Exploring the Demand Response Potential of a Smart-Grid Ready House Using Building Simulation Software

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Abstract

The emergence of buildings as a potential demand response resource in the nascent smart electrical grid has led to increased interest in integrating load shifting/forcing solutions in buildings to address grid supply demand supply unbalances and obtain economic benefits. Such demand responsiveness is only possible if buildings accommodate flexibility, which can be defined as the ability to shift or force electrical power consumption to another time. Residential buildings are an important component to this challenge, particularly if they implement controllers capable of responding to price schemes or signal, either by delaying or pre-empting electricity consumption. The present paper explores the potential of thermal flexibility of a smart-grid ready all electric domestic building, which is equipped with a 12 kW heat pump, a 0.8 m^3 water storage tank and an electric vehicle. The assessment, based on an analysis using EnergyPlus, result to an overall economic saving of 20% for the owner during the year. The control scheme adopted halved the generation costs and provides flexibility to the system operator.

1 Introduction

During the last decade there has been a significant increase in the installed wind power capacity in Ireland, resulting in displaying today one of the highest wind penetration levels in the world (O Gallachoir, et al., 2007). In 2012, wind generation levels were above 40% instantaneous penetration for 46 days throughout the year; while over the entire year, wind was responsible for 17% of gross electrical production (Eirgrid, 2013). This trend is likely to continue for the foreseeable future because of Ireland's national 2020 target of 40% electricity production from renewable energy sources (RES) by 2020 (SEAI, 2012). Wind generation is variable which leads to demand/supply imbalances. Increasing levels of wind in the system is likely to result in additional variability in the system with associated technical problems which is posing new challenges for system operators. These challenges may be solved by the next 'generation' of electric grid known as smart grid because of the latter's controllability of loads and generators (Farhangi, 2010). The deployment of the smart grid allows buildings to provide flexibility as the ability to shift or force electrical power consumption, which is normally aligned with real-time energy demand, to other times. Flexibility, from the end use perspective, can be enhanced by the electrification of building thermal loads and subsequent installation of local thermal energy storage. Increased electrification of building thermal loads also has the potential to contribute to an overall decrease of CO_2 emissions (Feeley, et al., 2008).

The IEA Roadmap for Energy Efficient Buildings forecasts a reduction of CO_2 emission and an increased energy flexibility in residential buildings through a better insulation, as well as more energy efficient technologies for space heating and domestic hot water (IEA, 2011). Among these technologies heat pumps are a particularly effective way of electrifying residential thermal loads as they can be easily coupled with thermal energy storage systems, either active, such as water tanks, or passive system such as underfloor heating. According to (IEA, 2011), it is expected that there will be a significant growth in the number of heat pump installations throughout the world. In the future, the electrification of domestic heating systems through heat pumps is expected to change substantially the residential electric energy demand patterns (Veldman, et al., 2011). In such dynamic environment, electric heating systems like heat pumps, by using sophisticated control schemes, can provide demand response flexibility to the power grid.

Demand response flexibility in the residential sector could facilitate the increase of renewable energy sources on the power system, decrease the carbon footprint of the residential sector, ultimately enabling countries to reach their renewable energies and CO_2 emission targets. From the point of view of the residents, demand response flexibility leads to a meaningful economic savings.

The objective of this paper is to explore the potential demand response flexibility provided by an all-electric smart grid-ready house. The house is controlled by an algorithm that reacts to a price signal. The system uses the thermal flexibility of the building and of its thermal storage to produce economic savings and reduce the annual CO_2 emissions.

2 Building description

Architecture and building physics

The building used as a test case for the current work is shown in Figure 1. It is located in the east of Ireland and is equipped with thermal energy storage (TES), a heat pump, PV, solar thermal collectors, heat recovery ventilation and an electric car.

Figure 1: Test bed house and its 3D representation with Google SketchUp

Although its architectural characteristics are those of a typical rural Irish bungalow of the 1970s, its fabric specifications are very close to the current Irish building regulation values (Irish Government Publications, 2011) as outlined in *Table 1*. The floor area is 205 m^2 and the overall window to wall ratio is 15%, with a 22% and 10% ratio on the south and north faces, respectively. The house has 12 rooms at ground floor and 1 attic.

Table 1: U-Values of different building elements

Building Component	U-Value Test building (W/m^2K)	U-Value Irish Building Regulation 2011 (W/m^2K)
Walls	0.25	0.21
Roof	0.25	0.21
Windows	1.5	1.6
Floor	0.21	0.21

HVAC system

For space heating the house is equipped with a 12 kW ground source open loop heat pump and a large hot water tank of thermal storage of 0.8 m^3, which supplies a hydronic heating system. The heat pump was modelled with EnergyPlus, using physical parameters taken from the heat pump user manual. These parameters are used by the software to estimate the performance of the heat pump (Hui, 2002). The water tank was modelled as water heater fully mixed. The tank has a double layer of insulation and is located into the utility room inside the house. The limited heat losses from the tank are represented as an internal heat gain for the utility room where the water tank is located. A radiator is present in each room, while in the kitchen there is, a 5 kW wood stove. The wood stove is used only during the heating period, from October to April. The stove has a significant effect on the energy performance of the house and a dramatic impact on the thermal conditions of the kitchen and the adjacent living room. Since the door between those two rooms usually remains opened, increased air mixing was assumed. The heat recovery ventilation (HRV) system uses the heat from the exhaust air of the kitchen and bathrooms to warm up the fresh air supplied to the bedrooms and living room. The HRV has an average sensible heat transfer effectiveness of 80% and operates only during the heating period.

