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Methodology to assess business models of dynamic pricing tariffs in all-electric houses

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ABSTRACT

There is a need for methodologies that integrate energy simulation and cost calculation to assess grid rent business models as incentive for demand-side management (DSM) in buildings. Despite the proliferation of energy simulation and cost calculation tools, there are no tool (e.g., software program) with appropriate methodology that caters specifically for the assessment of business models based on aggregation of dynamic pricing tariffs. Furthermore, the majority of existing methodologies focus on evaluating the supply-side management (SSM) of energy grids, and largely overlook the issue of influencing the customer to make good choices when it comes to DSM and/or design/renovation actions. This paper introduces energy and cost oriented methodology that provides informative support for utility companies and electric-grid customers including households' occupants to assess the economic incentives of different energy and power dynamic pricing tariffs. A physical model-based building simulation tool (IDA-ICE) is used to assess the energy performance of a representative residential benchmark including 96 all-electric houses in Norway with and without renewable energy technology. A business model-based cost calculator is developed and linked with the energy simulation's outputs to assess the effectiveness of three dynamic pricing tariffs, suggested recently by the Norwegian Water Resources and Energy Directorate (NVE). The effectiveness of the three pricing tariffs is compared (improving building's energy efficiency vs enhancing grid's demand side load shifting). Overall, results indicate that the Tiered Rate tariff is the most effective business strategy for customers to reduce the electric-based heating load during high demand periods. However, the methodology generated a comprehensive suite of scenarios analysis that allow customers, utility companies and policy makers to accurately address several building renovation variations and demand side management strategies to make the right decision upfront.

1. Introduction

1.1. Background

In Europe, demand-side management (DSM) plays an important role in balancing the demand and supply and transforming the building stock and the grid into a flexible, decarbonised European Super-grid [1,2,3]. Moreover, smart nearly zero energy houses and DSM, with a demand-follows-generation perspective, can contribute to decrease peak loads and increase the matching between generation from renewable energy sources and the demand [4,5]. This can decrease the use of fossil fuels, lessen the pressure on the grid and increase its flexibility, so that even for the expected increase in future demand, an expansion of the grid can be postponed or avoided [2,6]. Thus the rules for balancing, ancillary, and real-time trading should be adjusted to accommodate aggregated load flexibility [7].

1.2. Literature review

Several studies reported the benefits of DSM and when it works best [8,9,10,11]. DSM is most beneficial when customers can con-

Abbreviations: ASHP, Air source heat pump; COP, Coefficient of performance; DSM, Demand-side management; DHW, Domestic Hot water; ECM, Energy conservation measure; EUR, Euro; EV, Electric vehicles; EVB, Electric vehicles batteries; NOK, Norwegian krone; NVE, Norwegian water resources and energy directorate; nZEB, nearly zero energy building; nZEH, nearly Zero Energy Houses; NZEB, net Zero Energy Building; OBC, Occupant behaviour changes; PV, Photovoltaic; RES, Renewable energy systems; SS, Storage systems; SSM, Supply-side management; STC, Solar thermal collector.

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trol their energy consumption and when energy provides can reduce the peak load demand to reshape the load profiles [13]. The DSM systems employ specific optimisation technique and algorithms that are rely mainly on user interaction, load shifting capacity and pricing strategies. However, DSM is considered successful only if it promotes flexibility in terms of power demand from power grids [14]. The flexibility of smart buildings can flatten peak electricity demand and shift the loads [15]. In turn, this is best achieved when users' interacts with the grid and more importantly, receive incentives to trigger their interactions [8,16,17,18].

User interaction and dynamic pricing tariffs are two primary factors that cannot be neglected in the development and operation of all-electric nZEB [19,4]. In the context of designing and operating smart and energy neutral buildings and decarbonised smart grids in Europe, there is a need to transform current buildings and grids into smart interactive objects [5,20,21,3]. Several studies in various countries confirm the need to reform our regulation and policy landscapes to provide dynamic pricing of grid rent tariffs [22,23,24,25]. Recent research in the field of DSM has been focused recently on storage technologies in smart buildings [26,27,28,21].

Despite DSM importance being acknowledged in literature, so far only limited attention has been paid to assess and evaluate the influence of different business models of dynamic pricing tariffs on occupants' behaviour in all-electric nZEH [7,29].

Strbac [10] identified the reasons why DSM has been slow, including the lack of ICT infrastructure, lack of competitively of DSM-base solutions compared with traditional approaches and the inappropriate market structure and lack of incentives. Torriti [3] assessed how active occupancy levels of single-person households vary in single-person household in 15 European countries. He advised to seek a diversified European Super grid-wide DSM strategy, and confirmed that what is needed is the change of behavior of consumers. These findings are confirmed by the work of Gottwat et al. [8], Marszal-Pomianowska et al. [30] and Schulte et al. [31], who created a simulation model that generates household load profiles under flat tariffs and simulates changes in these profiles in Germany and Denmark. However, in their studies they found that a simple change of existing flat tariffs to time-based prices does not necessarily provide enough monetary incentives for households' occupants to change their behavior.

The type of findings presented above, contribute to the need of providing informed decision making methodologies that can assess the impact of grid rent dynamic tariffs and their influence of households' occupants' behavior [32]. We proofed that there are several studies that confirm the need to for tools and methodologies to assess the effectiveness of DSM business models in order to accelerate the slow market uptake of DSM and encourage utilities companies and convince households' occupants.

Considering this overview of literature, it is clear that there are currently no established methodologies available to support the decision making of households occupants and utilities managers regarding the cost-effective grid rent business models for dynamic tariffs pricing of all-electric nearly Zero Energy Houses (nZEH). Also, from the perspective of DSM, there are many research questions regarding the load shifting capabilities and storage capacities of nZEH [10]. For example, it is currently unknown what are cost of different dynamic pricing tariffs and how to stabilize the grid and reduce gap between the demand and supply gap (e.g. cost of tariff vs. storage capacity, or cost of tariff vs. ideal heat shift) ([33,7]). This lack of knowledge may inhibit the transition towards decarbonised and smart grids and buildings.

1.3. Contribution of this paper

In Norway, to give incentive to load shift and reduction of peaks in buildings, the Norwegian Water Resources and Energy Directorate (NVE) want to introduce a new grid rent tariff by the end of 2020. They are suggesting three different business models for grid rent, with either higher cost for higher power drain (*Measured Power Rate* tariff and *Tiered Rate* tariff), or higher cost during high demand periods (*Time of Use* tariff). The Norwegian energy sector relies predominantly on hydroelectricity and typical households are mainly heated by electricity compared to other European countries (see Fig. 1). Therefore, Norway is considered as a test ground for grid electrification, decentralization and deep decarbonisation, on European and International levels [34,2,35].

Therefore, the aim of this study is to find a methodology that allows investigation of the impact by different business models of dynamic pricing tariffs, and be able to calculate the ideal heat load shift for cost-effective energy-efficient house based on the hourly demand. The paper will investigate how household customers in single-family houses are affected by a change in tariff, and how they can reduce their cost by load shifting and improvement in building physics. The following research questions will be investigated in this research:

Q1 Which business model gives the largest economic incentive to improve building physics for reducing the energy operating cost?

Q2 Which business model gives the largest economic incentive to load shift for avoiding large size of power grid?

To answer these questions, we have taken the three tariff models suggested by NVE and compared the results with the cost of today's model. The example costs are based on the scenarios from the Norwegian Energy Directorate [6]. On the short term, the developed methodology for tariff model assessment can help utilities and grid distribution companies to shape a dynamic pricing policy that can increase the power grid's flexibility and robustness. On the long term, a tool can be developed to encourage more efficient power use, encourage use of renewable energy systems (RES), encourage storage use (heat storage in buildings and controlled charging of electrical vehicles) and encourage behavioural changes (the use of indirect heating systems). This will help the customer make good choices when it comes to energy- and power use, and prepare for new technology and innovative markets that can reduce cost or increase utility and end-user flexibility.

2. Methodlogy

In this section, we present the research methodology, including the study concept. Our research methodology combines building performance simulation (BPS) and cost analysis using a self-developed algorithm in Excel to evaluate the different electricity pricing tariff business models. We developed a study conceptual framework that summarizes and visualizes our research methodology, as shown in Fig. 2. Our conceptual study framework is based on four steps that will be described in the following sub-sections.

2.1. Simulation of representative building benchmark

One of the challenges to developing the assessment methodology was to implement a representative benchmark or reference building for dwellings. The benchmark should represent Norwegian detached all-electric single-family houses. For this study, we selected a reference model based on a recent research, conducted by Karlsen et al. [36], to develop a reference model for the Norwegian residential building sector. The reference model represents the current minimum technical requirements for new buildings in Norway, which are nZEBs, based on the Norwegian Building Technology Regulations [37]. The house consists of two floors with a total floor area of 149.46 m^2, and is built on flat ground with no basement. The building is placed in a suburban area in Oslo. The weather file for Oslo, Gardermoen was downloaded from

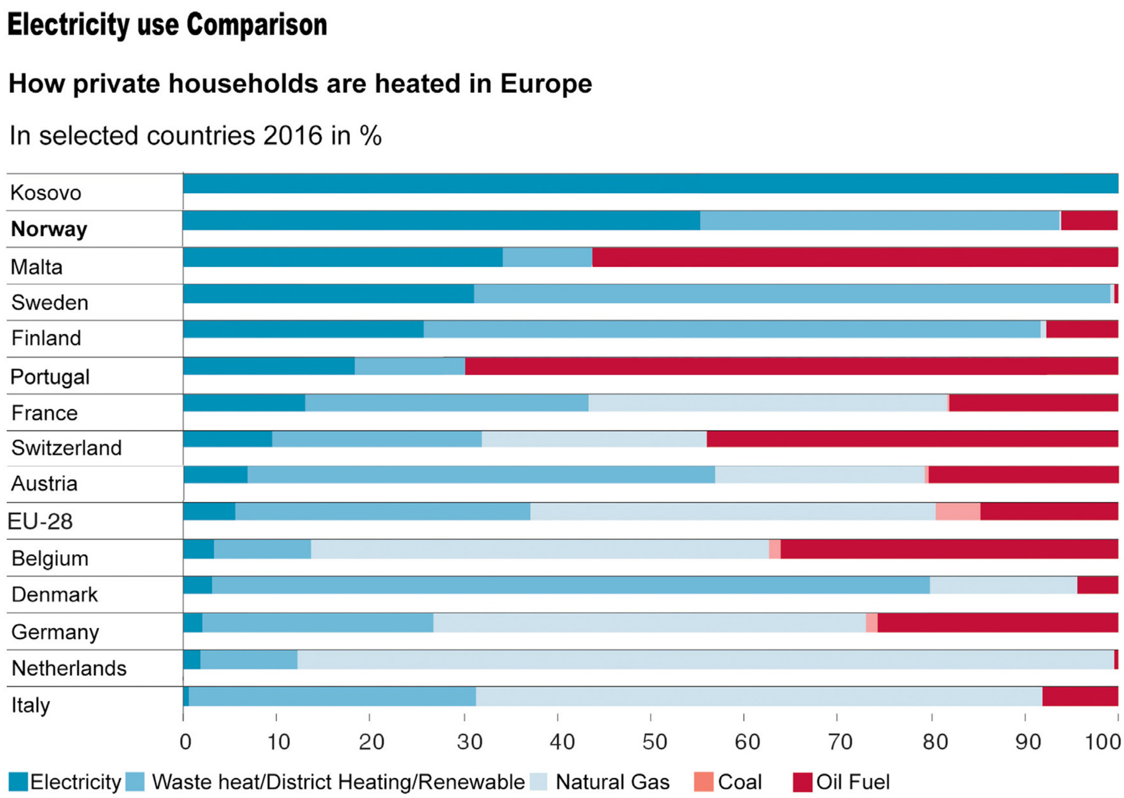

Fig. 1. heating source for residential building in Europe [12].

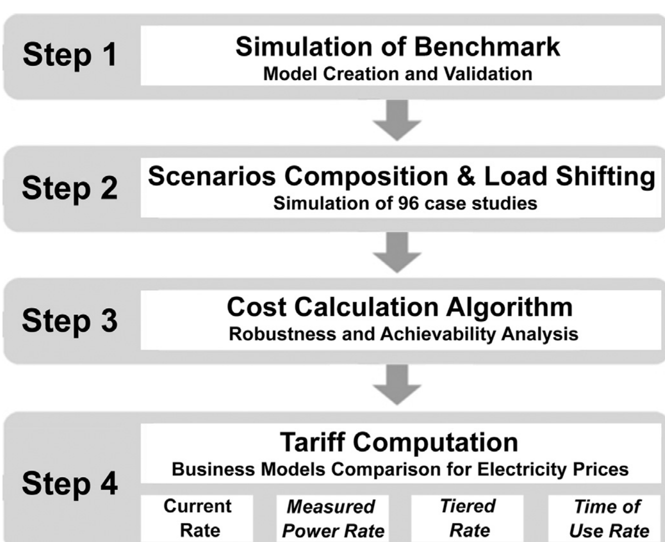

Fig. 2. the study conceptual framework.

