the thermostat is replaced then as well (the life span of the automatic valves of the six-zone system is estimated at 30 years). This scenario is depicted in Figure 6.
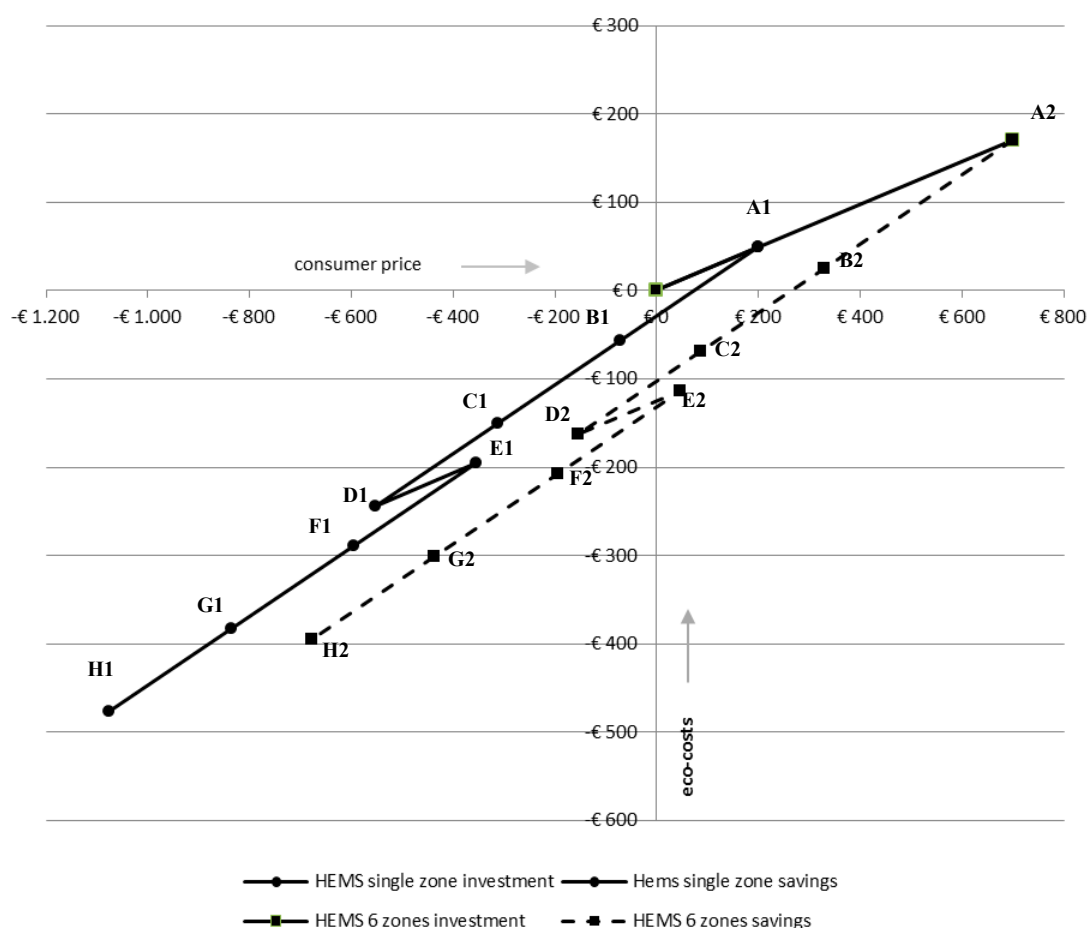

Figure 6. The relation between eco-costs and market price of the HEMS single zone strategy over a period of 30 years, for the two-story house of Figure 3, R = 2 (m^2 K/W) of the outer walls (the lines starting from the origin up to points A1 and A2 represent the eco-costs and consumer prices of single zone and multiple zone HEMS; points A1 and A2 are the start of the use phase; B1 and B2 after 5 years; C1 and C2 after 10 years; D1 and D2 after 15 years; E1 and E2 after replacement of thermostat; F1 and F2 after 20 years; G1 and G2 after 25 years; H1 and H2 after 30 years).

It can be concluded from Figure 6 that the HEMS single zone system scores better than the HEMS six zone system in terms of net price savings, however, the single zone system depends heavily on the rebound effect, as depicted in Figure 4.

The underlying assumption in Figure 6 is the savings line of Figure 7. After the introduction of a single zone HEMS, a percentage of 14.5% can be expected (Table 2, single zone), which is estimated to deteriorate to 6.5%, as described above. In the first weeks there is a steep learning curve, but from the third month on the decay will start. Figure 7 presumes an exponential curve for the learning stage as well as for the decay. The parameters for the decay stage have been chosen so that the curve approaches the measurements [20] previously discussed in Figure 1, namely:

S = a + b × EXP [−(t − 3)/5], for t > 3, where S is the percentage savings, and t = time in month.

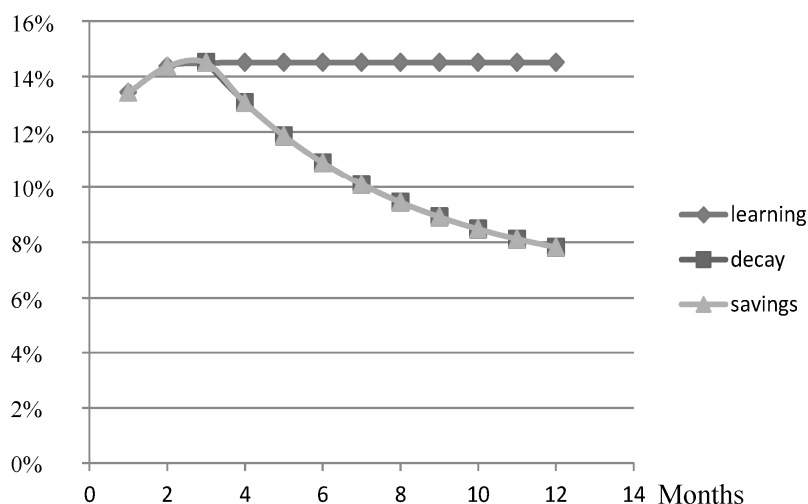For the single zone Hambase simulation a = 6.5% and b is 8%, which is depicted in the savings line of Figure 7.