Occupancy and Air Exchange

Two adults occupy the house. The occupancy profiles, use of electric equipment and lights, domestic hot water (DHW) use patterns and the respective distribution of internal heat gains were calculated based on the process described by (Neu, et al., 2013). To build the necessary profiles, a time of use activity survey was utilised. The profiles were calibrated with the appropriate occupant adjustments to better replicate the real life activity patterns. The building is naturally ventilated with local exhaust extraction fans only present in the kitchen and bathroom. Following the trends of buildings with similar construction features, the sum of infiltration and ventilation was adjusted to an annual average value of close to 1 ACH, with the exception of the kitchen and bathroom where the respective value was higher than 1.5. Two zone mixing air exchanges were modelled, (i) between the living room and the kitchen, where the door is frequently open (2 ACH), and (ii) between the living room and the corridor (1 ACH). Seasonal (between winter and summer) and daily (between night and day) variations of both infiltration and ventilation were considered.

Heating period and schedules

The heating season is from Oct 1st to April 30th according to user schedule preferences. In the living area (kitchen and living room) a temperature of 21^{o} C is ensured due to the contribution of the wood stove. In the remaining zones, the temperature set point of the heating system is 18^{o} C which is in accordance with the current Irish regulation (AECOM House, 2013).
As a consequence of the occupants' habits, between 1:00 and 6:30, the temperature can decrease from 18^{o} C to 17^{o} C in order to increase the energy stored in the TES.

During weekdays, occupants are usually at home before 9:00 and after 17:00. The algorithm optimises the energy based on this typical occupancy pattern. During the weekends, the occupants spend most of their time at home, so the algorithm always maintains the temperature at the user set point.

Photovoltaic system

The array of photovoltaic panels has a nominal power of 6 kWp. It is placed 30 meter from the house and it faces south with 30 degrees of inclination. The system has 30 PV panels of 200 Wp allocated in three arrays of 10 panels each.

Domestic hot water

The domestic hot water is provided by two solar thermal collectors, each consisting of 30 vacuum pipes and feeding a 250 litre water tank. The overall surface area of the solar collectors is 6.15 m^2. A 2 kW immersion resistance in the water tank provides auxiliary heating. The water tank was modelled in EnergyPlus as fully mixed. Although a stratified model of the water tank would have been more accurate, in the simulation results, the electric consumption of the heating element was aligned with the real data available from the electric meter installed.

Electric Car

The electric car is a Nissan Leaf, with a 24 kWh battery pack. The daily distance travelled is approximately 50 km. According to (Smith, 2010), the energy consumption by EVs depends on the season due to the air conditioning requirements of the cabin, which can dramatically affect the energy performance of the car. Liaising with the householder and using archived data of his car energy consumption, the normalised electricity consumption of the EV for the building simulation was set to 150 Wh/km during the summer and 250 Wh/km during the winter. The car is charged over night when electricity prices are lower. The daily energy requirement of the car is 12.5 kWh in the winter and 7.5 kWh in summer time. During night time charging, the electricity drawn follows the pattern suggested by (Marra, et al., 2012).

Weather and simulation period

The closest weather station to the house is located 35 km away at Dublin airport and this data was used as the input for the building energy simulation analysis (Lundstrom, 2012).

3 Methodology

The dwelling model was built using EnergyPlus and calibrated with the energy consumption data available from the energy meters installed in 2012. The house has 13 rooms, each corresponding to a thermal zone. During the heating period, the schedules of the heating system and the occupancy profile were scheduled to reflect the preferences and behaviour of the users.

The control model of the smart-grid house was built progressively; the first version called "No control" does not have any control, except a thermostatic set point. The energy consumption, environmental impact and electricity cost, both from the owner and utility perspective, act as the reference case. To obtain realistic results, assumptions were based on occupant survey and collaboration.

The occupancy profile was adjusted according to the working time of the occupants and their typical weekend and evening activities. The appliances typical time of use was also tuned according to their habits. Specific schedules based on typical use were adopted for washing machine, dishwasher, oven and cooking hobs.

A control algorithm was implemented and tuned with three different settings and compared with the reference case. The control is responsive to a time-of-use price signal (TOU). For each setting, a 15 minute time step simulation was performed with real weather data. This resolution is acceptable in power systems for demand response and electricity trading analysis. Albeit a resolution in the order of seconds to minutes is necessary to capture all the details of the residential consumption pattern and to exploit flexibility for frequency control. However, in this case, the objective was to assess the flexibility potential of a single building from an energy trading and environment perspective. For such purposes, in Ireland, the data available has a thirty minute resolution. Thus, from a power system perspective, to aggregate the flexibility potential of individual residential buildings, a fifteen minute resolution is appropriate.