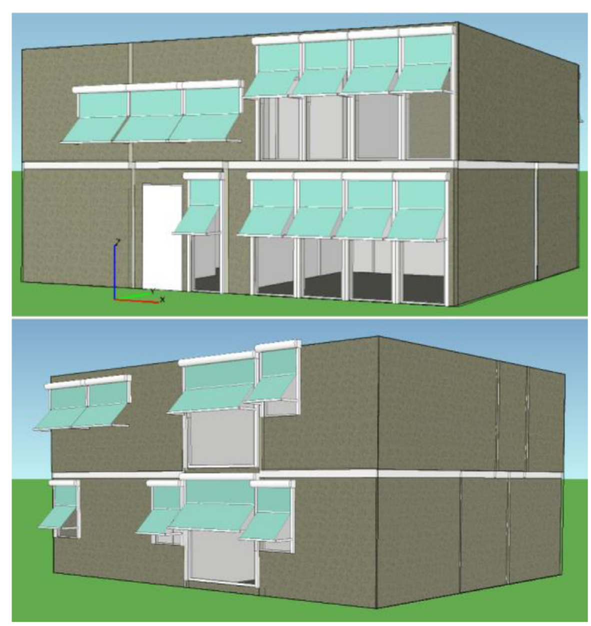

Fig. 3. 3 D visualisation of the Norwegian reference model.

ASHRAE IW2 database provided inside IDA ICE [38]. The model developed by Karlsen [40] describes the building layout and construction, including solar shading. The selected reference model is shown in Fig. 3 and allows maximum design flexibility for a range of parameters, including the energy conservation measures (ECM), renewable energy systems (RES), storage systems (SS), electric vehicles batteries, and occupant behaviour changes (OBC) as shown in Section 3. Prescriptive simulation recommendations from the Norwegian Standard are translated into input default values and embedded in the model. The model had to comply with the acceptable range of indoor air and operative temperatures recommended thermal comfort categories of the EN 16 798 (2017) (formerly EN 15 251) standard) [39]. Further details regarding the modelling assumptions of occupancy schedules or OBC for light, equipment and domestic hot water (DHW) can be found in Appendix I and the study of Karlsen [40].

The energy demand for buildings is simulated separately for each of the different building physic parameters described earlier. Models with variations of envelopes and window openings is created and simulated with IDA ICE. The heat collection and energy

Table 1
Building physic cases.

Group	Parameter	Notation
Envelope	TEK17 requirements	TEK17
	Typical standard in a house for the ’60 s	’60 s
Heating system	Direct electric heating	Direct
	Air source heat pump	ASHP
Solar thermal collector	Without solar thermal collector	NoSTC
	With solar thermal collector	STC
Photovoltaic panels	Without PV panels	NoPV
	With PV panels	PV
Windows	Windows with normal openings	WN
	Windows with occupants openings	WO
Electric Vehicles	No electrical vehicle	NoEV
	Typical charging of electrical vehicle	EVc
	Delayed charging of electrical vehicle	EVc

Table 2
Parametric arrangement of the group parameters.

Number	Parameter	Notation
1	Reference case	TEK17 Direct WN NoSTC NoPV NoEV
2	‘60 s	‘60 s Direct WN NoSTC NoPV NoEV
3	ASHP	TEK17 ASHP WN NoSTC NoPV NoEV
4	STC	TEK17 Direct WN NoSTC NoPV NoEV
5	PV	TEK17 Direct WN NoSTC PV NoEV
6	WO	TEK17 Direct WO NoSTC NoPV NoEV
7	EVc	TEK17 Direct WN NoSTC NoPV EVc
8	EVd	TEK17 Direct WN NoSTC NoPV EVd

production by STC and PV is simulated separately, also in IDA ICE. IDA ICE is a tool for building simulation of energy consumption, the indoor air quality and thermal comfort. IDA ICE version 4.8 was used, which is validated using the BESTEST: Test Procedures [41,38].

The total load profile for each case according to heating system, STC, PV and EV with typical and delayed charging is all post processed in Excel. Macro buttons ensure that all the parameters can easily be chosen. The building physics installations described in Appendix I and II are used as default values. These can however be changed by changing the input from each of the installations. For different STC and PV panels, new simulations would have to be run with IDA ICE. A different heat pump would need a new equation input, and a different electrical vehicle would need new charging time or power drain.

2.1.1. Model validation

The model validation was done over a year and involved several reviews from peer modellers. The entire load schedules listed in Appendix I was included in both models. The most significant validation strategy was the coupling of the lighting schedule and daily distribution of plug loads with the DHW schedule during winter schedule. Three major operation periods are defined resulting in a match with the surveyed monthly electric utility bills profile. There is good agreement in annual energy consumption behaviour and curve shapes between the simulated data and the survey collected data. The estimated energy demand curve shapes are slightly offset towards high limits than the predicted consumption during summer months and the total annual predicted consumption is higher than the actual by about 2%.

2.2. Composition and selection of scenarios

Six groups, with a total of thirteen different building physics design parameters, have been investigated. They are presented in Table 1, with explanation and notation. All possible combinations of the parameters have been conducted, and in total 96 cases have been compared in this study. The reason for interest in these groups of building physics is presented in the following:

- The two types of building envelopes represent the old buildings in the building stock, and new or renovated nZEBs. It is of interest to investigate the cost for each grid rent tariff for buildings of different age, and the potential saving of deep renovation of old buildings.
- The air source heat pump (ASHP), solar thermal collector (STC) and photovoltaic (PV) panels are all examples of expected future installations of renewable energy sources implemented directly in the buildings to decrease the electricity demand. Literature indicates that it is of large importance to stakeholders that the new tariff implemented makes it beneficial for the household owners to continue to invest in these installations [42,43]. The different openings of windows is an example of typical behaviour in Norway, where the electricity is low-priced, and people are used to have freedom to consume energy in the pattern and amount they desire. Occupants often open windows during night-time if more ventilation is needed, without turning down the space heating in the rooms. It is investigated how this end user behaviour affect the cost with a new tariff.
- Electric vehicles are an example of the future way to travel, and drastically change the demand profile of households. They are normally put to charge in the afternoon and will therefore increase the already high evening peak. The amount of electrical vehicles is increasing rapidly in Norway and it is important to keep the incentive for use of electrical vehicles, as the European governmental goal is to decrease fossil fuel consumption by 40% by 2030 and 80% by 2050. Therefore, a comparison between an early afternoon charging and a delayed charging is done.

Some of the results are presented in a parametric arrangement to illustrate how the business models affect the different groups (see Section 3.1). A total of eight cases represent each group, see Table 2. Further details regarding the modelling assumptions of ECM, RES, SS and electric vehicle batteries can be found in Appendix II and the study of Karlsen [40].

2.2.1. Load shifting scenarios

The ultimate goal of the change of grid rent tariffs is to change the way people consume energy. The loads that can be made flexible are thermal or electric. The loads that can be made flexible include space heating, domestic hot water heating, washing machines, dryers and dishwashers, and charging of electrical vehicles. For example, for nZEBs with hydronic heating system a hot water storage tank can save the heat. Thermal mass and phase change materials in the building can also be utilised to delay the need for heating. As heating of buildings is the largest part of the energy consumption in buildings, and also the main reason for critical peaks during winter, shifting of the heat load has been investigated for all cases. For Norwegian households the heating is for most buildings done by electricity. Therefore, we focused on electric heat shifting that can be achieved by the use of batteries without including any thermal technology or measure.

Also, we assumed the heat shift to be ideal. Ideal heat shift is a theoretical optimal amount of load shifted to obtain the lowest cost according to the business model. Ideal heat shift is considered differently for each business model in regards to the amount and time of shift, which is an essential element of the research. Based on a stakeholder consultation, conducted in Oslo in 2018 [40] to investigate the potential of implementing a new grid rent models, stakeholders pointed out that running washing machines, dryers, and dishwashers during off peak periods often means running them at night or when people are not at home. Running washing machines, dryers, and dishwashers during off peak periods in-

Table 3
Energy model tariff used today and the three tariff models suggested by NVE (illustrated in Fig. 5).

TARIFF	Fixed cost Annual	Energy cost Total amount of energy use		
CURRENT ENERGY RATE	1749 NOK/year	0.194 NOK/kWh		
MEASURED POWER RATE	1749 NOK/year	0.050 NOK/kWh	Measured power cost Highest peak daily 1.86 NOK/kWh/h	
TIERED RATE	1749 NOK/year	0.050 NOK/kWh	Subscription power limit cost (Annual) 689 NOK/(kWh/h)/year	Overuse cost Power used above limit 1.00 NOK/kWh/h
TIME OF USE	1749 NOK/year	Energy cost winter night 20 pm – 6am Nov to March 0.152 NOK/kWh	Energy cost winter day 6am – 20 pm Nov to March 0.380 NOK/kWh	Energy cost summer All day April to Oct 0.122 NOK/kWh

creases the risk of longer reaction time in case of fire. Therefore, we decided to not shift the loads of those appliances, and we assumed that people will continue to utilise these appliances in the evening when occupants are home and awake. However, delay of charging electrical vehicles was allowed. Assumptions that have been made for heat shifting in this research are that:

- the heat shift is ideal
- all heat load can be shifted
- heat load can be offset within the same day for up to 24 h
- there are no losses when heat is shifted
- there is no need to increase the heating when it is shifted

2.3. Cost calculation algorithm

In step 3 of the study, we developed a new algorithm to calculate the cost impacts associated with each case study and business model pricing tariff. We could not find any tool in literature that allows calculating prices according to power, and necessary amount and time of heat shift to obtain an ideal shift for each case study. Therefore, a new algorithm has been created for this purpose as part of this study. The algorithm is created as a template workbook in Excel, and one workbook for each case was created. The workbook takes hourly energy demand for a building case and the outdoor temperature at the location as input. The algorithm computes time and amount of ideal heat shift and costs for four pricing tariffs (described later in Section 3.4), both with and without ideal heat shift, for each investigated case. Another workbook combines and compares all the cases, by importing the results from the 96 workbooks of tariff computations. Both these workbooks, Tariff_computation_template.xlsm and Case_comparison.xlsx, are added to the paper, see Appendix A and B.

2.3.1. Robustness

The robustness of the business models for different building design with and without shift was calculated to validate our business assessment methodology. The robustness of the model reflects how strong it is. The more robust the business model is, the smaller the range of the cost between the cases. Therefore, the standard deviation was calculated against the median cost. Section 3.3.1 reports the robustness calculation results.

2.3.2. Achievability

Next, we calculated the achievability to validate our business assessment methodology. How well a model is achieving the aim of the project depends on the cost difference before and after ideal heat shift, and the amount of heat that needs to be shifted to obtain this cost reduction. If a very high amount of heat needs to be shifted, a large storage tank or battery is needed, and it is more difficult to achieve the full cost reduction. Also, if the cost reduction is low, the probability that people will invest in a system to shift heat is less. Therefore, the achievability of load shift and cost for each of the groups, with and without shift, was calculated to check the trade-off for each of the groups. The results in Section 3.3.2 report the achievability calculation results.

2.4. Tariff computation and cases comparison

In this section we present a description of the business pricing model used today and the three dynamic business pricing models suggested by NVE see Table 3 and Fig. 5. The illustrations and values presented are based on information from the stakeholder consultation [40], and do not include taxes or levies [6].

2.4.1. Current energy rate tariff models

The model used for grid rent cost in 2018 consists of two parts. One part is a fixed annual cost equal for all customers. The second part is an energy cost model based on the individual customers' energy consumption. Today the grid rent cost in Norway varies between the different grid distribution companies, and the pricing costs presented here are average numbers [6]. The tariff and according prices are shown in Table 3.

2.4.2. Measured power rate tariff model

The *Measured Power Rate tariff* model consists of three parts. A fixed part, an energy part and a power part, see Table 3. The power part is based on the highest power drain (kW) during the measuring period. Drawbacks of this model are that customers with atypical use may be charged for large power drain at times when the grid has good supply capacity. The longer the measuring period, the smaller is the probability for coincidence between peak demand for customers and the grid. Also, if a peak has already occurred in the measuring period, the customer can continue to keep a high power drain within the size of the peak, without extra charge. Today (2018) many industrial customers have a *Measured Power Rate* tariff, and the measure period is usually one month. However, in this study, the peak is set to be measured daily to reduce the drawbacks.

2.4.3. Tiered rate tariff model

In the *Tiered Rate* tariff the customer pays an additional overuse cost if their power drain is above an in advance set limit. This tariff consists of four parts. One fixed part, one subscription limit, an energy part, and an overuse part, see Table 3.