Figure 7. The percentage of energy savings as a function of time, applied to the calculations of the HEMS single zone strategy.

3.2. The Insulation Strategy

Insulation is an energy conservation strategy that does not compromise thermal comfort, therefore, it has the potential of fulfilling the double objective of eco-efficient value creation, as mentioned in Section 2.2. On top of that, insulation has the potential for surplus value, as discussed in Section 1.2.3.

To find the maximum potential cost savings, as well as savings in the eco-costs, calculations have been made on the reduced heat flux per year through a 1 m^2 wall, as a function of the heat resistance of the insulation slab (m^2·K/W), the so-called R value. The calculations are based on 3000 heating degree days per annum (which applies to domestic heating in, e.g., the Netherlands, Belgium, the United Kingdom, Denmark, Germany, and the cities of New York and Vancouver).

The base case is R = 2, which refers to a reasonably well insulated house (insulation slab thickness of 7 cm for stone wool, approximately 8 cm for expanded polystyrene [EPS], and 4.4 cm for polyisocyanurate [PIR]). The consequences of thicker insulation slabs have been determined up to R = 8 (approximately 28 cm for stone wool, approximately 31 cm for EPS, and 18 cm for PIR).

Consumer prices in 2015 were taken from www.rockwool.nl for stone wool, from www.isobouw.nl for EPS, and from www.dakconcept.com for PIR (all accessed August 2015).

Figure 8 depicts the eco-costs versus the consumer price of stone wool for four cases of increased heat resistance. This graph has the same structure as Figure 2. The investment is depicted by the line, which starts in the origin, and goes up to eco-costs of approximately €2.73/m^2, corresponding with a price of €23.72/m^2 for R = 8 (when the added R value is added, the price and the eco-costs increase). The savings are the lines that go down. The savings in price and eco-costs are related to the reduction of natural gas for heating for a total period of 30 years (six steps over five years).
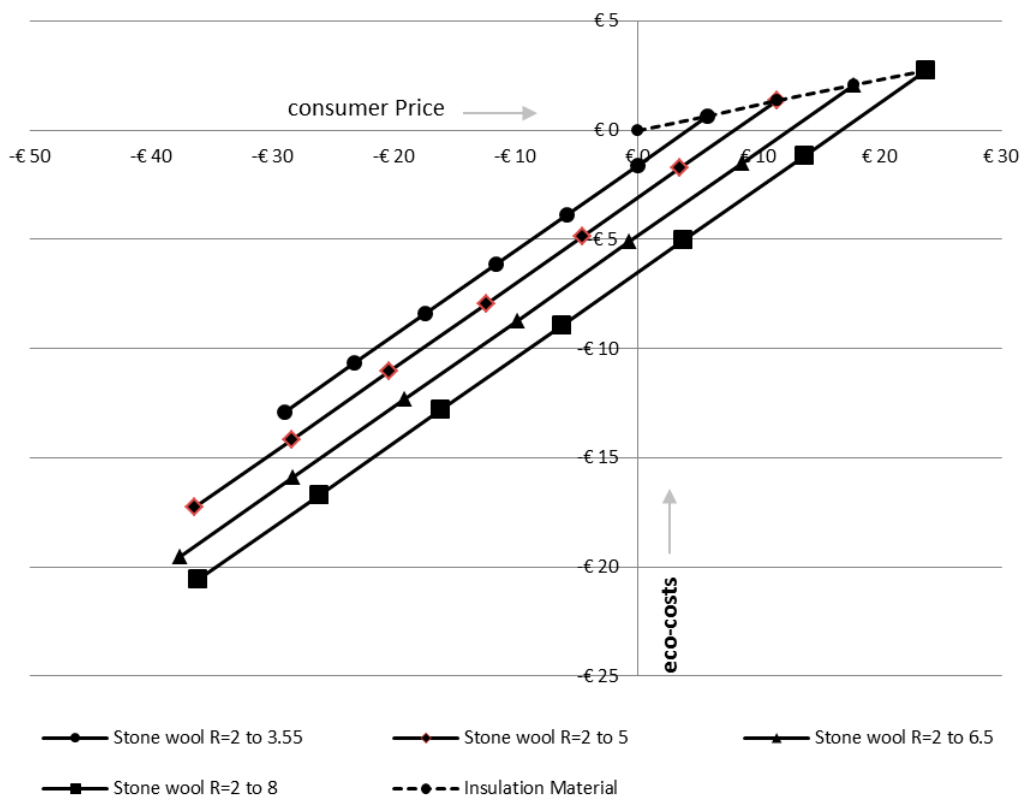
Figure 8. The eco-costs and the consumer price for the additional insulation of stone wool (increase of R from 2 to 3.55, 5, 6.5, and 8, respectively) for a wall of 1 m^2 over a period of 30 years.

A remarkable conclusion is that, over a period of 30 years, the differences in net price savings of R = 2 to R = 5, R = 2 to R = 6.5, and R = 2 to R = 8 are rather low, however, higher R values relate to lower eco-costs.

Note that two segments of the savings line have to be distinguished, the lines at the right of the y-axis (consumer price $\geq$ 0), and the lines at the left of the y-axis (consumer price $\leq$ 0). The savings at the left of the y-axis will have a rebound (as explained in Section 2.2). At the point of the pay-back time (consumer price = 0 at 5–12 years), there are already remarkable reductions in eco-costs (at the right of the y-axis), especially for high insulation values.