Electricity Price

In 2010 the Irish Commission for Energy Regulation initiated a smart meter trial (CER, 2012) introducing several TOU tariffs to the dwellings enrolled, as shown in Table 2. These tariffs were used to evaluate the responsiveness of the electricity end users to a price difference between peak and off peak time following the average pattern of the market price.

Table 2: Time of Use electricity tariffs

Tariff type	**Night** 23.00-08.00	**Day** 08.00-17.00 all days 17.00-19.00 weekends and holidays 19.00-23.00 all days	**Peak** 17.00-19.00 Monday to Friday excluding holidays
	€/ kWh	€/ kWh	€/ kWh
A	0.12	0.14	0.20
B	0.11	0.135	0.26
C	0.10	0.13	0.32
D	0.9	0.125	0.38
Flat	0.135	0.135	0.135

Control algorithms

The control system was developed in EnergyPlus utilising the Energy Management System and the relative programming language (Ellis, et al., 2008). The objective function of the control algorithm is to reduce, the owner energy cost keeping the comfort limit constraint valid:

$$\boldsymbol{min}\left(\sum_{t=0}^{24} \boldsymbol{C_e(t)}\ \boldsymbol{P_e(t)}\right)$$

Subject to comfort constraints

where $\boldsymbol{C_e(t)}$ is the price of electricity at time **t** and $\boldsymbol{P_e(t)}$ is the power consumption at time **t**. Three different settings of the algorithm, which optimise the energy consumption and exploit the electric flexibility of the heating system were compared. The algorithm controls the temperature of the thermal storage and adapts the temperature to the heat demand and the electricity price. The algorithm is divided in four cases as described by the Table 3.

Case 1: The temperature in the building is below the comfort constraint for the period, or the photovoltaic electricity production is bigger than heat pump consumption. When this condition is verified then the heat pump is switched on to fully charge the TES.

Case 2: During the night (23:00 – 08:00), the TES is charged by the heat pump. When the TES is full then the heat pump supplies heat to the house.

Case 3: During the week days, before the peak electricity price (15:00 – 17:00), the heat pump is switched on to charge the TES.

Case 4: During the weekdays, during the peak (17:00 – 19:00), the heating system uses the energy stored until the TES temperature reaches the lower limit. The same case is applied during the weekdays between 08:00 – 15:00 and 19:00 – 23:00.

Table 3: Algorithm Pseudocode

Case 1: Not Valid ComfortConstraints
    OR (PVProduction – CurrentElectricityConsumption) > 3 kW
    SET ThermalStorageSetPoint = MAX Temperature
Case 2: Night Off-Peak
    SET ThermalStorageSetPoint = MAX Temperature
Case 3: Day Off-Peak and Time Is Between 15:00 to 17:00
    SET ThermalStorageSetPoint = MAX Temperature
Case 4: Day Off-Peak OR Day On-Peak
    SET ThermalStorageSetPoint = MIN Temperature

A parameter analysis was performed on three key parameters and each configuration of the parameters is referred to as an algorithm setting.

The first parameter is the number of thermostatic controls in the house. In the reference case and in setting number 1, the heating system was controlled by a single thermostatic controller installed in the corridor. In settings number 2 and 3 the zones were divided into three groups: bedrooms, living rooms and kitchen and bathrooms. In each group, a thermostatic controller was installed. The temperature of the zone groups was tuned according to the users' occupancy profiles. For weekdays, the temperature setpoint in the bedrooms between 7:00 – 9:00

and during the evening from 19:00 – 24:00, is one degree higher than during the rest of the day. While for the weekend, the temperature setpoint is always one degree above the comfort level.

The second parameter is the minimum and maximum temperature set point of the thermal energy storage. For the case reference ("No Control") the two parameters were set at 40°C and 55 °C respectively. The maximum temperature of the TES is equivalent to the maximum outlet temperature from the heat pump. The minimum temperature was set at 40°C after a parametric analysis. The algorithm setting 3 uses 35°C as the minimum temperature, nevertheless it does not improve the economic savings, as the algorithm cannot maintain the comfort constraints during the coldest days.

The third parameter considered, is the PV output threshold. In the reference case, when the PV electricity output exported to the grid was higher than the heat pump electricity peak consumption (3 kW) then the heat pump was switched on. In the setting 3 case, the threshold was lowered to 2 kW. This change did not affect the overall economic savings, compared to setting 1 or 2.

The simulation was performed with a time step of 15 minutes and the control algorithm evaluates the sensors at each time step and regulates the heat pump. The economic savings, the environmental impact, and the flexibility assessment of the reference case and the three algorithm settings are reported into the Results section.

Table 4: Features of the different settings

	Setting 1	**Setting 2**	**Setting 3**
Schedule weekdays	Single	Divided for room category	Divided for room category
Schedule weekend	Single	Single	Single
TES - MIN & MAX settings point	40°C – 55°C	40°C – 55°C	35°C – 55°C
Use of PV for increase the TES charge	when the kW of PV available > 3 KW	when the kW of PV available > 3 KW	when PV available > 2 kW
Hours before peak price to begin charge the TES	2	2	2

4 Results

Electricity Consumption

Figure 2 illustrates the annual hourly cumulative electricity consumption for the heating system, displayed over 24 hours for each algorithm setting and for the reference case ("no control"). The red line is the average system marginal price (SMP) for the heating period indicated in euro per MWh. In the reference case, to meet the comfort constraints, electricity is consumed when it is needed, even during peak times. In this case the TES temperature is always at the established maximum set point. The algorithm' setting 1 increases the consumption during the night and just before the peak price, resulting in overall electricity cost savings.