For most customers, the overuse will match with the hours when there is a high stress on the grid, as well as most customers have a smaller power drain at times with good capacity on the grid. As the overuse part of the tariff is accounting for all

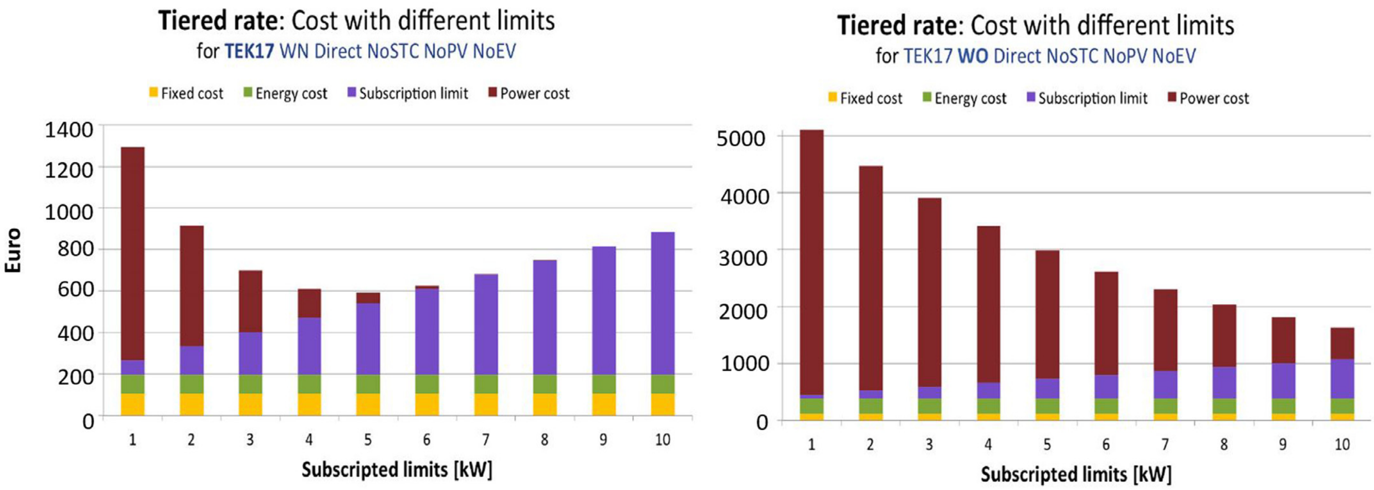

Fig. 4. Cost with different Tiered rate limits for two buildings cases.

hours and power size that is above the subscription limit, one hour of overuse will not lessen the customers' economical incentive to avoid overuse at later hours. Drawbacks with the model are that customers using power above the limit at hours with good capacity on the grid will also be charged overuse cost. If these customers adjust their demand to avoid the overuse cost it will have no value to the grid, and it represents a social-economical loss. Also, if customers reduce their power drain to the subscripted limit, there is no economical incentive to reduce it further, even though there is still a peak on the grid. The exact number of power limits is not decided by NVE, but 10 limits ranging from 1 to 10 kW is a suggestion. Some limits above 10 kW may also be necessary, but the step is suggested to be larger than 1 kW, and the limits are not set. In this study, 10 limits are used for the model when investigated. The customer themselves can choose the limit, but is not allowed to change more often than every 12 months. If the limit is set too high, the subscription power cost will be higher than necessary. If the limit is set too low, the overuse cost will be higher than necessary. In practice, the grid distribution companies are supposed to help the customers to choose the best limit for their consumption. In this paper, we optimized the limit for all 96 cases studies. Fig. 4 shows the optimal limit (i.e., the limit that leads to minimum annual cost) of case 1 and 6 presented in Table 2.

2.4.4. Time of use *tariff model*

In the *Time of Use* tariff some hours have higher energy price than others see Table 3. The hours with high pricing are the hours which historically have a high grid pressure. All customers will get incentive to reduce their entire load in these hours, and not only the customers with the highest consumption, or consumption above their limit, as for the other two suggested models. The model is suggested to have a higher price during winter, especially in daytime, as these are the critical hours for stress on the grid today (2018) in Norway. A drawback of this model is that the income of the grid distribution companies will, to a larger extent, rely on consumption that depend on the outside temperature, which vary largely from year to year.

The model is intuitively easy to communicate to the customers, and also relatively easy for the customers to understand and react to as the pricing is attached to energy (kWh), and not power (kW). During the stakeholder consultation session, NVE considered the *Tiered Rate* model to be the most accurate model to achieve the goals of the tariff change [6]. However, other stakeholders disagreed with this opinion.

3. Results

In this chapter, a selection of the results from the simulations and cost calculations are presented. The full simulation and cost analysis can be found in manuscript of Karlsen [40]. First in this chapter, the total energy demand of the cases is presented, and then the scenarios composition and load shifting profile for the four different business models tariffs are presented. The average day load profile presented for each group is calculated as the daily average demand for each hour over the whole year. Then, the third section presents the cost calculation algorithm including its robustness and achievability. The final section compares the results of applying the different business models for electricity tariffs.

3.1. Energy demand simulation

To compare the difference in energy demand of the 96 cases, all of the cases have been investigated and results have been classified under six major groups including envelope, heating system, PV, STC, window openings, and EV charging. Each of the groups (Table 1) contains the results of simulation for all 96 cases. To investigate the influence from the parameters variations (Table 2) on the energy demand, the results in each group have been divided in two, or three, according to the parameters. All the results have been inserted into one box plot for comparison, see Fig. 6.

- The first two boxes in the plot illustrate the two different envelopes, TEK17 and '60 s. The cases with envelope as a typical '60 s house have a significantly higher energy demand than the ones with envelope according to TEK17. The standard deviation between the cases is quite similar, but the TEK17 cases have a median that lies lower in the range. This indicates that more cases with the TEK17 envelope have a demand in the low section of the range, than the cases with '60 s envelope, which have more cases in the upper part of the range.
- The next group reports the results of varying different heating systems. The ASHP is largely reducing the energy demand in buildings. The buildings which already have low energy demand with direct electric heating can save about 5000 kWh a year if they change the heating source from direct electrical heating to an ASHP, while the buildings with high heating demand can save up to about 25,000 kWh a year. This is a huge reduction in demand. The standard deviation decrease of demand reduction with the ASHP indicates that the ASHP makes the demand more stable.

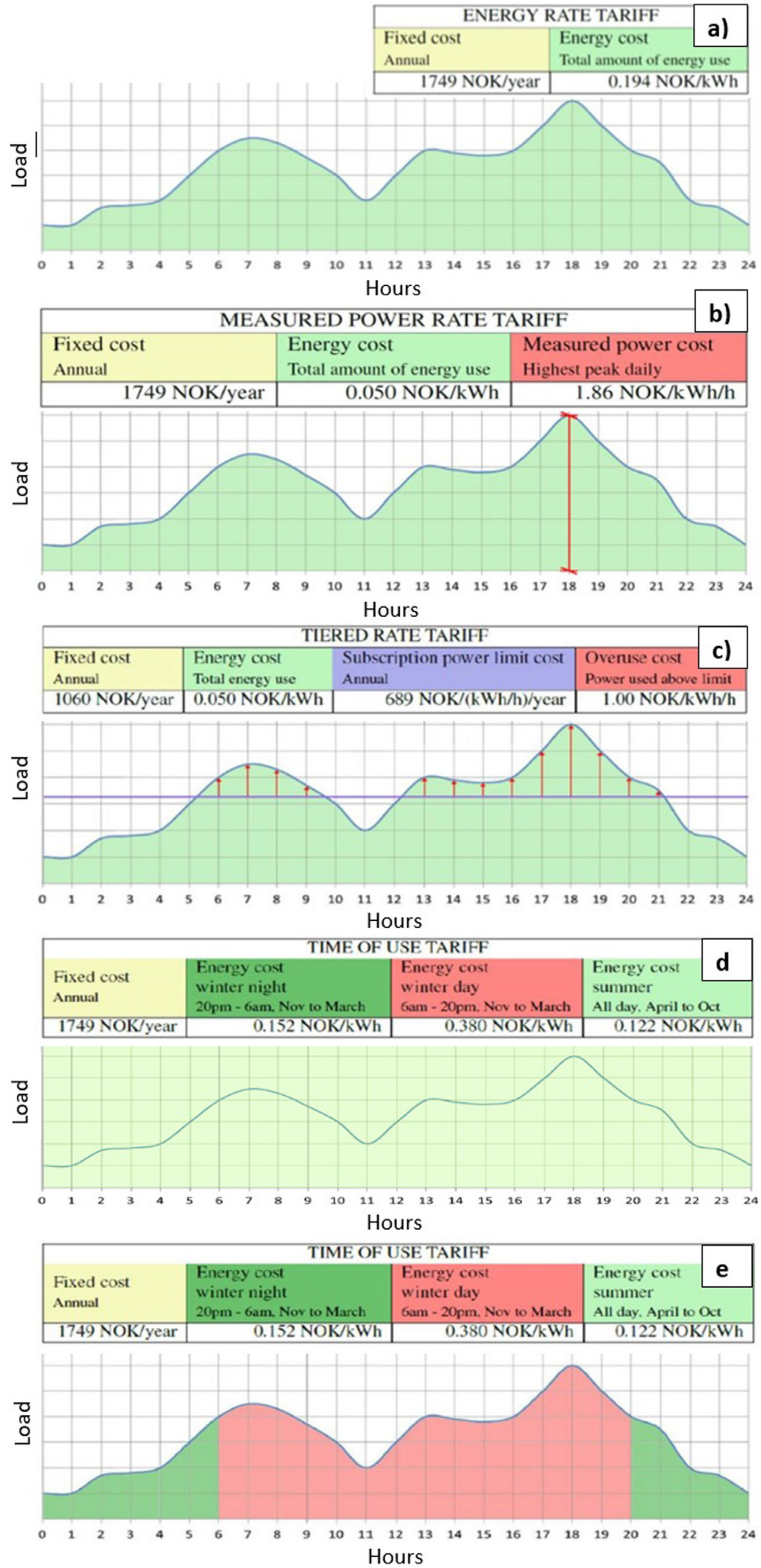

Fig. 5. a: Illustration of cost for the Current Energy Rate tariff; Fig. 5b: Illustration of cost for a Measured Power Tariff; Fig. 5c: Illustration of cost for a Tiered Rate Tariff; Fig. 5d: Illustration of cost for a Time of Use tariff – summer rates. Fig. 5e: Illustration of cost for a Time of Use tariff- winter rates.

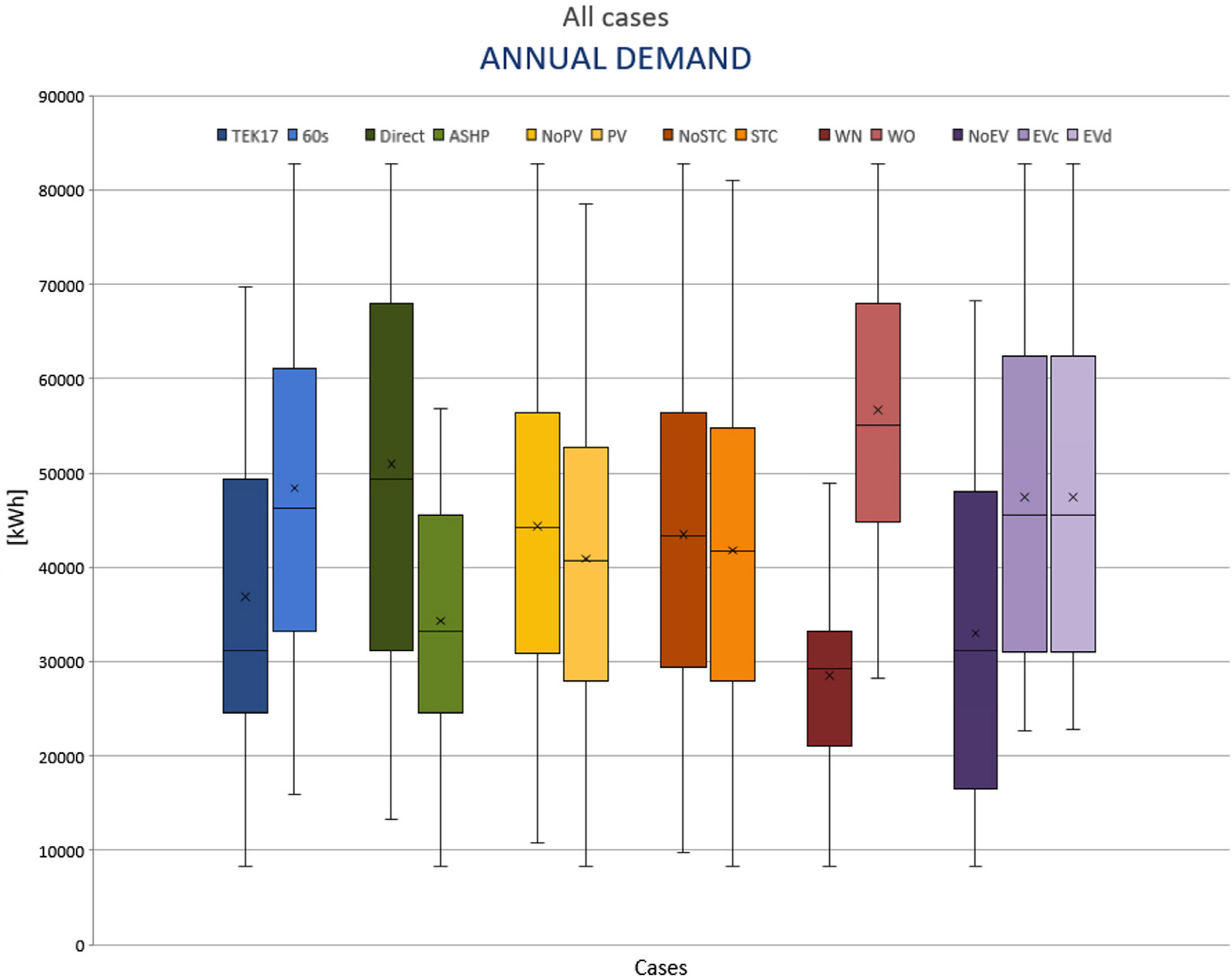

Fig. 6. Box plot comparing annual demand between all the groups of cases.