These LCA calculations (for the insulation slabs cradle-to-gate) have been done for other single indicators as well, namely, the carbon footprint (kg CO_2 equivalent) and ReCiPe H/A Europe (mPt). Although the indicators are different, the graphs for the stone wool show the same pattern. Table 4 shows the main results on the extra eco-burden of the production, and the reduction of eco-burden in the use phase. Table 4 also shows the results for expanded polystyrene (EPS) and polyisocyanurate (PIR), which are quite similar to the results for stone wool. Table 4 shows that stone wool is the best solution in terms of eco-costs (environmental savings), and that PIR scores better in terms of price (cost savings). This result is also depicted in Figure 9.

The results for the PIR insulation are quite remarkable; as the eco-costs/price slope of PIR is similar to the eco-costs/price slope of natural gas, there is, at the pay-out time point, no savings in eco-costs, see Figure 9. That means that PIR insulation does not have an inherent environmental benefit (see point C and D in Figure 2, Section 1.2). Therefore, the environmental benefits of PIR solely depend on the customer behaviour with regard to the rebound effect (i.e., when the savings are spent on products with a low EVR, like diesel for driving, the overall environmental benefit of this type of insulation is negative).

Table 4. The costs, eco-costs, carbon footprint, and ReCiPe data for insulation improvements for stone wool, EPS, and PIR (R = 2 to R = 5).

| Insulation from R = 2 to R = 5 for 1 m² Outer Wall	Price and Eco-Burden of Investment (a)	Pay-Back Time (Year) (b)	Net Savings over 30 Years (c)	Gain Eco-Burden Divided by Price Investment (d)
Stone wool		7		
price (per m²)	€11.50		−€36.41	
eco-costs (per m²)	€1.36		−€17.28	−1.50 (euro/euro)
carbon footprint (per m²)	4.83 kg CO_2e		−129.48 kg CO_2e	−11.26 (kg CO_2/euro)
ReCipe points (H/A Europe)	0.47 mPt		−5.92 mPt	−0.51 (mPt/euro)
EPS (expanded polystyrene)		9		
price (per m²)	€14.21		−€33.47	
eco-costs (per m²)	€2.40		−€16.16	−1.08 (euro/euro)
carbon footprint (per m²)	5.75 kg CO_2e		−126.22 kg CO_2e	−8.46 (kg CO_2/euro)
ReCipe points (H/A Europe) per m²	0.63 mPt		−5.60 mPt	−0.38 (mPt/euro)
PIR (Polyisocyanurate)		6		
price (per m²)	€9.89		−€39.25	
eco-costs (per m²)	€3.61		−€15.51	−1.57 (euro/euro)
carbon footprint (per m²)	8.77 kg CO_2e		−127.25 kg CO_2e	−12.87 (kg CO_2/euro)
ReCipe points (H/A Europe) per m²	0.89 mPt		−5.53 mPt	−0.56 (mPt/euro)
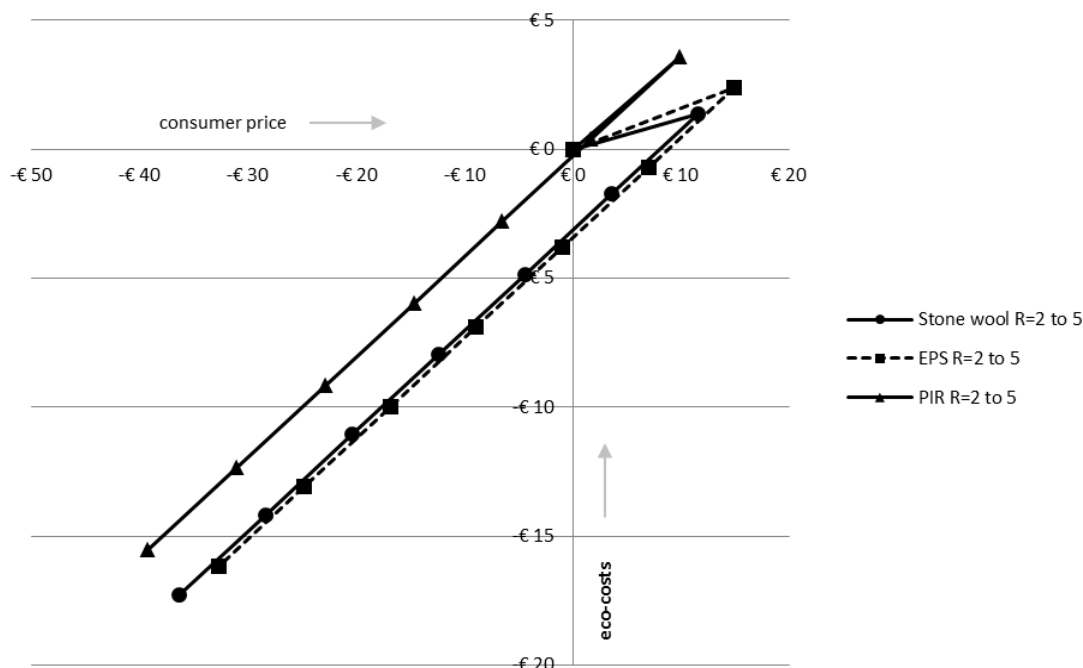
Figure 9. The eco-costs/price ratio for R = 2 to 5 insulation upgrade for stone wool, expanded polystyrene (EPS), and polyisocyanurate (PIR) for 1 m^2 of outer wall, over a period of 30 years.

3.3. Combination of Insulation and HEMS

In the Netherlands, new buildings require a minimum of R = 5 insulation, as of 1 January 2015. Potential energy-aware buyers might want to choose between further upgrading their insulation or accept the minimum required insulation combined with the use of a thermal HEMS. The modelled building in HAMBASE (which was modelled as a typical modern Dutch mid-terrace house, see Section 2.1) and its energy use are calculated for the two conservation strategies for a 113 m^2 surface area of the exterior walls. The scenario for insulation is based on a 30 year lifespan, where the thermal HEMS is assumed to have a lifespan of 15 years (the life span of a central-heating boiler). The remote operated valves in the six zone systems are assumed to have a life span of 30 years. The results are depicted in Figure 10.