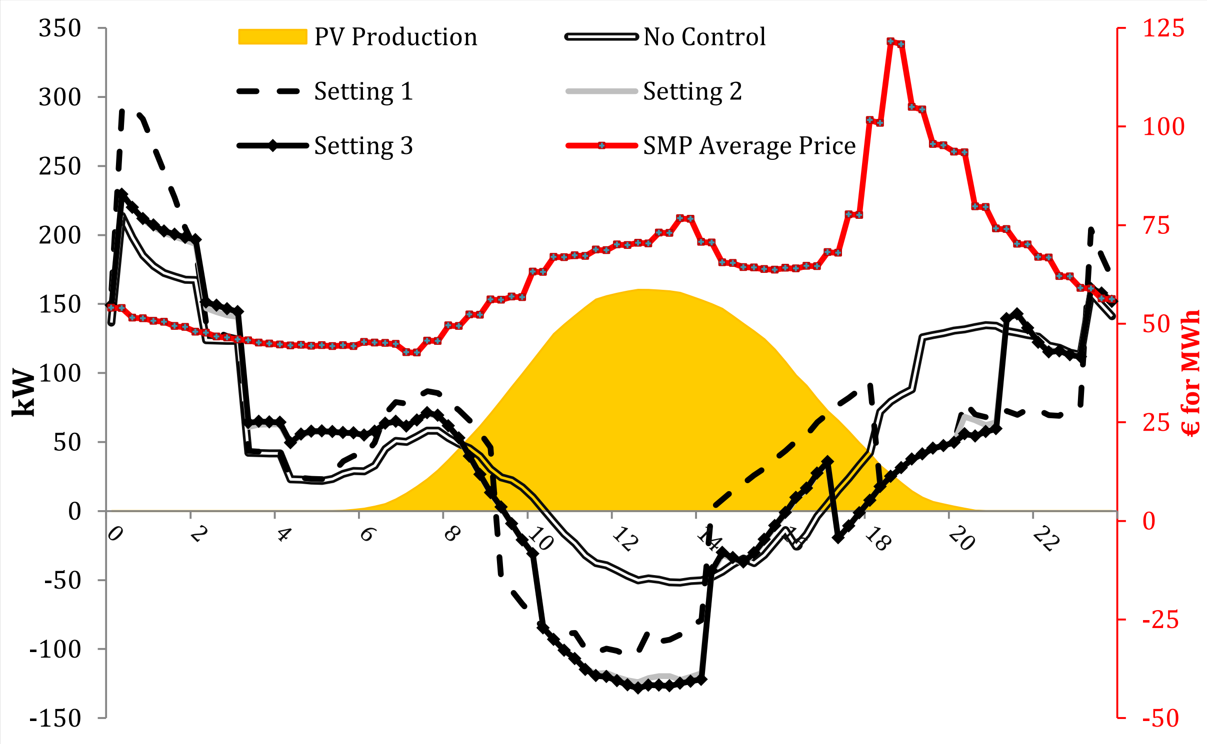

Figure 2: Hourly cumulative electricity consumption

Setting 2 results in a further increase in savings because the algorithm is driven by a separate thermostatic control for each room category, so before peak, it increases the temperature of the TES and in the bedrooms, decreasing the heat demand from the bedrooms until the off-peak at 19:00 hrs. This separation allows the energy stored in the TES to last for the whole peaking time without affecting the comfort.

Setting 3 attempts to push the energy extraction from the TES, using 35°C as the lower temperature threshold however it is not able to obtain relevant savings and it does not meet the comfort constraints all the time.

Economic Performances

The four different TOU schemes outlined in Table 2 were used to assess the economic performance of the three settings of the algorithm and the reference case. The objective was to automatically adapt the charging of the thermal storage to the peak/off-peak tariff in order to maximize the savings.

The algorithm objective is to shift the heating load to an off peak time, maximizing the charge of the thermal load during the night. As consequence, the economic savings are proportional to the price difference between peak and off peak as illustrated by Figure 3. Setting 1 has the lowest economic performance due to a fixed schedule for all the rooms without using the occupancy behaviour data. Using the setting 3 is possible to achieve savings in a range from 15% for tariff A to 20% for tariff D, which includes very low off peak and very high on peak prices.