- The next group with and without PV panels shows that PV panels do decrease the energy demand with about 3000 kWh a year for cases with high demand. Cases with high demand save more than cases with less demand, even though the panels produce the same amount for all cases. This is due to the fact that the excess production from the PV panels is not considered in this study. Buildings with higher demand also have a higher demand during the hours when energy is produced from the panels. More of the energy produced with PV will therefore be used, and less will be exported.
- The next group in the chart is illustrating the groups with and without solar thermal collector. As the collector is only affecting the hot water, which has the same schedule and amount of demand for all cases, STC will decrease the demand with equal amount for all cases, 1718 kWh a year.
- The largest difference in demand in the chart is found between buildings with and without windows opened by occupants. The demand and standard deviation is much larger for those cases that have openings by occupants. This type of consumer behaviour holds a large potential for demand reduction.
- The last cases compared are the three scenarios for charging of electrical vehicles. When the charging of an electrical vehicle is included in the building load the demand increases, but the demand for the cases have the same standard deviation. In other words, the demand is increased with the same amount for all cases. If the vehicle is charged with typical or delayed charging this does not affect the demand, and all cases have the exact same demand.

Comparing the annual energy demand for the 6 groups of cases indicates a significant disparity between all different scenarios from an energy efficiency point of view. According to Fig. 6 the most influential energy efficiency measure is related to OBC when occupants close windows. Another significant measure is the installation of an ASHP. Also the results indicate that add an EV will increase the demand. However, the presented results in their current format provide only a picture on the annual energy demand without incorporating any cost aspect or load shifting strategy. Therefore in the next section, we present the results of coupling the annual energy demand simulations to dynamic pricing and load shifting calculations to better inform the decision making about the effectiveness of those combinations.

3.2. Scenarios composition and load shifting

Ideal heat shift is the load shifting of heat demand that will result in the highest possible cost reduction in grid rent. For each of the business models, the highest cost reduction is obtained by different patterns of shifts, and the load profiles for ideal heat shift will look very different for each of the business models, as demonstrated in Fig. 7.

- If energy is shifted with the *Current Energy Rate* tariff it can be convenient for the grid, but it will have no effect on the grid rent cost for the customer. It can therefore be assumed that the customer will implement no shift, even if they were encouraged to do so. The first load profile in Fig. 7 illustrates a typical load profile for a building without shift, and this is also the ideal load profile for the *Current Energy Rate* tariff, as the price is not changing.
- For a *Measured Power Rate* tariff the reducible part of the cost without reducing the demand is the power cost. The power cost occurs for the highest peak in each day, and minimisation of this cost happens when the power load is shifted to be constant during the day, so the peak is as low as possible. Ideal heat shift will therefore create a flat load profile. High, short peaks can result in a small load shift but a large cost reduction, while smaller, wide peaks will give a large load shift with a small cost reduction. Therefore, this model is good for reduction of short, high peaks.
- Ideal heat shift with a *Tiered Rate* tariff will result in shifting all loads above the subscription limit, and the overuse cost will be decreased to zero. The ideal heat shift will therefore shift all heat occurring above the peak to hours with available amount of kW below the limit. This model is good for reducing the top of the peak in each individual household.
- For the *Time of Use* tariff the high cost occurs for winter day. Optimal heat shift therefore shift all heat during winter from winter day to winter night. In summer, no load shifting is necessary, and the profile will stay similar to the profile for the *Current Energy Rate*.

Fig. 8 presents the cost for cases with and without ideal heat shift. For all the business models, cases with high cost without load shift have a large reduction in cost with heat load shift, while the cases with low cost without load shift have about the same cost with shift. Without shift, the *Current Energy Rate* has the lowest cost, but with a load shift it is the tariff with highest cost. The *Tiered Rate* has the largest decrease in cost, but is still the most expensive (except for the *Current Energy Rate*) with heat shift. The *Measured Power Rate has* the lowest cost.

Fig. 9 illustrates the cost of all cases, for all tariffs, both with and without ideal heat shift. The plot reveals that without load shift the *Current Energy Rate* tariff has the lowest cost for all cases, but with ideal heat shift, *Current Energy Rate* has the highest cost for all cases. The cost of the other tariffs varies more. For nZEBs with low energy demand, the *Measured Power Rate* tariff is cheapest with ideal heat, while the *Tiered Rate* tariff is cheapest for the few cases with the highest energy demand. The *Time of Use* tariff is very stable in cost, while the *Measured Power Rate* and the *Tiered Rate* tariff vary more.

3.2.1. Daily ideal heat shift

As the profile of ideal heat shift is different for each business model, the amount of heat that needs to be shifted to achieve the cost reduction is also different. A higher amount of heat shift requires a larger storage, and will make the cost reduction less achievable. In Fig. 10a, the maximum daily storage capacity that is needed to daily shift the heat necessary to obtain the highest possible cost reduction is illustrated for each business model. The heat shift for the *Current Energy Rate* is zero. Each business model has a different pattern for the optimal load shift, and the amount shifted and cost reduced is different for each case. The saving per kWh shifted heat is also unlike for each tariff, and this saving is plotted in Fig. 10b.

- The Figure reveals that the amount of saving is 0 EUR/kWh for the *Current Energy Rate*, as the cost is not affected by load shift.
- The *Measured Power Rate* tariff *has* a range of different savings per kWh for the cases. The reason for this variation is the difference in shape of the peaks. High, short peaks will give large cost saving per kWh, while low, wide peaks will give a low saving per kWh. The business model works very well for cost reduction for cases with large power difference between peak and off-peak hours.
- For the *Tiered Rate,* the saving is constantly 0,1 EUR/kWh. As the price for overuse is 0,1 EUR/kWh, it is logic that every kWh of reduced overuse will save this same amount of money. There are a few cases with even higher saving per kWh than for *Tiered Rate*. These are the cases with a very high demand, which have a subscription cost limit of 10 kW, but could be better off with a higher limit. They have a large amount of overuse that is available for shift. If there were more limits in the tariff these cases would have a lower amount of overuse, less shifted heat, and a lower saving per kWh.
- The *Time of Use* tariff has the smallest saving per kWh. As the heat is shifted from winter day with the cost of 0.0380 EUR/kWh, to winter night with 0.0152 EUR/kWh the saving is equal and constant to the difference of 0.0228 EUR/kWh.
- According to Fig. 10, the *Time of Use* tariff requires the largest capacity for heat storage followed by the *Tiered Rate* tariff and the *Measured Power Rate* tariff.

3.3. Cost calculation algorithm

3.3.1. Robustness

The robustness of the business models for different building design with and without shift is illustrated in the plots in Fig. 11. In this Figure, the standard deviation is plotted against the median cost. The plots reveal that without heat shift the *Measured Power Rate* tariff and the *Time of Use* tariff has about the same standard deviation as the *Current Energy Rate* tariff, while the *Tiered Rate tariff* has a very high standard deviation. With heat shift most cases for all the three tariffs get a standard deviation lower than the *Current Energy Rate*. The most robust model is for most cases the *Measured Power Rate tariff*. The median cost also decreases for all models with heat shift. This indicates that the business models will work as an incentive to load shift.

3.3.2. Achievability

How well a model is achieving the aim of the project depends on the cost difference before and after ideal heat shift, and the amount of heat that needs to be shifted to obtain this cost reduction. If a very high amount of heat needs to be shifted, a large storage tank or battery is needed, and it is more difficult to achieve the full cost reduction. Also, if the cost reduction is low, the probability that people will invest in a system to shift heat is less.

In the following graphs in Fig. 12 the load shift and cost for each of the groups, with and without shift, is plotted to illustrate the trade-off for each of the groups. For all of the models without ideal heat shift the price is higher than with shift. Usually the *Current Energy Rate* is the cheapest model without shift. This means that for any of the models introduced, this will for most customers mean an increased grid rent if they do not change their load profile. This in itself will be an incentive to change the profile.

Fig. 13 illustrates the amount of kWh left available for shift provided that the household reduce their limit with one step below the optimal limit. Consequently, choosing a lower limit will for most cases result in an overuse cost even with a high amount

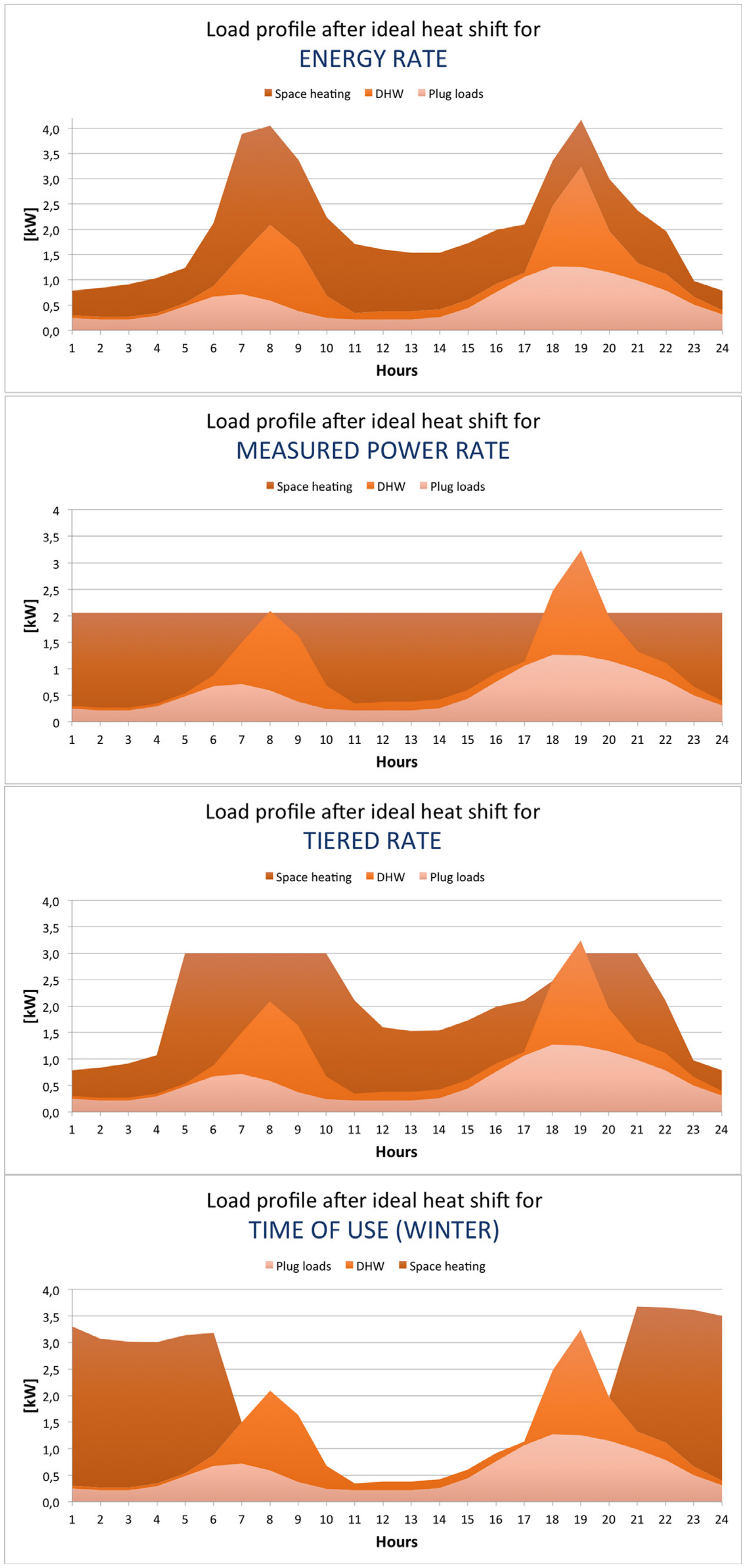

Fig. 7. Load profile for ideal heat shifting with different business models.