Figure 10 shows rather long pay-out times for the additional investments, almost 20 years for the HEMS single zone system, and approximately 22 years for the additional insulation. The positive aspect of these long pay-back times is that there is hardly a rebound effect. The HEMS six zone system, however, does not even reach the pay-back point within 30 years, and there are hardly eco-costs savings (the eco-pay-back time is 27 years).

The issue in Figure 10 is whether or not to invest either in HEMS, or in extra insulation (in addition to the insulation of R = 5). Figure 11 depicts the situation when, in addition to the insulation of R = 5, an extra investment is done in an extra insulation plus a HEMS system.
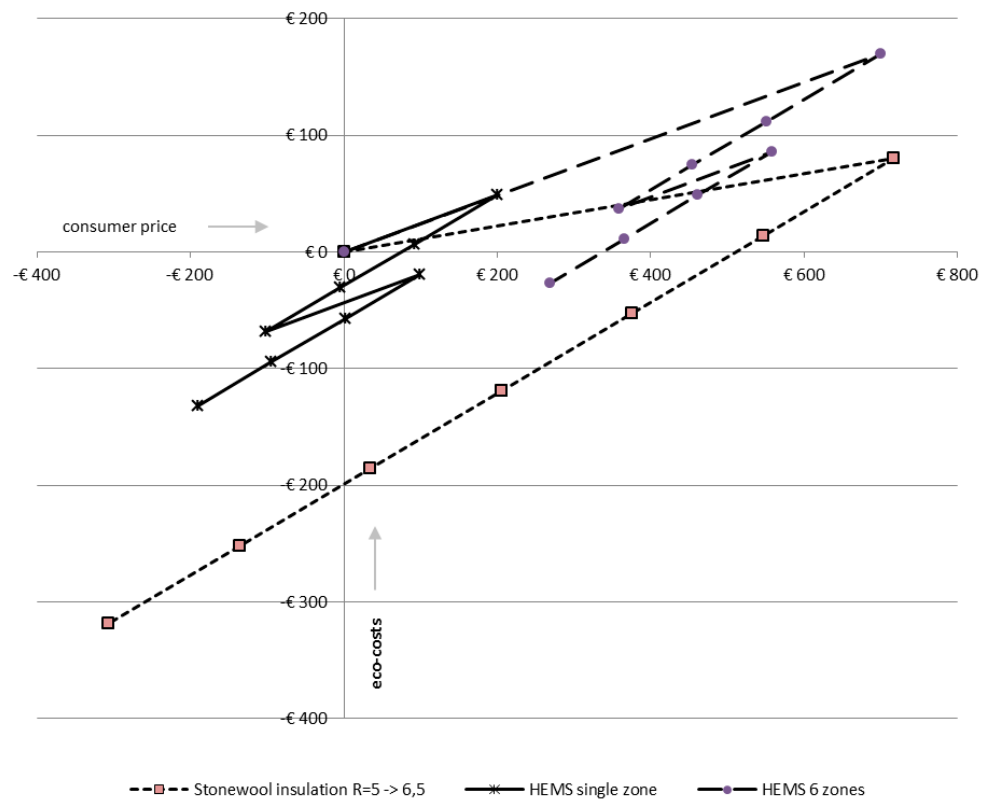
Figure 10. Case-study for the Dutch context, comparing stone wool insulation improvements from R = 5 to R = 6.5 for 113 m^2 of outer wall, against implementing HEMS over a period of 30 years (additional to insulation of R = 5).
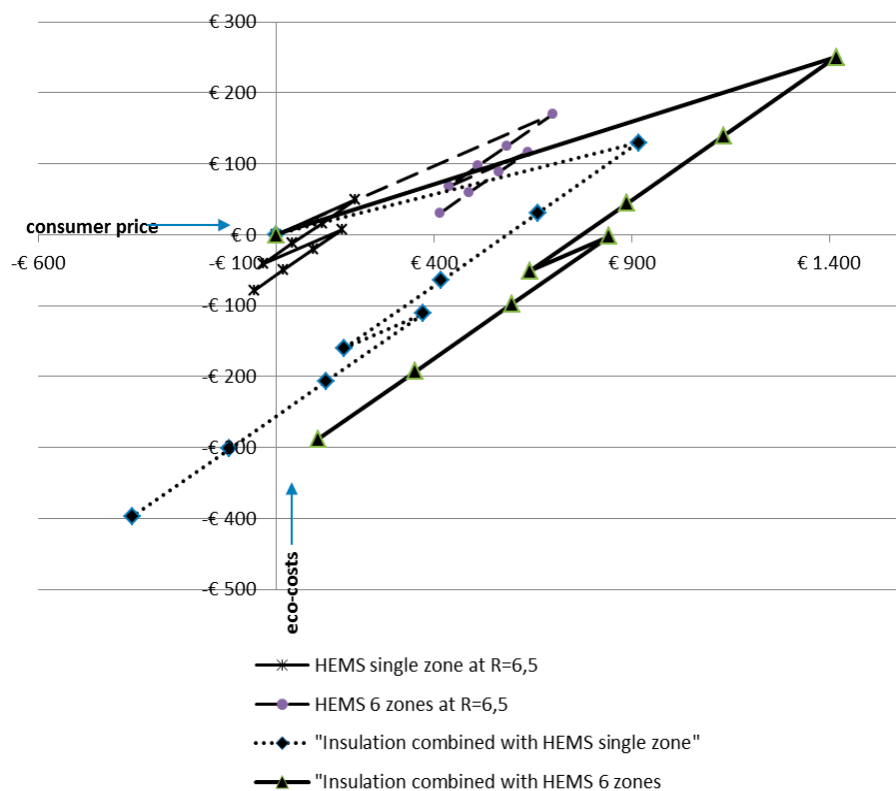

Figure 11. The integrated results for combining extra insulation (from R = 5 to R = 6.5) with either HEMS single or HEMS six-zone systems.