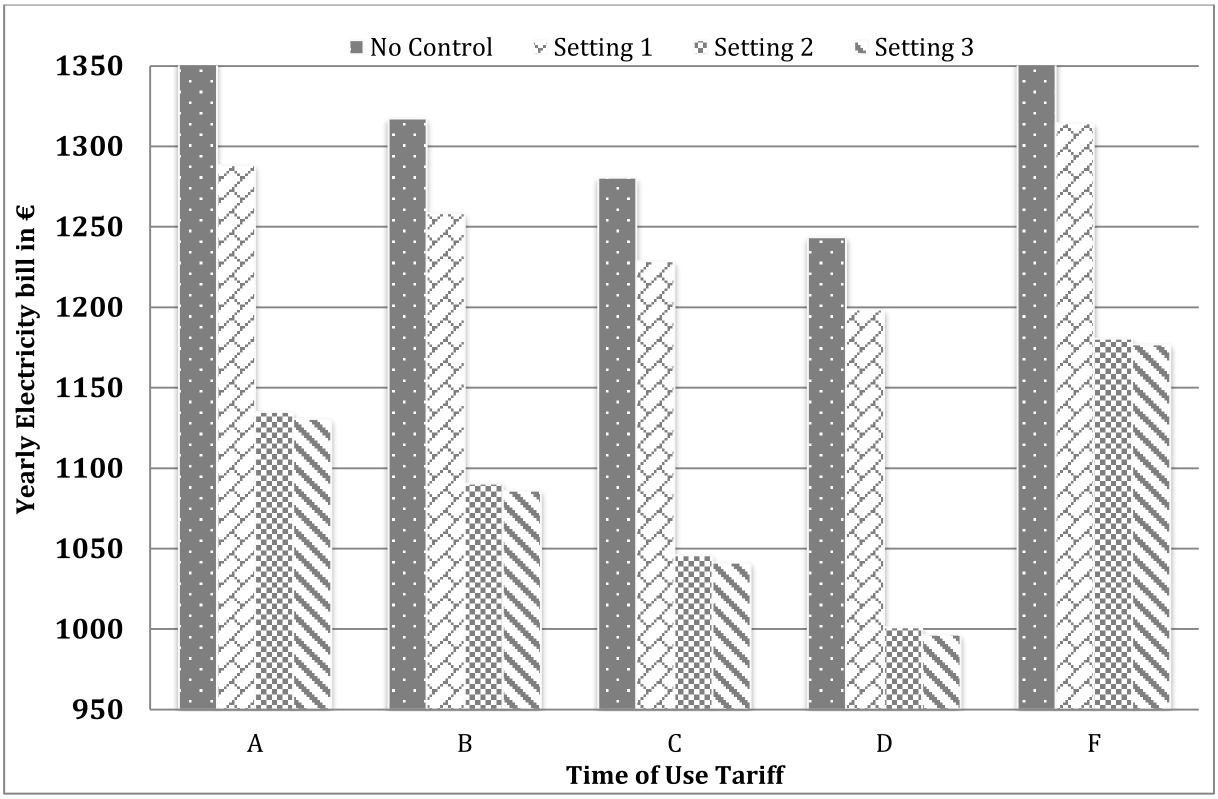

Figure 3: Electricity cost with different time of use tariffs and algorithm settings

Impact on the utility

The electricity demand of the building was also compared to the System Marginal Price (SMP), which is the wholesale single island-wide price for each half hour trading period in a typical day. The electricity consumption was multiplied for the SMP price every half an hour in order to evaluate the yearly generation cost for the building from the utility point of view. The result is illustrated in Figure 4.

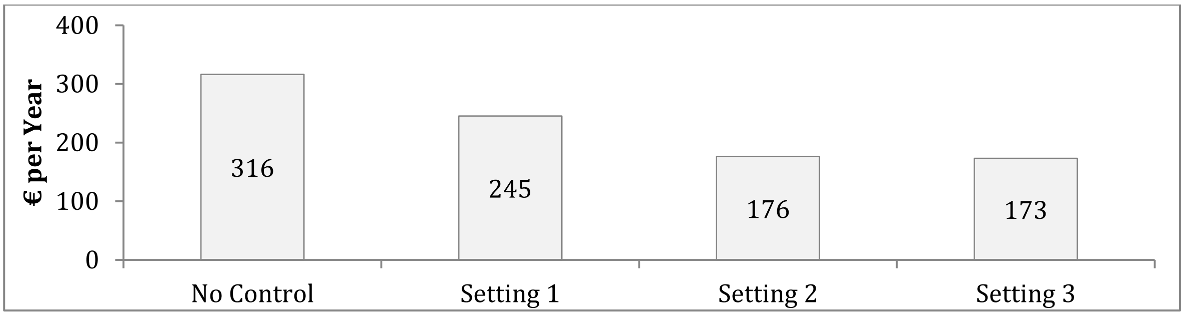

Figure 4: Utility point of view: electricity cost at system marginal price for the residential dwelling with and without the control algorithm.

The electricity peak demand of the building was shifted an hour before the system peak demand. As Figure 2 illustrated the average electricity SMP price difference between peak and off-peak is more than one third. From the point of view of the utility, using the algorithm setting 2 or 3, the overall generation cost for the building is decreased more than 45%.

Environmental Impact

The building's carbon footprint is calculated using the data from the Irish transmission system operator, Eirgrid. The data contains the Irish power system grid fuel mix and the wind generation at 15 minutes at time steps. The real time CO_2 emission in tonnes per hour was extracted according to the methodology developed by Eirgrid (2012). Then the figure was scaled in g/kWhe of CO_2 and, using regression analysis, was stepped every 15 minutes.