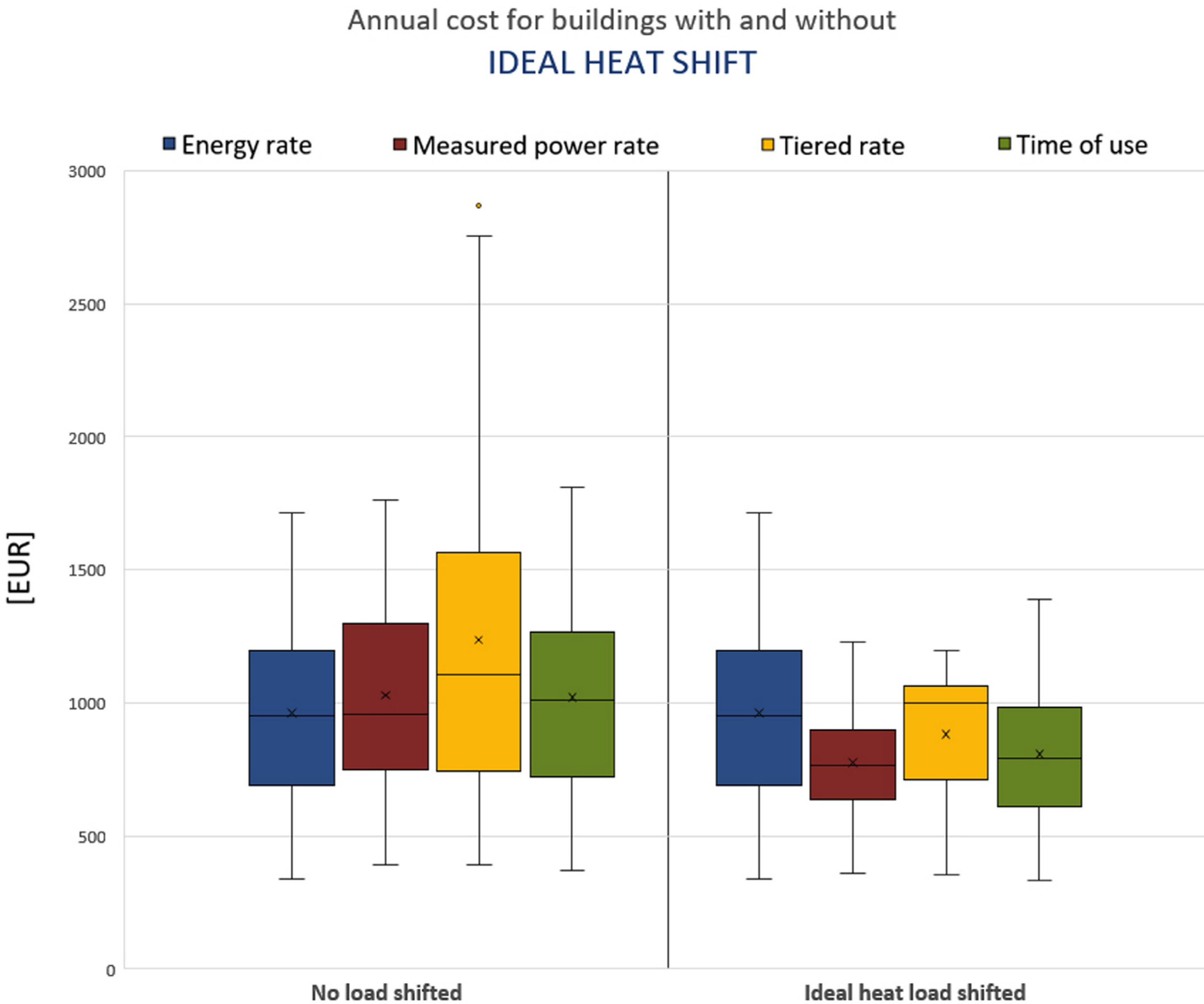

Fig. 8. Box plot for all 96 cases with and without ideal heat shift.

of heat shift. The total cost will then still is higher than for *Measured Power Rate* tariff, and the amount of necessary heat shift a lot larger.

3.3.2.1. Time of use tariff. The *Time of Use* (TOU) tariff has in all cases the largest ideal heat shift, 2–4 times larger than for *Measured Power Rate.* With heat shift TEK17 envelope have a lower cost for TOU rate than for both *Measured Power Rate and Tiered Rate*. For all other cases with heat shift the cost is lower than for *Tiered Rate* and higher than for *Measured Power Rate* tariff. This makes the TOU rate less achievable for reaching the ideal cost reduction than both of the other two models. It is also an important issue that large shifting of electricity load can potentially also create stress on the grid.

3.4. Business models comparison for electricity tariffs

In Fig. 14, the cost for grid rent with the different business models is compared for the reference building case. The cost is shown for each tariff with (W) and without (WO) ideal heat shift. For the case without heat shift all the new tariffs leads to a higher cost than the *Current Energy Rate*. With ideal shift the *Measured Power Rate* tariff and *Time of Use* rate has a lower cost than the *Current Energy Rate*, while the *Tiered Rate* is still high.

- Business model with largest economic incentive to improve building physics

Table 4 presents the business models that give the largest, and smallest, incentive for most cases with each of the building physics improvements.

- Business model with the largest economic incentive to load shift

The tariffs with the largest, and smallest, cost reduction when heat load shift is implemented in the cases are illustrated in Table 5. For most cases *Measured Power Rate* tariff and TOU tariff is giving the largest economic incentives. *Tiered Rate* tariff is for most cases the tariff giving the smallest economic incentive to shift.

4. Discussion & conclusion

4.1. Summary of main findings

In this study we developed an assessment methodology for dynamic pricing tariffs in all-electric houses that can be used by util-

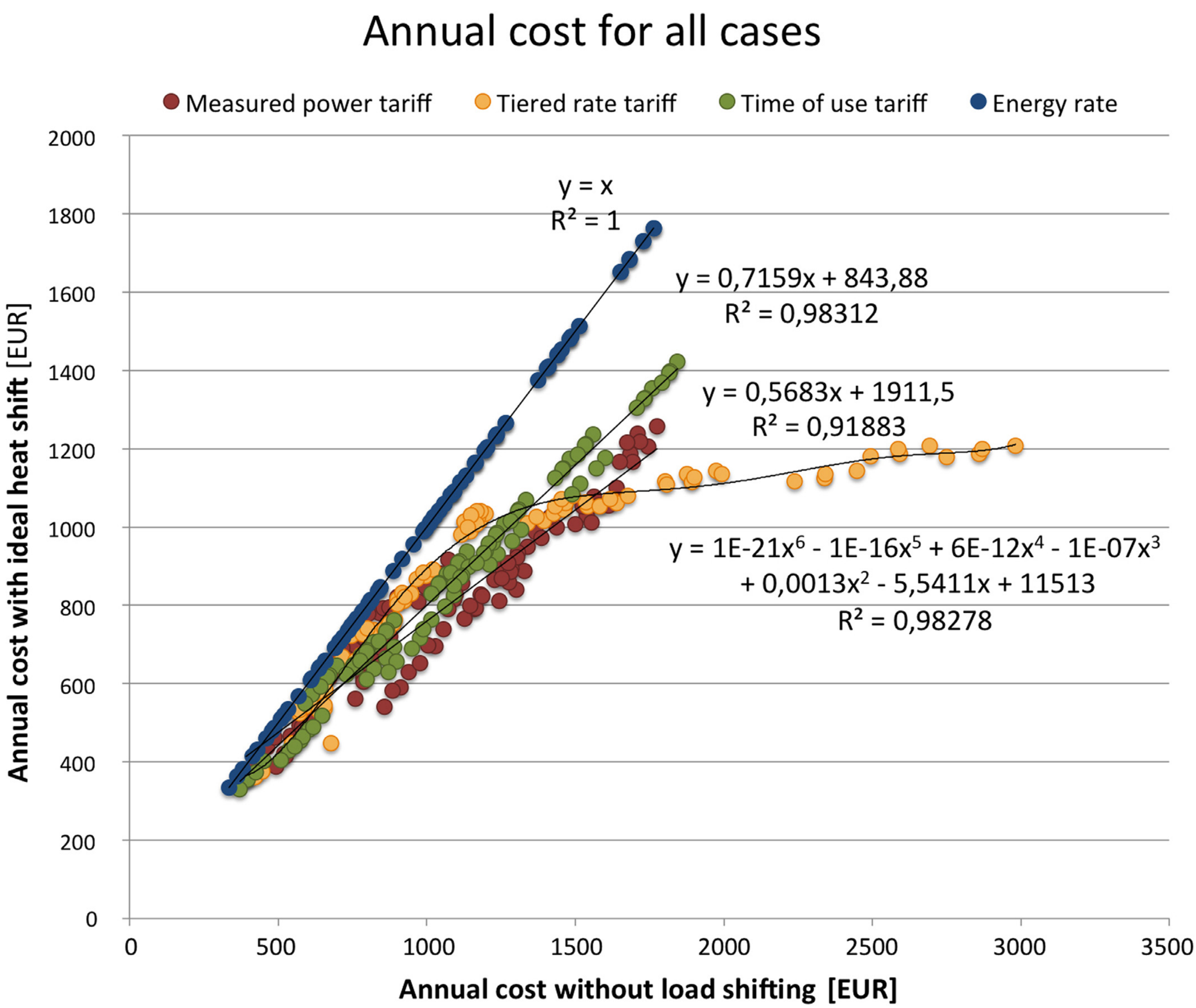

Fig. 9. Annual cost for all cases, for all tariffs, with (y-axis) and without (x-axis) ideal heat shift.

Table 4
Business models giving the largest and smallest economic incentive to improve building physics.

From	→ To	Business model	
		Largest incentive	Smallest incentive
'60	→ TEK17	TOU tariff	Measured power tariff
Direct	→ ASHP	Tiered rate tariff	Measured power tariff
NpoPV	→ PV	TOU tariff	Tiered rate tariff
NoSTC	→ STC	Measured power tariff	Tiered rate tariff
OOW	→ TCW	Tiered rate tariff	Measured power tariff
EVc	→ EVd	Tiered rate tariff	Measured power tariff

Table 5
Business models giving the largest economical incentive to shift heat load.

Parameter	Business model	
	Largest incentive	Smallest incentive
TEK17	TOU tariff	Tiered rate tariff
'60	TOU tariff	Tiered rate tariff
Direct	Measured power tariff	Tiered rate tariff
ASHP	Measured power tariff	Tiered rate tariff
NoPV	TOU tariff	Tiered rate tariff
PV	TOU tariff	Tiered rate tariff
NoSTC	Measured power tariff	Tiered rate tariff
STC	Measured power tariff	Tiered rate tariff
OOW	Tiered rate tariff	TOU tariff
TCW	TOU tariff	Tiered rate tariff
EVc	Measured power tariff	TOU tariff
EVd	Measured power tariff	Tiered rate tariff

ity companies and electric grid customers including households' occupants. By simulating the energy demand of different cases studies and creating a financial cost calculation algorithm for three major business models of pricing and load shifting, the study succeeds to identify and classify effectiveness of different behavioural and building related demand-side management strategies.

In general, we recommend the *Tiered Rate* tariff under the current energy policy in Norway. However, if policy makers are looking to align with the European Union goals to achieve a low and zero-emission building stock by 2050, they will need a variation of business models depending on the vintage of buildings. Our results

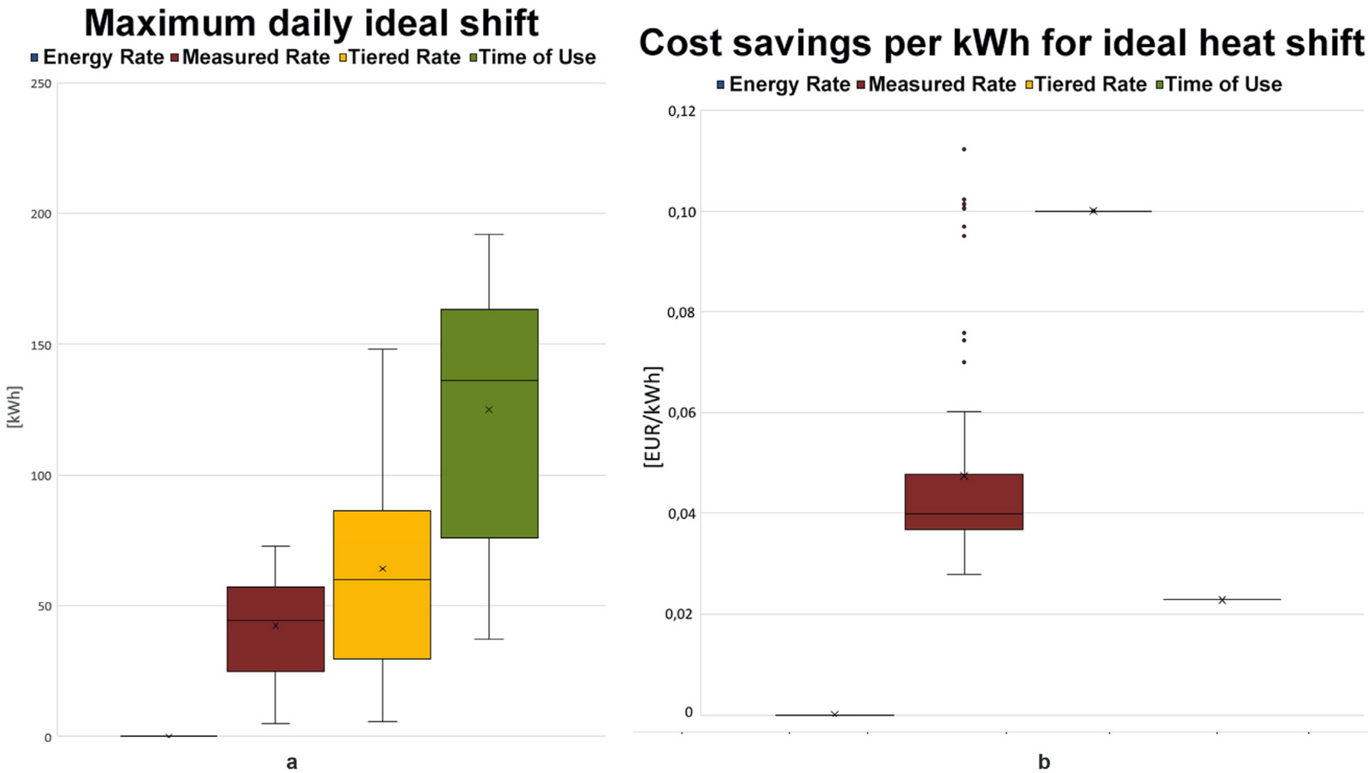

Fig. 10. a: Box plot for maximum daily ideal heat shift, Fig. 10b: Box plot for the cost saving per kWh with ideal heat shift.

presented in Tables 4 and 5 are helpful for policy makers, housing owners and tenants to select the most cost effective grid rent tariff according to the households' characteristics and grid rent alternatives. More importantly, our methodology can inform policy regulators and utilities managers about the ways to structurally improve the DSM and increase the energy efficiency of the existing building stock in cities. As a summary of our findings we can describe the three major investigated grid rent business models as indicated below according to their effectiveness:

- ***Tiered Rate* tariff**: For the *Tiered Rate* the amount of ideal heat shifted is low, but the cost incentive is very high. The hours which get incentive to shift load is random, but for customers with a typical consumption pattern the incentive will usually occur during peak hours in winter. For power use below the limit there is no incentive for load shift.