4. Discussion

In this multivariate analysis, the cooling of houses has not been analysed, as the forced cooling of houses is not common in the Netherlands. However, the same principle applies to HEMS and insulation, as, in summer, less cooling energy is needed because of improved insulation, whereas with HEMS, the automated setback savings are estimated to be marginal (4%) if the residents do not accept a higher comfort temperature [54].

Man-hour installation costs have not been taken into account, as it is assumed that the extra insulation does not require significant extra installation hours for new buildings. For HEMS, these extra installation hours are out-of-scope as well. Additional insulation in existing dwellings, however, usually requires many man-hours. Often, these installation hours are done by the owner (DIY), and, in that case, these hours are not to be counted. When these installation hours are done by a contractor, the installation costs are likely to be substantial. A rule of thumb is that, in that case, €20 per m^2 must be added to the investments, which are used in this study. The inclusion of such costs could significantly influence the economic pay-back time, and is likely to cancel out the rebound effect for insulation.

The price increases of natural gas have not been taken into account in the current analysis. Overall, the expectation is that the prices for fossil energy will continue to rise. Especially for insulation strategies, the economic pay-back time could be significantly reduced when prices of energy increase more than inflation.

Another issue is that the surplus value of insulation has not been taken into account in this analysis. In this case, the surplus value can be found in the increased value of the house on re-sale, mainly due to the lowered expected energy bills but also less quantifiable values such as, increased comfort and better noise insulation.

In current policies of many European countries, better insulation of dwellings, and HEMS are regarded as good strategies to reduce greenhouse emissions. This study, however, reveals that, in practice, such strategies may have less effect than the expected environmental impact reductions related to the total potential energy savings, because of the following three main issues:

(a) The environmental impacts related to the production of insulation materials and HEMS
(b) The reversion of changed user behaviour
(c) The rebound effect after the pay-back period

An interesting aspect is that the systems with a long pay-back period have less rebound, resulting in less environmental pollution.

Note that the relative importance of point (a) is higher for single indicators, which takes resource depletion into account (i.e., eco-costs and ReCiPe points), than for, for example, the carbon footprint indicator.

Our case study is about new dwellings where the outside measures are already fixed; it is about the decisions of individual future owners in a later stage of the architectural design, where only the internals can be individualised. Such a case is not much different from existing dwellings. Consequently, the living area (the functional unit in LCA) is a bit smaller. This will result in higher costs (as well as the eco-costs) per m^2. In the example of Section 3.2, this increase is 0.8% of the floor area for R = 5 to R = 6.5 for stone wool and EPS. The price per m^2 living area was approximately €2300 for the house of Figure 5 (200 m^2) in 2015. So, the loss of m^2 results in an economic loss of a value of 2300 × 200 × 0.8% = €3679, which is much more than the €718 of the marginal costs required to insulate the house from R = 5 to R = 6.5.

When the inner living area is kept constant, the outside size of the building must be enlarged to accommodate the thicker insulation material. This has the consequence that the building costs of the house will increase (approximately with a similar amount, as calculated above, as the house will be 0.8% larger). The footprint of the house will be more in that case. In the urban areas of big cities, where the price of land is high, the extra costs of land will be even higher than the costs of

the insulation material. The price of land in the Netherlands varies from 200–2000 €/m^2, resulting in increased costs of the house of Figure 5: €175–€1750 (109.5 m^2, 0.8%).

Please note that the reader is free and encouraged to adapt the assumptions in this approach to their own specific scenario and context. This could include variations to the model applied to simulate energy savings and thermal comfort. Although we feel that the main conclusions regarding energy use and thermal comfort will stand, the magnitude of both metrics might differ slightly. Additionally, other models and simulation software packages might include more or other variables for modelling energy use and thermal comfort that are suitable to other specific situations.

5. Conclusions

The combined analyses of costs, eco-costs, and value (i.e., the EVR approach) explains the potential magnitude of the rebound effect, as it clearly demonstrates the point of economic and environmental payback and the likelihood for potential rebound effects. The rebound effect plays an important role, because of two issues, namely:

The net environmental benefit of the energy savings is often overestimated because of the rebound effect.

A long financial pay-back time seems to be beneficial for the environmental benefit, as it reduces the rebound effect.

Hence, it is concluded that the eco-efficient value creation approach and the eco-costs/value ratio are valuable design and evaluation tools for balancing ecological and economic considerations.

With regard to the three research questions of Section 1.1, three conclusions are provided in the following paragraphs: Research Question 1: "Is a HEMS system an efficient and effective solution for energy savings, and if so under which conditions?". Because of the high absolute price for the insulation of a house compared to HEMS, it is more likely that consumers will invest in HEMS rather than in insulation in their existing houses. This is especially true if the installation costs of insulation are to be included as well. This paper shows that HEMS are a reasonable solution for existing houses with poor insulation (R = 2 or less), see Figure 6. The strength of HEMS is that the high heat loss due to poor insulation makes it worthwhile to shut off the heating system or reduce the mean temperature settings by 1 or more degrees.

Research Question 2: "Is there an optimum insulation thickness of the outer walls, and if so, what is the optimum for which type of insulation material?".

The optimal insulation for stone wool, EPS, and PIR seems to be U = 6.5 (±1.5), see Figures 8 and 9. From an environmental impact perspective, stone wool insulation material has lower impacts than EPS and PIR. The difference in environmental impacts over the full life-cycle between stone wool, EPS, and PIR, however, can be considered to be marginal. The differences in the economic terms over the total life cycle (LCC) are also small, see Table 4. Research Question 3: "What are the implications of combining a high level of thermal insulation with a HEMS system?".

For well insulated houses, HEMS is less effective, see Figures 10 and 11. However, governmental strategies that only focus on the insulation of newly built houses (R = 5 or more), will result in a transition that is far too slow. This is because of the long life-span of houses (longer than 50 years); it will take a long time before a significant share of houses are well-insulated.