During the system demand peak time, electricity generation has an increased CO_2 intensity caused by the activated peak units. Therefore, using the smart control, a significant decrease of CO_2 emission was expected. As Figure 5 illustrated, between the "No Control" and the algorithm setting 2 there is a difference of 27% in emissions.

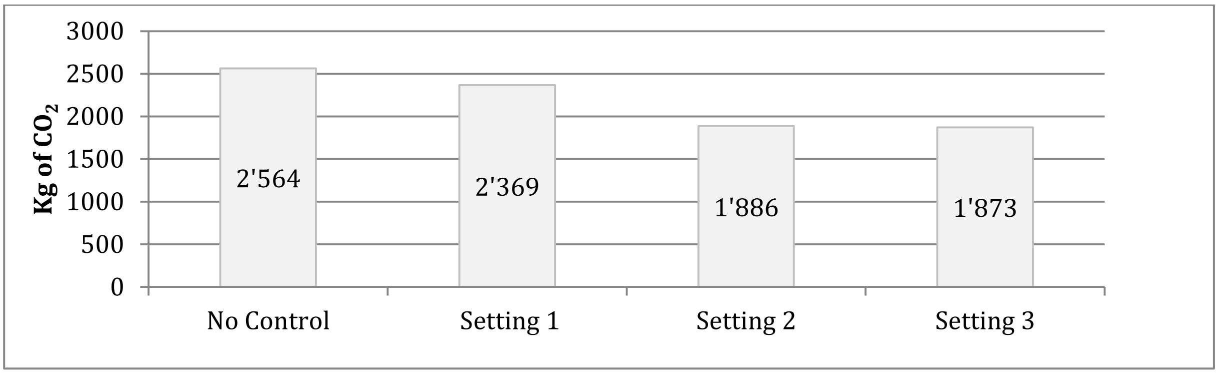

Figure 5: Carbon Dioxide emission of the building during the year 2012, comparison of the building emissions with and without the control algorithm.

Flexibility

Flexibility is defined here as the ability to shift or force electrical power consumption acquired from the power grid, which is normally aligned with real-time energy demand, to other times. In practice, this is normally achieved by means of electro/thermal storage, which allows power supply excesses to be stored and used later when a power supply deficit exists. In the context of energy systems in buildings, storage is usually achieved by thermal storage, either active by means of engineered storage devices or passive by means of the building fabric itself.

The amount of flexibility in kilowatt-hour at a certain time step is a function of the energy demand, the amount of energy stored on the TES and the rating of the heating system. Although the energy demand of the building depends on many uncontrollable factors such as the weather and user behaviour, it is possible with an appropriate pool of assumptions to assess upper and lower limits of flexibility using building simulation software and an operative methodology (Nuytten, et al., 2013). To assess the flexibility of the heating system, the upper and lower temperature set points of the storage tank can be defined according to the heat pump specs and a sensitivity analysis. Radiators need a higher temperature compared to radiant floor to transfer heat properly to the house. After a parametric analysis the temperature range of the storage tank of the case study was set between 40 and 55 degree Celsius. When the temperature goes below this value, the heat transfer cannot satisfy the heat demand so it is necessary to switch on the heat pump. The first step to calculate flexibility is to have a function that forecasts the PV output for the next hour. The electricity production of the PV system in kWh in the next hour is part of the flexibility potential as such electricity is not taken from the grid. In the case study, the forecast electricity PV production was calculated with the available weather data and using the previous simulation output. Thus at each hour, the next hour's PV output was forecasted. In the equation the forecasted PV output for the next hour is indicated as $\boldsymbol{P_{t+1}}$ and the units are kWh.

The flexibility, in terms of load shifting, is the amount of kWh that could be shifted to the hour $t + \mathbf{1}$. Having the forecasted PV output for the next hour the shifting flexibility $\boldsymbol{S_t}$ is calculated at time $t + \mathbf{1}$ as follow:

$$\boldsymbol{S_{t+1}} = \frac{\left(\mathbf{4.2} * \boldsymbol{Z} * (\boldsymbol{T_t} - \mathbf{40})\right)}{\mathbf{3600} * \boldsymbol{C}} + \boldsymbol{P_{t+1}}$$

where the specific heating capacity of water is $4.2\, kJ/kg\ K$ and $\boldsymbol{Z}$ is the volume of the thermal storage, $\boldsymbol{T_t}$ is the temperature of the TES at time t and $\boldsymbol{C}$ is the heat pump average COP. At time $t + \mathbf{1}$ the heating system can shift $\boldsymbol{S_{t+1}}$ kW to the next hour.

At the same time the potential load forcing flexibility in kWh is calculated as:

$$\boldsymbol{F_{t+1}} = \frac{\left(\mathbf{4.2} * \boldsymbol{Z} * (\mathbf{55} - \boldsymbol{T_t})\right)}{\mathbf{3600} * \boldsymbol{C}}$$

where the specific heating capacity of water is $4.2\, kJ/kg\ K$, $\boldsymbol{Z}$ is the volume of the thermal storage, $\boldsymbol{T_t}$ is the temperature of the TES at time t and $\boldsymbol{C}$ is the heat pump average COP. At time $t + \mathbf{1}$ the heating system can force the consumption of $\boldsymbol{F_{t+1}}$ kW to the next hour. In this case the forcing potential at each time step is the amount of electricity in kW can be used to fully charge the thermal storage in the next hours. Using such definitions is possible to estimate the potential flexibility of the heating system at each time step of the simulation for the following hours. Figure 6 shows the 2012 yearly average flexibility potential during 24 hours.