For customers with a typical pattern the tariff gives a very good and precise incentive to reduce the load during high demand periods. As the overuse cost is very high per kWh, and will make a huge impact on the energy bill, it is likely that more households will take action to change their load profile with this tariff, than with the other tariffs where the penalty is smaller per kWh. If many households are able to shift their peaks slightly, this change can be enough for the grid. A disadvantage is that for those who are not able to shift their load the payment will be very large. Furthermore, customers of this business model who use a high amount of energy during off-peak hours will pay extra, even though there is no stress on the grid at this time.

- ***Tiered Rate* tariff** is easy to react to, and the subscription limit gives a clear picture for the end-consumer of what high-energy consumption is for the individual household. Keeping the consumption below the limit for *Tiered Rate* is easier than keeping a very flat demand profile as for *Measured Power Rate* tariff. Choosing the right limit may, however, be more difficult.
- ***Time of Use* rate tariff:** The *Time of Use* tariff gives incentive to shift a large amount of load, but the incentive per kWh is quite small. The model encourages shift only during those hours, which strain the capacity of the grid, and all load during those hours have incentive to be shifted. The *Time of Use* rate tariff is the model with the easiest prediction of when to shift the load, as the hours when load should be avoided is clearly defined. No penalty is given if a large amount of load is used during off-peak hours. For this model costumers should take into account the available storage possibilities. We advise household occupants to consider in their decision the available storage opportunities. They should think about the storage solutions that give the smallest losses and highest cost reduction, in relation to their size of capacity necessary for their household. In addition, how many hours is the heat load needed to be shifted.
- ***Measured Power Rate* tariff:** for the results show that the *Measured Power Rate* tariff *the* daily amount of shift is small, and the saving for each kWh is varying largely, as shown in Fig. 10. This tariff gives incentive to shift load at all hours, all year. The tariff gives a large annual amount of load shift, even though the daily amount is small. The cost reduction is achievable with a smaller sized storage device, as indicated in Section 3.2, than for the other business models, but the load shifting during summer is not necessary to improve the peak power hours that stress the grid. Load shifting during summer can still be wanted due to reasons such as matching the demand with supply from renewable energy sources. However, in that situation a flat demand profile is most likely not the optimal solution and a business model with flexibility would be a better tariff for this purpose.

To obtain the flat load profile ideal for the *Measured Power Rate* tariff is almost impossible, as it is very difficult to predict when the load shift should occur during the day to create this profile.

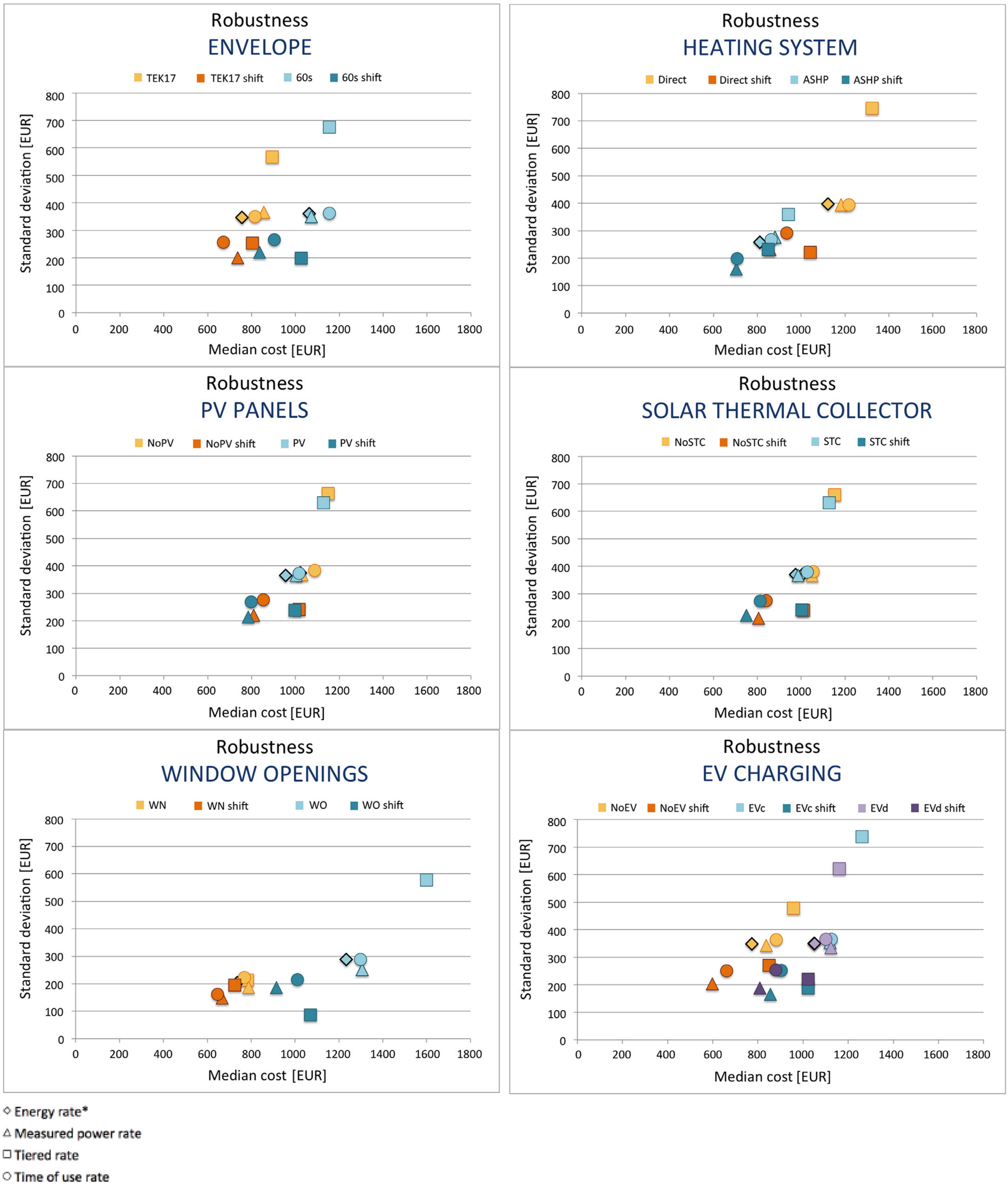

Fig. 11. Robustness of the business models for different building designs, with and without ideal heat shift. *The Current Energy Rate has no ideal heat shift, and the cost and standard deviation will be the same with and without any shift.

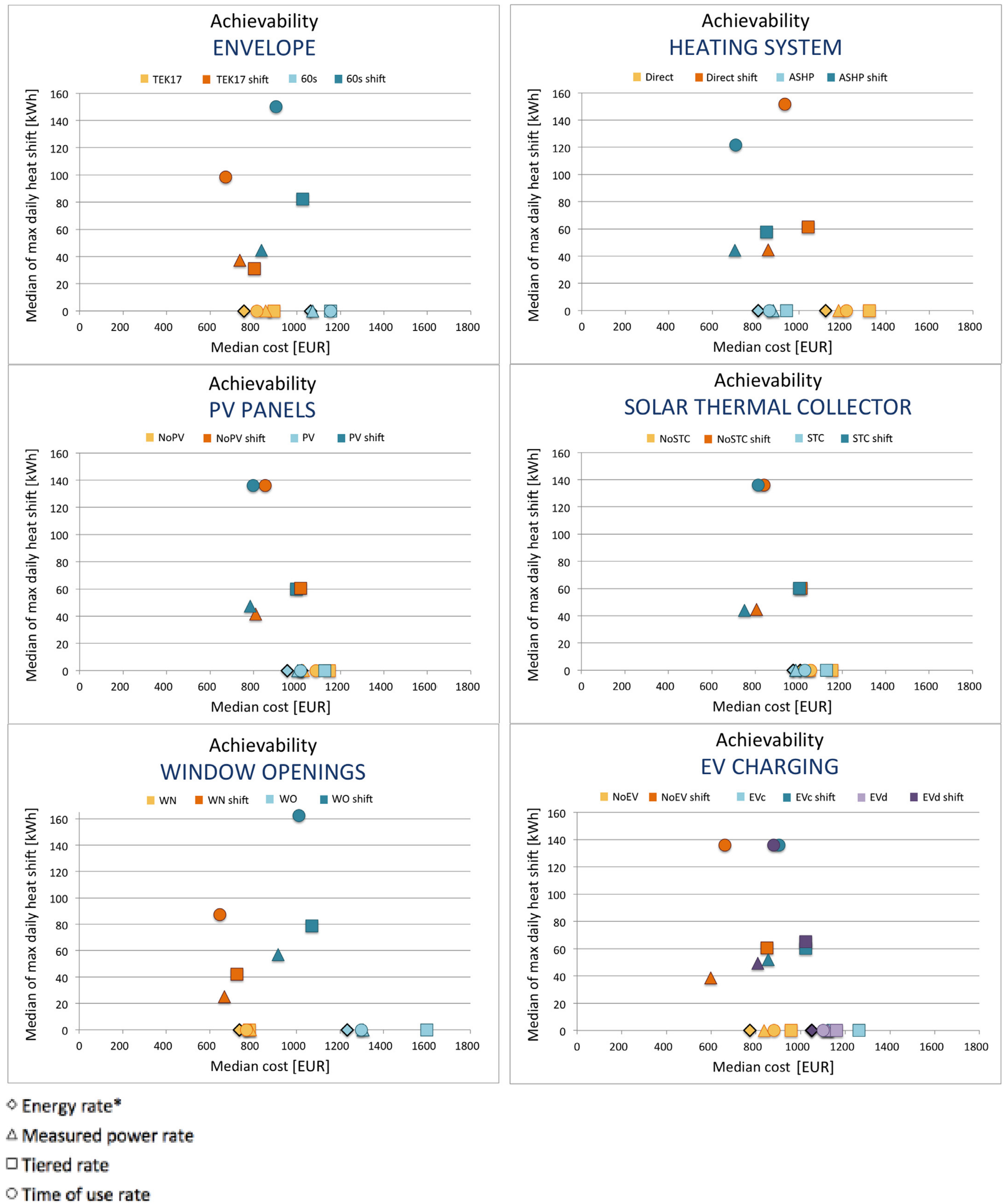

Fig. 12. Achievability of the business models for different building design, with and without ideal heat shift. *The Current Energy Rate has no ideal heat shift, and the cost will be the same with and without whatever shift.

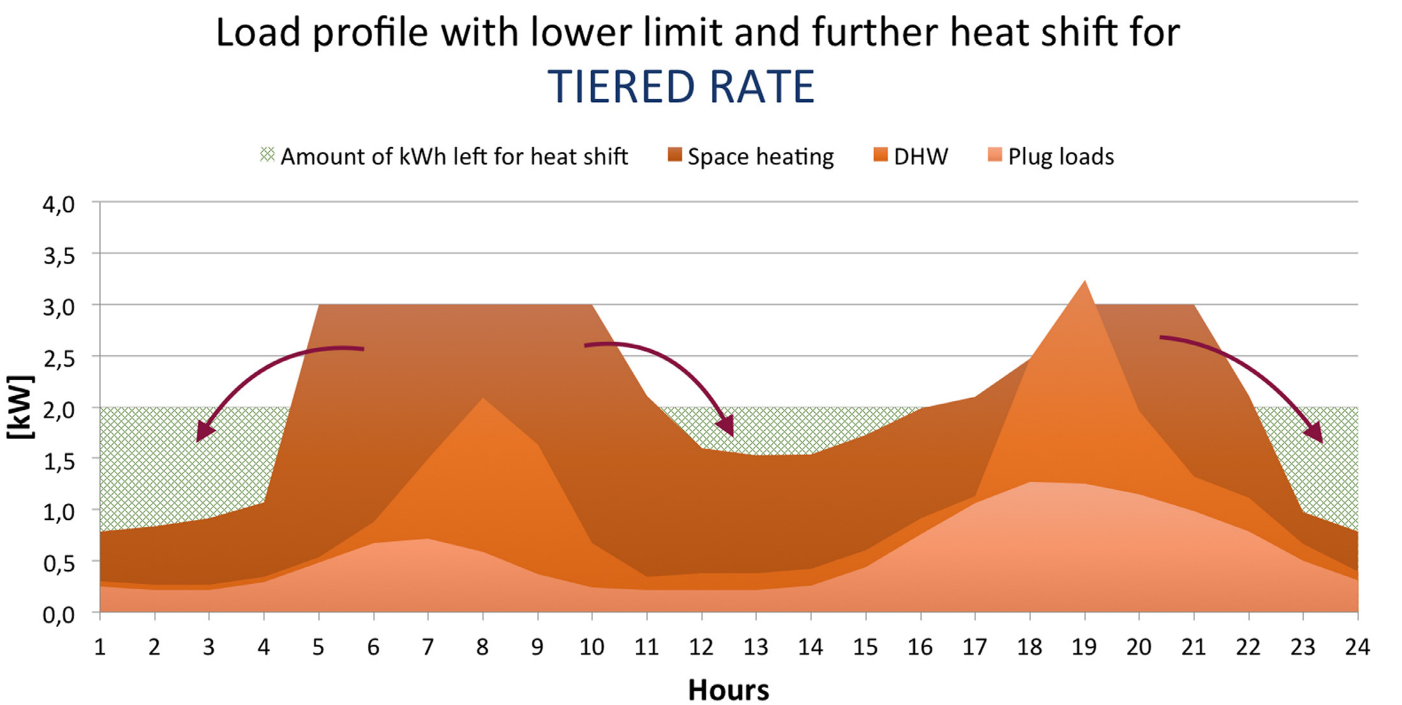

Fig. 13. Amount of kWh available for heat shift if a lower power limit is chosen for the reference case TEK17 WN Direct NoSTC NoPV NoEV.