Appendix A. Simulation of Scenarios for Building Energy Use

The HAMBASE tool used to model and simulate the building energy use was selected based on the following four selection criteria:

- good user-interface
- accessible coding
- multitude of available reference data (outdoor climate, building construction characteristics, heating systems, etc.)
- the capability to simulate: multiple zones within the building, radiator as well as floor heating systems, multiple time-periods, and temperature set-points.

HAMBASE is capable of simulating the indoor temperature, indoor humidity, and the energy usage for heating and cooling in a multiple-zone in Matlab/Simulink [55]. HAMBASE has been used in research projects and its results were within limits of the ASHRAE-test [56]. Within the context of the Nieuwveense Landen project, no data about the exact construction details were available at the time of simulation, therefore two buildings were modelled according to the following input parameters for the HAMBASE simulation.

Appendix A.1. Input Parameters

The following generic dimensions were used to model a free-standing house and apartment, as shown in Tables A1 and A2.

Table A1. Size of the modelled houses for the simulation.

Building Type	Dimensions (m)	Area (m^2)	Volume (m^3)	Window Area (m^2)
Two floor Detached House	$7.2 \times 15.2 \times 5$	200	500	47.7
One-Story Detached House	$15.5 \times 10.0 \times 2.6$	139	361.4	27.7

Table A2. Sizes of the zones modelled for the simulation.

Building 1: Two-Floor Detached House		
Zone	**Rooms**	**Volume (m^3)**
Zone 1	Living room, kitchen	145.0
Zone 2	Office	32.5
Zone 3	Bedrooms (3)	190.0
Zone 4	Bathroom	20.0
Zone 5	Entrance, halls	77.5
Zone 6	Toilets (2), storage/technical area	35.0
Building 2: One-Story Detached House		
Zone	**Rooms**	**Volume (m^3)**
Zone 1	Living room, kitchen	140.4
Zone 2	Office	26.0
Zone 3	Bedrooms (2)	83.2
Zone 4	Bathroom	20.8
Zone 5	Entrance, halls	65.0
Zone 6	Toilet, storage/technical area	26.0

Appendix A.1.1. Modelling the Exterior Walls and Roof

The exterior walls of the building prototypes are modelled as four material layers with different thicknesses, a 214 mm layer of limestone, followed by an insulation layer (glass wool) of 120 mm, a well-ventilated cavity of 50 mm, and 100 mm of brick. It was also assumed that there are no thermal bridges observed at the ceiling of the building. For the two prototype buildings, the construction characteristics of the exterior walls are the same.

A flat roof design is modelled for both buildings as soft board, with expanded polystyrene as an insulation layer and a thin polyvinyl chloride (PVC) roofing membrane.

Appendix A.1.2. Modelling the Windows for the HAMBASE Simulation

It is assumed that the windows have HR++ glazing with an interior sunblind. The surface area of glazing in the modern houses is estimated at 20% of the total surface area of the building, that is, 40 m^2 for the two-story houses and 27.7 m^2 for the apartment buildings. It was assumed that there were no external obstacles that create shadows over the windows' effective area.

Appendix A.1.3. Constant Temperature Boundaries

The floor construction is modelled as a 250 mm concrete slab with a 80 mm layer of insulation (expanded polystyrene [EPS]) in the middle, as follows:
Adiabatic external walls,
The building is modelled without adiabatic walls, and
Internal walls.

It was assumed that the inner walls are made of a plaster layer (13 mm), an insulation layer (74 mm of glass wool), and a second plaster layer (13 mm). Additionally, the walls separating the toilets and the bathroom with another room are made of tiles (10 mm) and limestone (70 mm).

Appendix A.1.4. Climate, Time, and Internal Gains

The simulations were executed from 1 January 2006 until 31 December 2006 using the outdoor climate conditions of De Bilt, The Netherlands. The simulation time was 365 days in order to evaluate the annual performance of the system. Three different seasons were modelled with different inputs for clothing, activity levels, and window operation.

For each zone in the modelled houses, a different profile is assigned based on the inputs described in Table A3.

Appendix A.1.5. Time Periods

Table A3. Time setting virtual thermostat used for the simulation.

	Two-Floor House (Working Days)								
			Floor Zones		**Individual Zones**				
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–06:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	-
06:00–09:00	21.0	21.0	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
09:00–17:00	21.0	21.0	21.0	15.5	21.0	15.5	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	15.5	21.0	21.0	21.0	21.0	18.0	-
18:00–22:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
22:00–23:59	21.0	15.5	15.5	21.0	15.5	15.5	21.0	15.5	15.5	-

Table A3. *Cont.*

Two-Floor House (Weekend)									
			Floor Zones		**Individual Zones**				
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–08:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	-
08:00–10:00	21.0	21.0	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
10:00–17:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	15.5	18.0	-
18:00–23:00	21.0	21.0	21.0	15.5	21.0	21.0	15.5	21.0	18.0	-
23:00–23:59	21.0	15.5	15.5	21.0	15.5	15.5	21.0	15.5	15.5	-

One-Story House (Working Days)								
					Individual Zones			
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–06:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	-
06:00–09:00	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
09:00–17:00	21.0	21.0	21.0	15.5	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	21.0	21.0	21.0	18.0	-
18:00–22:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
22:00–23:59	21.0	15.5	15.5	15.5	21.0	15.5	15.5	-

One-Story House (Weekend)								
					Individual Zones			
Time Schedule	**Base**	**Single Zone**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**
00:00–08:00	21.0	15.5	15.5	15.5	15.5	15.5	15.5	-
08:00–10:00	21.0	21.0	21.0	15.5	21.0	21.0	18.0	-
10:00–17:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
17:00–18:00	21.0	21.0	21.0	21.0	15.5	15.5	18.0	-
18:00–23:00	21.0	21.0	21.0	21.0	15.5	21.0	18.0	-
23:00–23:59	21.0	15.5	15.5	15.5	21.0	15.5	15.5	-

Appendix A.1.6. Heating and Cooling Systems

The convection factor of the heating system is 0.8 when the radiators are installed and 0.6 when a floor heating system is installed.