During the off-peak period there is a high potential in shifting because the system can keep the thermal load fully charged. Consequently the force load is really low. In the morning the shifting potential increases due to the PV system production. The shifting potential curve is proportional to the TES temperature while the force curve is inverse proportional. During the peak time then the system start shifting the load and so the force potential increases while the shift potential decreases.

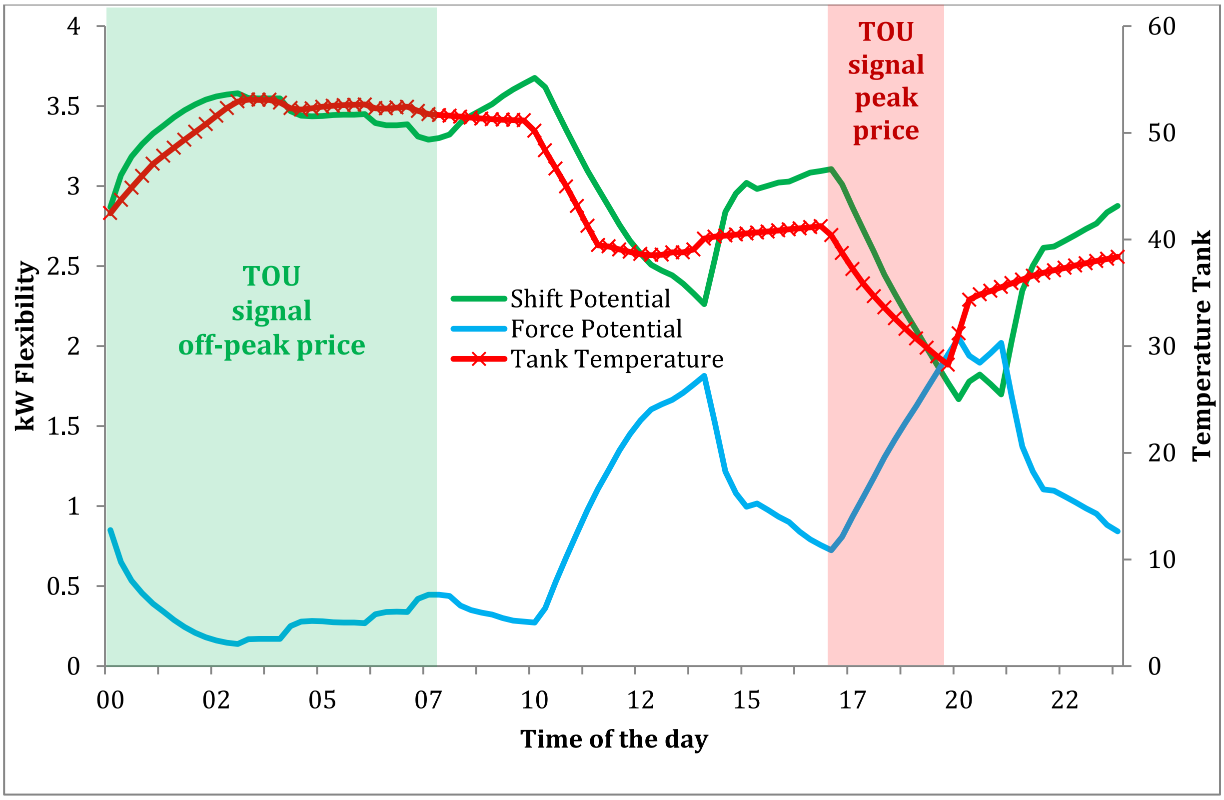

Figure 6: Flexibility, yearly average flexibility potential under time of use price signal.

5 Discussion

There are several points arising from this study related to the use of building simulation for addressing issues of demand response in smart grid all-electric residential buildings. First of all, the building simulation allows developers and researchers to test sophisticated control schemes and evaluate the results without physically implementing the controller. Its use is valuable to assess the merit of the dynamic performance of a smart grid-ready all-electric house. The economics, although static TOU tariffs were used, were precisely calculated and specific operation schedules of the systems were selected to adjust to the pricing schemes. Additionally, the building simulation results were used to tune the operational features of the different systems.

In term of comfort the settings 1 and 2 maintain comfort levels the majority of the simulation time. Setting 3 cannot be accepted, as during the coldest period of the year, it cannot maintain the same comfort level. Setting 3 also, does not provide substantial economic benefits compared to settings 1 and 2.

When the control is optimised and tuned for the specific house thermal performances, small changes in the parameters could result in violation of the comfort constraints and so making the algorithm not usable in a real test bed. In this case, it could be interesting to evaluate a methodology to automatically search for these parameter’s boundaries with more accuracy.