If the customer has access to their load data, they will be able to find patterns in their use, and reduce load at typical peak hours. Large reduction in peaks will be possible to obtain with this tariff, and the amount of savings resulting from ideal heat shift is highest among the three scenarios (see Fig. 8). The reason behind this high energy saving is that the heat load scenarios assumes a flat profile, which hard to achieve in reality. Moreover, if peaks occur at off-peak hours, the customer will be penalised for it with this tariff.

4.2. Strength and limitations

We are not aware of any conducted study that aimed to set up a methodology to assess business models of dynamic pricing tariffs in all-electric houses. Despite its scientific approach, our methodology benefited from the contribution of stakeholders consultation that fostered a consensus on the different grid rent business models and parametric variations of our investigated case studies. Involving stakeholders, from the beginning of our research, takes our work one step further and brings our findings closer to reality rather than being only a theoretical endeavour. Accordingly, this research aimed to define the intrinsic incentives of different building stock renovation measures and household behaviours. Therefore, we believe that our methodology can be transferred to other cities. In this sense, we do not provide local results that apply only for Norway, but other countries such as Kosovo, Malta, Sweden, and Finland (where more than 25% of space heating energy is based on electricity)can use our methodology in their context. More importantly, we believe that our methodology can provide the foundation for the development of a new user interactive tools that can be used to inform various stakeholders.

We validated our calculation algorithm by investigating the robustness of the proposed business models and their achievability. The robustness testing results, in Section 3.3.1, indicate that the business model will work as an incentive to load shift. Also the achievability testing (Section 3.3.2) ranks the business models according to their ability to shift the loads in a cost-effective way.

We acknowledge that our study is limited to fully electric operated buildings (i.e., all-electric houses). We did not explore any technology or measure related to water tank storage, phase change materials or thermal mass. Findings on tariff incentive variance in this study apply to single person households only. Also, the lack of consideration of excess production from the PV is a clear shortcoming of this calculation algorithm, and an area for improvement. The model could also drive benefit from being more automated. Easier connections to input and output from the excel workbooks could decrease the number of operations needed to do changes in the workbooks. We also did not distinguish the weekend daily profiles from the workday daily profiles, in Section 3.2. We expect that future work will address those shortcomings to consolidate the methodology much more or build on it.

4.3. Implications for practice and future research

Electrification of nZEBs is becoming a trend and is expected to increase in the future [5]. The dynamic pricing of grid rent tariffs will be a crucial factor with this new structural tendency. In this paper, we developed a research methodology based on the Norwegian national context. The result from this investigation could be basis many more analysis than those included in this paper. Also, our developed algorithm could be used for investigation of new cases to support the decision making of policy makers, utilities managers and households occupants. We find it important that future research builds on our findings and develops more comprehensive assessment methods of dynamic pricing tariffs that empower grid customers. There is still uncertainty regarding the impact of our study findings. For example, load shifting of residential households as the *Time of Use* rate tariff or the *Tiered Rate tariff* would create problems in terms of 'rebound' of peaks and potential additional peaks [44]. For a Norwegian smart grid DSM strategy, what is needed is the change of behaviour of a fraction of consumers. Hence, future study should deal with DSM strategies which based on the consumers fractions and building typologies

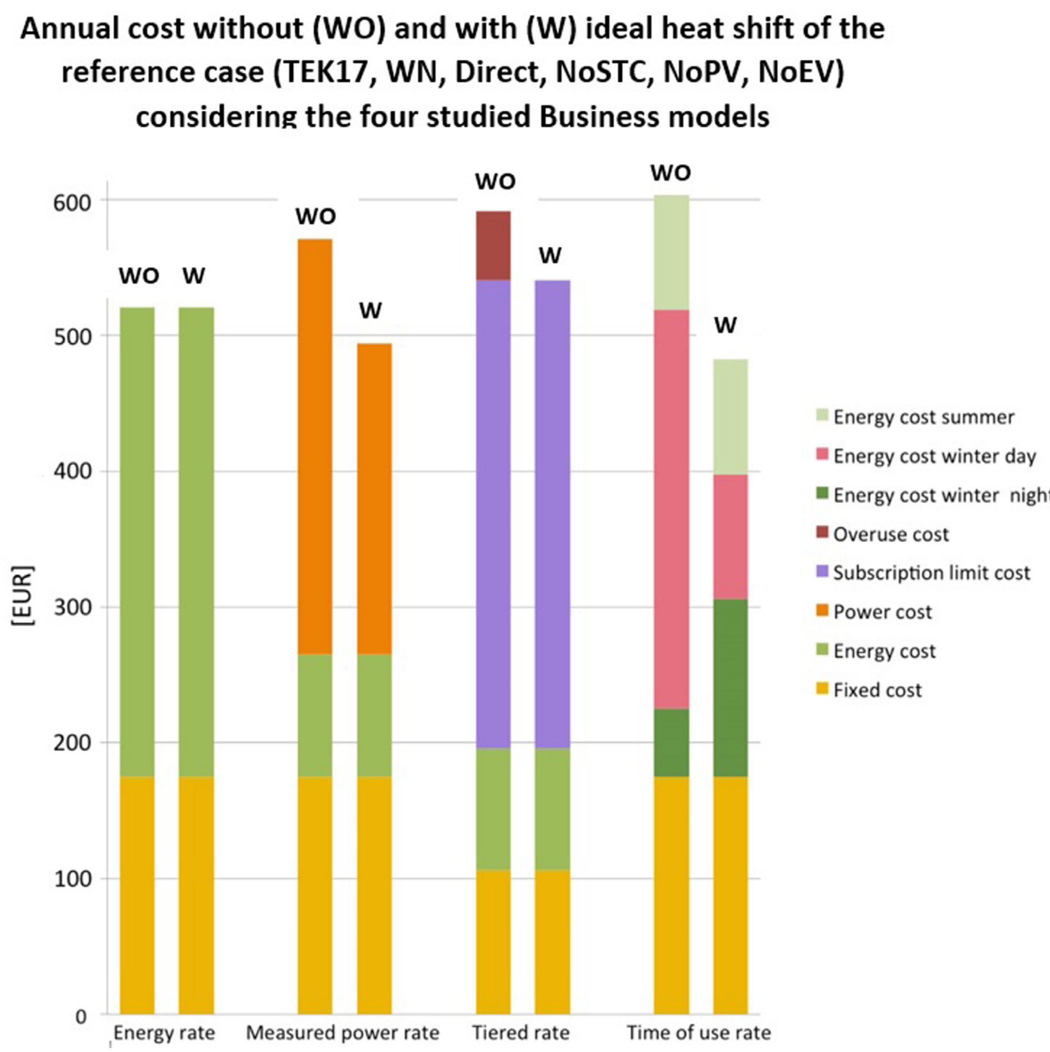

Fig. 14. Annual cost without (WO) and with (W) ideal heat shift of the reference case (TEK17, WN, Direct, NoSTC, NoPV, NoEV) considering the four studied Business models.

[3]. There are several areas that will need further investigation, amongst these are:

- **Building cases and consumers fractions:** A broader building spectre need to be investigated to be able to research which tariff model is the better for the whole building stock, not only single family houses.
- **Aggregated load shift:** A study on how aggregated load shift for different models will change the grid load profile, the strain on the grid, and the income for grid distribution companies are important factors when deciding on a tariff that should be the next step to investigate.
- **Flexibility:** For renewable energy sources like wind and solar power to be a large part of the energy supply on the grid, it is an absolute necessity to incorporate flexibility into the grid. The development of a flexible business model, that can include a third party operator to handle the flexibility, needs more investigation. The new grid rent tariff would benefit from having taken this issue into account before deciding.
- **Excess PV production:** Investigation of what is most profitable for excess PV production – exporting to the grid, implementing a battery, or implementing a control system to match supply and demand.

Declaration of Competing Interest

There is no conflict of interest.

Acknowledgements

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Appendix I

Schedules

Realistic schedules for light, equipment and domestic hot water (DHW) are used to increase the reliability of the energy demand profiles in the model. The technical specification SN/TS 3031:2016 [45] is a standard made for calculation of the energy performance of buildings with standardised requirements and are developed as reference conditions for simulation. Typical load from DHW and technical equipment is found in Table A.2 and A.3, “småhus” (single family house), in SN/TS 3031:2016 [45]. A schedule for light is also found in the standards, but this one is static, with the same

Table A1-1
Different load schedules for a single family house, from SN/TS 3031:2016 (2016). For lighting, only the daily amount is used.

Hour	DHW [Wh/m^2]	Equipment [Wh/m^2]	Lighting [Wh/m^2]
1	0.00	0.96	
2	0.00	0.96	
3	0.00	0.96	
4	0.00	0.96	
5	0.00	0.96	
6	0.96	0.96	
7	6.87	0.96	
8	0.96	1.92	
9	0.96	1.92	
10	0.96	0.96	
11	0.96	0.96	
12	0.96	0.96	
13	0.96	0.96	
14	0.96	0.96	
15	0.96	0.96	
16	0.96	2.88	
17	0.96	4.81	
18	13.74	4.81	
19	13.74	4.81	
20	1.37	4.33	
21	1.37	4.33	
22	1.37	2.40	
23	0.96	240	
24	0.00	0.96	
Daily operational	68.67	48.05	31.28
hours	18	24	

Table A1-2
Lighting schedule. Distribution is taken from Hamdy et al. [46] and annual amount from SN/TS 3031:2016 (2016).

Hour	Winter [Wh/m^2]	Spring [Wh/m^2]	Summer [Wh/m^2]	Autumn [Wh/m^2]
1	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00
5	2.59	1.55	1.24	1.55
6	5.18	3.16	2.44	3.16
7	5.18	3.16	2.44	3.16
8	2.59	1.55	1.24	1.55
9	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.78
15	1.30	0.78	0.62	1.55
16	2.56	1.55	1.24	1.55
17	2.56	1.55	1.24	3.16
18	5.18	3.16	2.44	3.16
19	5.18	3.16	2.44	3.16
20	3.89	2.38	1.87	2.38
21	3.89	2.38	1.87	2.38
22	2.59	1.55	1.24	1.55
23	2.59	1.55	1.24	1.55
24	1.30	0.78	0.62	0.78
Total	46.64	28.03	22.18	28.30
Days	90	92	92	91

amount of light all day, every day. As lighting in Norway is changing over both the year and day due to different amounts of solar light, the schedule is made dynamic to create a more realistic scenario. For instance, typically lighter is used during winter evening than summer day. The total annual amount of lighting is set equal to the amount in SN/TS 3031:2016, and the distribution is based on a lighting schedule created after a survey from households in Finland [46]. The schedules reproduced from SN/TS 3031:2016 in Table A1-1 is normalised input values. See Table A1-2 for the dynamic lighting schedule.

The distribution of the light, equipment and DHW demand for winter is illustrated in Fig. A1-1. For the other seasons of the year the profile will be similar, but the light demand will be lower.

Set point temperatures

The set points for temperature and operation hours are also used as in SN/TS 3031:2016, taken from Table A.8 and A.9, as shown in Table A1-3 [45]. These schedules and set points are equal for all the building cases.

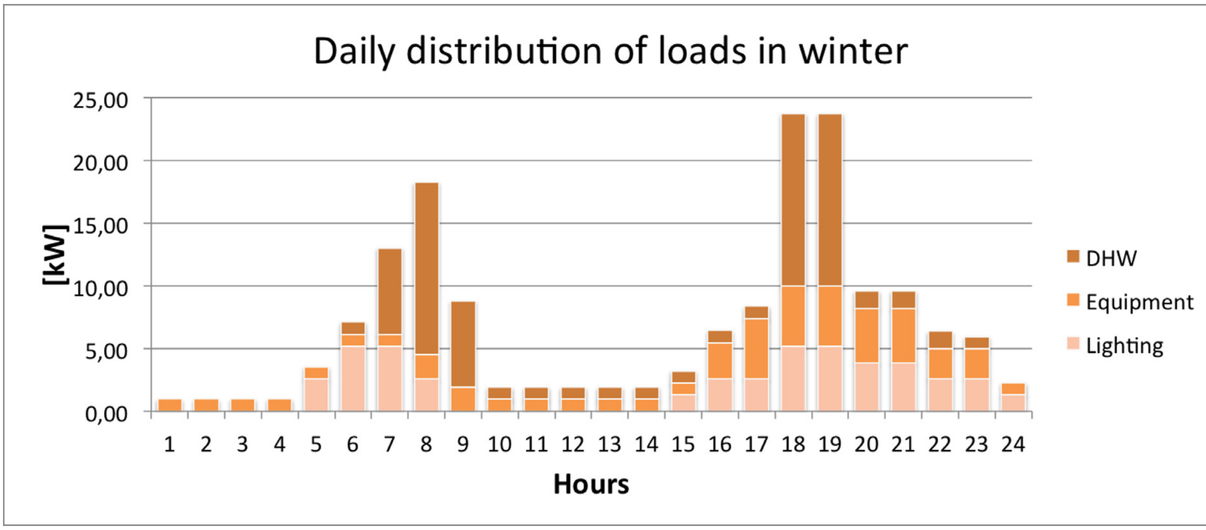

Fig. A1-1. Illustration of the daily distribution of plug loads and DHW during winter.