References

1. Guerra-Santin, O.; Romero Herrera, N.; Cuerda, E.; Keyson, D. Mixed methods approach to determine occupants' behavior—Analysis of two case studies. *Energy Build.* **2016**, *130*, 546–566. [CrossRef]
2. Dar, U.I.; Georges LSartori, I.; Novakovic, V. Influence of occupant's behavior on heating needs and energy system performance: A case of well-insulated detached houses in cold climates. *Build. Simul.* **2015**, *8*, 499–513. [CrossRef]
3. European Commission. Directive 2010/31/EC of the European Parliament and of the Council on the Energy Performance of Buildings—Recast (EPBD). *Off. J. Eur. Union* **2010**, *153*, 13–34.
4. De Boeck, L.; Verbeke, S.; Audenaert, A.; De Mesmaeker, L. Improving the energy performance of residential buildings: A literature review. *Renew. Sustain. Energy Rev.* **2015**, *52*, 960–975. [CrossRef]

5. Fokaides, P.A.; Papadopoulos, A.M. Cost-optimal insulation thickness in dry and mesothermal climates: Existing models and their improvement. *Energy Build.* **2014**, *68*, 203–212. [CrossRef]

6. García-Pérez, S.; Sierra-Pérez, J.; Boschmonart-Rives, J. Environmental assessment at the urban level combining LCA-GIS methodologies: A case study of energy retrofits in the Barcelona metropolitan area. *Build. Environ.* **2018**, *134*, 191–204. [CrossRef]

7. Kylili, A.; Ilic, M.; Fokaides, P.A. Whole-building Life Cycle Assessment (LCA) of a passive house of the sub-tropical climatic zone. *Resour. Conserv. Recycl.* **2017**, *116*, 169–177. [CrossRef]

8. Blengini, G.A.; Di Carlo, T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy Build.* **2010**, *42*, 869–880. [CrossRef]

9. Dylewski, R.; Adamczyk, J. Economic and environmental benefits of thermal insulation of building external walls. *Build. Environ.* **2011**, *46*, 2615–2623. [CrossRef]

10. Huijbregts, M.A.J.; Gilijamse, W.; Ragas, A.M.J.; Reijnders, L. Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. *Environ. Sci. Technol.* **2003**, *37*, 2600–2608. [CrossRef] [PubMed]

11. Erlandsson, M.; Levin, P.; Myhre, L. Energy and environmental consequences of an additional wall insulation of a dwelling. *Build. Environ.* **1997**, *32*, 129–136. [CrossRef]

12. Fischer, C. Feedback on household electricity consumption: A tool for saving energy? *Energy Effic.* **2008**, *1*, 79–104. [CrossRef]

13. Inoue, H.; Yamamoto, M. Development of home energy management system with advice function. In Proceedings of the 2011 IEEE International Conference on Communications Workshops (ICC), Kyoto, Japan, 5–9 June 2011.

14. Geelen, D. Empowering End-Users in the Energy Transition: An Exploration of Products and Services to Support Changes in Household Energy Management. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2014.

15. Köpp, C.; Von Mettenheim, H.J.; Breitner, M.H. Load management in power grids: Towards a decision support system for portfolio operators. *Bus. Inf. Syst. Eng.* **2013**, *5*, 35–44. [CrossRef]

16. Tweed, C.; Dixon, D.; Hinton, E.; Bickerstaff, K. Thermal comfort practices in the home and their impact on energy consumption. *Archit. Eng. Des. Manag.* **2014**, *10*, 1–24. [CrossRef]

17. Energy Star. 2009. Available online: http://www.energystar.gov/ia/partners/prod_development/revisions/downloads/thermostats/Summary.pdf (accessed on 22 February 2018).

18. Magnier, L.; Haghighat, F. Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network. *Build. Environ.* **2010**, *45*, 739–746. [CrossRef]

19. Van Dam, S.S. Smart Energy Management for Households. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2013.

20. Van Dam, S.S.; Bakker, C.A.; Van Hal, J.D.M. Home energy monitors: Impact over the medium-term. *Build. Res. Inf.* **2010**, *38*, 458–469. [CrossRef]

21. Yang, R.; Newman, M.W.; Forlizzi, J. Making Sustainability Sustainable: Challenges in the Design of Eco-Interaction Technologies. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'14), Toronto, ON, Canada, 26 April–1 May 2014; pp. 823–832.

22. Van Houwelingen, J.H.; Van Raaij, W.F. The Effect of Goal-Setting and Daily Electronic Feedback on In-Home Energy Use. *J. Consum. Res.* **1989**, *16*, 98–105. [CrossRef]

23. Banfi, S.; Farsi, M.; Filippini, M.; Jakob, M. Willingness to pay for energy-saving measures in residential buildings. *Energy Econ.* **2008**, *30*, 503–516. [CrossRef]

24. Wei, S.; Jones, R.; De Wilde, P. Driving factors for occupant-controlled space heating in residential buildings. *Energy Build.* **2014**, *70*, 36–44. [CrossRef]

25. Lähteenoja, S.; Lettenmeier, M.; Kotakorpi, E. The ecological rucksack of households—Huge differences, huge potential for reduction? Proceedings: Sustainable Consumption and Production: Framework for action. In Proceedings of the Sustainable Consumption Research Exchange (SCORE!) Network, Brussels, Belgium, 10–11 March 2008.

26. Jevons, W.S. *The Coal Question*, 2nd ed.; Macmillan and Co.: London, UK, 1866.

27. Khazzoom, D.J. Economic implications for mandated efficiency in standards for household appliances. *Energy J.* **1980**, *1*, 21–40.