Table A1-3
Set point temperatures for a single family house, from SN/TS 3031 [45].

	Heating	Cooling
Set points during operating hours	22 °C	24 °C
Set points outside operating hours	20 °C	24 °C
Daily operative hours	16	24

Appendix II

Envelope

Two different kinds of envelopes have been compared, one representing new buildings and one representing the old building stock. The new building is constructed according to the requirements in TEK17. The old building is based on the same model, but with insulation and windows equal to a typical building from the ’60 s. See Table A2-1 for the differences between the two building types.

Window openings

Two different window schedules were simulated. With temperature-controlled windows (TCW), the windows open when the temperatures get higher than the set point value for cooling, 24 °C, and the heating system is turned off. In the other case occupants open the windows (OOW) when the temperatures reach the set point for heating, without turning down the heating system. The set points are 20 °C at night and 22 °C during day. The windows are opened in bedrooms during night and in other rooms in evening if the temperatures reach the set point temperatures, to improve the ventilation and admit cool air during night. The heating demand will increase due to occupant’s ignorance.

The schedule used for the opening by occupants is found in Table A2-2.

Table A2-1
Differences between the two building types.

	TEK17 House	’60 House
U-value walls [W/m^{2}K]	0.40	0.18
U-value roof [W/m^{2}K]	0.38	0.13
U-value floor [W/m^{2}K]	0.60	0.10
U-value windows [W/m^{2}K]	2.90	1.20
Air tightness (50 Pa) [h^{-1}]	10.0	0.6
Thermal bridges [W/m^{2}K]	0.10	0.06

Table A2-2
Schedule for occupant openings of windows.

Hour	Bedroom windows [%]	All other windows [%]	
Hour	All week	Weekdays	Weekends
1	25	0	0
2	25	0	0
3	25	0	0
4	25	0	0
5	25	0	0
6	25	0	25
7	0	0	25
8	0	0	25
9	0	0	25
10	0	0	25
11	0	0	25
12	0	0	25
13	0	0	25
14	0	0	25
15	0	0	25
16	0	50	25
17	0	50	25
18	0	50	25
19	0	50	25
20	0	50	25
21	0	50	25
22	0	50	0
23	25	0	0
24	25	0	0

Heating system

The two heating systems evaluated are a direct electric heating system and an indirect heating source in the form of an air source heat pump (ASHP). The direct electric heating system has a COP equal to 1, which means that the supply power is equal to the delivered heating to the space. When 1 kWh of electricity is supplied to the system it delivers 1 kWh of heating to the space. The ASHP has a higher COP than 1, which means that it delivers more heating to the space than the amount of electricity supplied. The ASHP used for this case is based on the power values and COP from the Toshiba Heat Pump Daiseikai 9 RAS-35 [47], see Table A2-3.

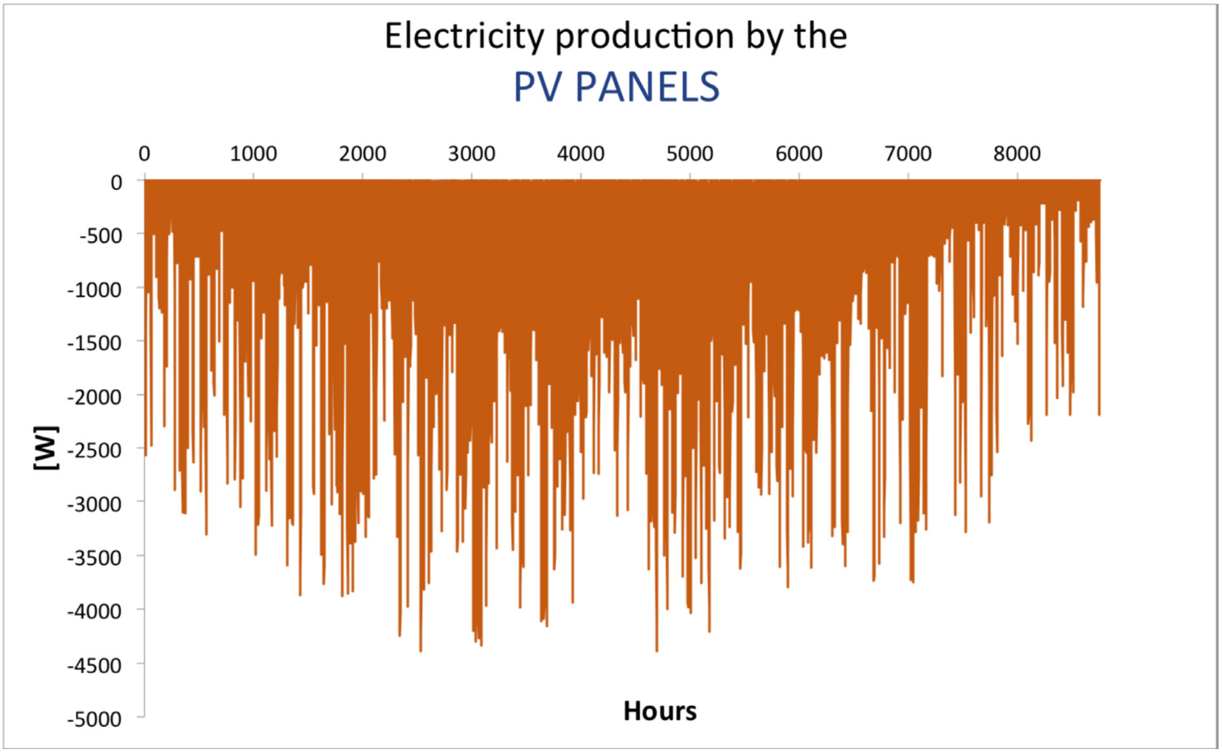

Fig. A2-1. PV production from the PV panels over the year.

Table A2-3
Characteristics for the heat pump [47].

	ASHP	RAS-35
At −7 °C	Maximum heating output [W]	5500
	COP	2.41
	Supply power [W]	2280
At −15 °C	Maximum heating output [W]	4500
	COP	2.21
	Supply power [W]	2040

Assuming the graphs for the power output and COP to be linear and mainly dependant on the outdoor temperature, the equations for the heat output of the heat pump are as given in Eq. (1) and 2. The outdoor temperature is taken from hourly weather data for Oslo, Gardermoen, from IDA ICE. The power demand from the heat pump is calculated hourly depending on the heating demand and outdoor temperature. For the hours with very cold weather the heat pump will deliver less energy than the demand. For the hours when it is too cold to gain any heat from the outside air the COP is equal to 1, as the heating coil in the heat pump will heat the space with direct electricity.

$$P(To) = 6375 + 125xTo[\mathrm{W}] \tag{1}$$

$$COP(To) = 2.585 + 0.025xTo[-] \tag{2}$$

PV panels

The energy production from the PV panels is simulated separately with IDA ICE. The panels are placed on the roof of the building, with the optimal angles of 15° from south towards west, and 60° from horizontal position, to obtain the highest gain. Default values for PV panels are used, and the overall efficiency is set to 0.15. The production by the panels is 5152 kWh/year, distributed as shown in Fig. A2-1.

The calculations with the energy from the PV panels are not considered in the cost. That means that when the PV panels are producing more energy than what is needed in the building in the same moment, the excess energy is lost. In real life the energy would most likely either be exported to the grid or stored in a battery. If the energy is exported, there will be a charge for grid rent from the customer to the grid distribution company, and a payment from the supply company. The total cost for grid rent will therefore increase with energy export, while the cost for supply will decrease. The total cost will in total be decreased with PV panels, but the exact price will depend on the subscription with the supply company. In this case the cost and sell prices are therefore not included in the analysis, and the excess production is considered as lost.

For hours when load shift is relevant to save cost, only the heat is shifted and DHW and plug loads are kept unaffected. Therefore, in these calculations the electricity from PV production is first used on the load from DHW and plug loads, and then on heating. In this way the potential amount of load for shift is kept as large as possible, and the cost saving is optimised.

Solar thermal collector

The effect of a solar thermal collector is simulated separately in IDA ICE. The collector is connected to a domestic hot water tank with the demand and schedule as described previously. Default values for a flat plated STC in IDA ICE are used. The collector is chosen to be 6 m^2, which is within the typical range recommended for a collector only connected to DHW. If the collector were to be used for space heating as well it should be larger. The STC is put on the roof, 5 m above ground. To optimise the gain, the angles are set to 15° from south towards west, and 60° from horizontal position, similar as for the PV panels. Fig. A2-2 displays the heat collected with the panels. This illustrates that the collector is even able to gain some heat during winter. When there is not enough heat gained through the STC the hot water tank is supplemented

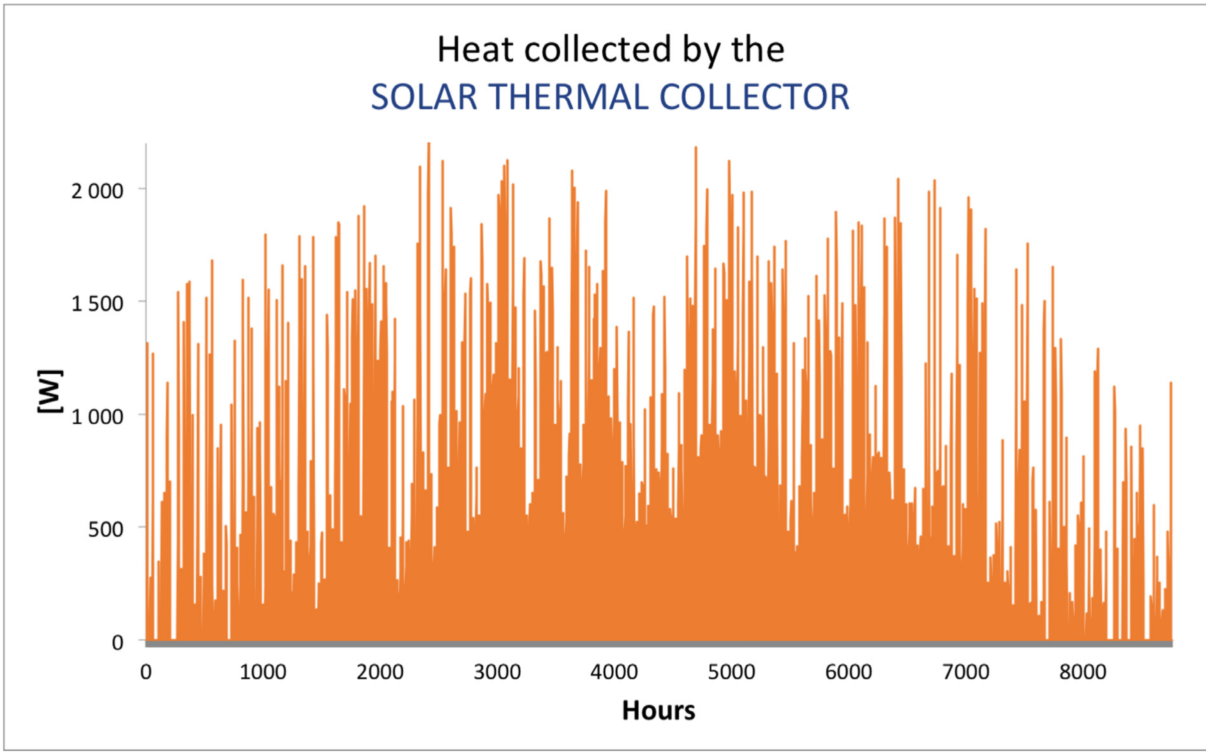

Fig. A2-2. Heat collection from the solar thermal collector over the year.

with an electric top heating with a COP of 1. The STC can reduce the DHW demand with 1718 kWh a year.

Electrical vehicle charging

To illustrate the charging of an electrical vehicle the very popular e-Golf from Volkswagen is used as an example. If a typical home charging station is installed in the household, with 20 A and 3,6 kW power, an e-Golf will need 10 h 50 min to charge from 0 to 100% (Volkswagen, 2018). In the calculations the car is assumed to be using about 80% of maximum capacity every day and will need 9 h of charging. Typical charging hours for an electrical vehicle starts at 16:00, when people are coming home from work. To examine the effect of a controlled charging, charging with 5 h delay is also calculated. The charging is started with a smart control at 21:00, to avoid the main evening peak on the grid and still be fully charged by morning. See the schedules for the different alternatives in Table A2-4.

Table A2-4
Schedule for charging of electrical vehicle.

Hour	No EV [kW]	EV typical charging [kW]	EV delayed charging [kW]
1	0	0	3.6
2	0	0	3.6
3	0	0	3.6
4	0	0	3.6
5	0	0	3.6
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	3.6	0
17	0	3.6	0
18	0	3.6	0
19	0	3.6	0
20	0	3.6	0
21	0	3.6	3.6
22	0	3.6	3.6
23	0	3.6	3.6
24	0	3.6	3.6

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