28. Brookes, L. The greenhouse effect: The fallacies in the energy efficiency solution. *Energy Policy* **1990**, *18*, 199–201. [CrossRef]

29. Grubb, M.J. Energy efficiency and economic fallacies. *Energy Policy* **1990**, *18*, 783–785. [CrossRef]

30. Sorrell, S. *The Rebound Effect: An Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency*; UK Energy Research Centre: London, UK, 2007.

31. Binswanger, M. Technological progress and sustainable development: What about the rebound effect? *Ecol. Econ.* **2001**, *36*, 119–132. [CrossRef]

32. Sorrell, S.; Dimitropoulos, J.; Sommerville, M. Empirical estimates of the direct rebound effects: A review. *Energy Policy* **2009**, *37*, 1356–1371. [CrossRef]

33. Gonzalez, J.F. Empirical evidence of direct rebound effect in Catalonia. *Energy Policy* **2010**, *38*, 2309–2314. [CrossRef]

34. Greening, L.A.; Greene, D.L.; Difiglio, C. Energy efficiency and consumption—The rebound effect—A survey. *Energy Policy* **2000**, *28*, 389–401. [CrossRef]

35. Alcott, B. Historical Overview of the Jevons Paradox in the Literature. In *The Jevons Paradox and the Myth of Resource Efficiency Improvements*; Polimeni, J.M., Mayumi, K., Giampietro, M., Eds.; Routledge: Abingdon, UK, 2007; pp. 7–78. ISBN 1-84407-462-5.

36. Alcott, B. Jevons' paradox. *Ecol. Econ.* **2005**, *54*, 9–21. [CrossRef]

37. Vogtlander, J.G.; Mestre, A.; Van der Helm, R.; Scheepens, A.E.; Wever, R. *Eco-Efficient Value Creation, Sustainable Strategies for the Circular Economy*; Delft Academic Press: Delft, The Netherlands, 2014.

38. Berkhout, P.H.G.; Muskens, J.C.; Velthuijsen, J.W. Defining the rebound effect. *Energy Policy* **2000**, *28*, 425–432. [CrossRef]

39. Druckman, A.; Chitnis, M.; Sorrell, S.; Jackson, T. Missing carbon reductions? Exploring rebound and backfire effects in UK households. *Energy Policy* **2011**, *39*, 3572–3581. [CrossRef]

40. De Wit, M. Heat Air and Moisture Model for Building and Systems Evaluation. Available online: http://archbps1.campus.tue.nl/bpswiki/images/3/3a/Hambasetheorydec_2009.pdf (accessed on 18 September 2016).

41. Vogtlander, J.G.; Scheepens, A.E.; Bocken, N.M.P.; Peck, D. Combined analyses of costs, market value and eco-costs in circular business models: Eco-efficient value creation in remanufacturing. *J. Remanuf.* **2017**, *7*, 1–17. [CrossRef]

42. Vogtlander, J.G.; Bijma, A.; Brezet, J.C. Communicating the eco-efficiency of products and services by means of the Eco-costs/Value Model. *J. Clean. Prod.* **2002**, *10*, 57–67. [CrossRef]

43. Vogtlander, J.G.; Brezet, H.C.; Hendriks, C.F. The virtual eco-costs '99 A single LCA-based indicator for sustainability and the eco-costs-value ratio (EVR) model for economic allocation. *Int. J. Life Cycle Assess.* **2001**, *6*, 157–166. [CrossRef]

44. The Model of the Eco-costs/Value Ratio (EVR). Available online: www.ecocostsvalue.com (accessed on 5 August 2018).

45. Wever, R.; Vogtlander, J.G. Eco-efficient Value Creation: An Alternative Perspective on Packaging and Sustainability. *Packag. Technol. Sci.* **2013**, *26*, 229–248. [CrossRef]

46. Mestre, A.S.; Vogtlander, J.G. Eco-efficient value creation of cork products: An LCA-based method for design intervention. *J. Clean. Prod.* **2013**, *57*, 101–114. [CrossRef]

47. Jin, S.; Scheepens, A.E. Evaluating the sustainability of Vietnamese products: The potential of 'designed in Vietnam' for Vietnamese vs. Dutch markets. *Int. J. Technol. Learn. Innov. Dev.* **2016**, *8*, 70–110. [CrossRef]

48. Scheepens, A.E.; Vogtländer, J.G.; Brezet, J.C. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *J. Clean. Prod.* **2016**, *114*, 257–268. [CrossRef]

49. Rivas-Hermann, R.; Köhler, J.; Scheepens, A.E. Innovation in product and services in the shipping retrofit industry: A case study of ballast water treatment systems. *J. Clean. Prod.* **2015**, *106*, 443–454. [CrossRef]

50. Vogiatzakis, P. Design of an Efficient Control Strategy for the Heating System of Nieuwveense Landen. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2013.

51. Van Dam, S.S.; Bakker, C.A.; Buiter, J.C. Do home energy management systems make sense? Assessing their overall lifecycle impact. *Energy Policy* **2013**, *63*, 398–407. [CrossRef]

52. Rijksdienst Voor Ondernemend Nederland, Monitor Energiebesparing Slimme Meters (Besparingsmonitor). 2014. Available online: www.rijksoverheid.nl/documenten/rapporten/2014/03/10/monitor-energiebesparing-slimme-meters (accessed on 6 October 2017).

53. McKerracher, C.; Torriti, J. Energy consumption feedback in perspective: Integrating Australian data to meta-analyses on in-home displays. *Energy Effic.* **2013**, *6*, 387–405. [CrossRef]

54. Nest, Nest Learning Thermostat Summer Savings, 2012. Available online: http://downloads.nest.com/summer_2012_savings_white_paper.pdf (accessed on 5 October 2017).

55. Schijndel, A.W.M.V. Integrated Heat Air and Moisture Modeling and Simulation. Ph.D. Thesis, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2007.

56. De Wit, M.H. *HAMBASE Heat, Air and Moisture Model for Building and Systems Evaluation*; Technical University Eindhoven: Eindhoven, The Netherlands, 2006; Volume 100.