The control algorithm also needs consideration. The control algorithm implemented required a direct feedback from the occupant of the house and was manually adjusted to the price scheme used. It will be the subject of further research in the area to have a collateral algorithm that can learn the user habits and occupancy profiles of each room. This concept is strengthened by the testing results of setting 1 compared to the setting 2 and 3. Settings 2 and 3 use an adaptive schedule for each room category. Adapting the heating demand to the real occupancy of each room could result in a relevant energy optimisation.

This investigation also explored an operational methodology to assess the potential flexibility of the heating system by using building simulation software, assessing it with a homogeneous measure for future aggregation. Such methodology is useful to size and evaluate residential energy systems not only from the point of view of local energy demand, but also to assess the flexibility contribution that such systems can give to the power system**.**

All the generated information can also be used stakeholders (households, utilities, grid operators, governments) to formulate energy plans suitable to their objectives. It is also interesting to note that the building encompasses all the technologies (with the exception of using PVs instead of CHP for micro-generation) suggested by (IEA, 2011) as those with the greatest long term potential for reducing CO_2 emissions.

The next step is to explore, develop and test more advanced control strategies for the electric systems of the house that can be easily incorporated in a future scenario of dynamic grid environment.

6 Conclusions

The present paper reveals that under the particularities of the Irish electric system, with the high wind penetration, dynamic TOU tariffs and its system demand profile, the performance of an all-electric dwelling subject to optimisation algorithms, can improve overall systems performance. The overall building, with its smart control system, displayed far better environmental and economic performance than the reference case. The building owner can save 20% on electricity cost and decrease the environmental impact by 27% while utilities can reduce the generation cost for the building of more than 45%. When taking into account the already decided and announced roll out of smart meters at a national level, which anticipated to be accompanied by time of use pricing schemes, the economic and environmental benefits of an all-electric building with energy storage capacity and a smart control algorithm are more than significant, and can contribute to the power system flexibility as a demand response resource.

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ABBREVIATIONS

CHP	COGENERATION OR COMBINED HEAT AND POWER
COP	COEFFICIENT OF PERFORMANCE
DHW	DOMESTIC HOT WATER
DSM	DEMAND SIDE MANAGEMENT
EV	ELECTRIC VEHICLE
HRV	HEAT RECOVERY VENTILATION
HVAC	HEATING VENTILATION AND AIR CONDITIONING
MAX	MAXIMUM THERMAL STORAGE SETPOINT
MIN	MINIMUM THERMAL STORAGE SETPOINT
PV	PHOTOVOLTAIC SYSTEM

RES	RENEWABLE ENERGY SOURCES
TES	THERMAL ENERGY STORAGE
TOU	TIME OF USE TARIFF

C	Average COP of the heat pump
$C_e(t)$	Price of electricity at time t
F_{t+1}	Forcing flexibility in kWh for the time t+1
$P_e(t)$	Power consumption at time t
P_{t+1}	Electricity production from the PV at time t+1
S_{t+1}	Shifting flexibility in kWh for the time t+1
T_t	Temperature at time t of the thermal storage
Z	Volume of the thermal storage

8 References

AECOM House, 2013. *Report on the development of cost optimal calculations and gap analysis for buildings in Ire-land under directive 2010/31/EU on the energy performance of buildings*, Ireland, Dublin: Department of the Environment, Community and Local Government and the Sustainable Energy Authority of Ireland.

Albadi, M. H. & El-Saadany, E., 2008. A summary of demand response in electricity markets. *Electric Power Systems Research,* 78(11), pp. 1989-1996.

Arteconi, A., Hewitt, N. & Polonara, F., 2012. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering.*

Brady, J. & O'Mahony, M., 2011. Travel to work in Dublin. The potential impacts of electric vehicles on climate change and urban air quality. *Transportation Research Part D: Transport and Environment*, 16(2), pp. 188-193.

Cappers, P., Goldman, C. & Kathan, D., 2010. Demand response in US electricity markets: Empirical evidence. *Energy,* 35(4), pp. 1526-1535.

CER, 2012. *Smart metering cost-benefit analysis and trials findings reports.*. s.l.:s.n.

Curtis, R., Lund, J., Rybach, B. & Hellstr{\"o}m, G., 2005. *Ground source heat pumps-geothermal energy for anyone, anywhere: current worldwide activity.* s.l., s.n., pp. 24-29.

Economic, T. & Social Research Institute, D., 2005. *Time-Use in Ireland 2005: Survey Dataset.* s.l.:s.n.

Eirgrid, 2013. *ANNUAL RENEWABLE REPORT 2013*, Dublin: EirGrid.

Ellis, P. G., Torcellini, P. A. & Crawley, D. B., 2008. Simulation of energy management systems in EnergyPlus.

Farhangi, H., 2010. The path of the smart grid. *Power and Energy Magazine, IEEE,* 8(1), pp. 18-28.

Feeley, C., O'Malley, M., Bryans, A. & Nyamdash, B., 2008. *The viability of balancing wind generation with storage.* s.l., s.n., pp. 1-8.

Grahovac, M., Liedl, P., Frisch, J. & Tzscheutschler, P., n.d. ON-OFF BOILER, THERMAL STORAGE AND SOLAR COLLECTOR: ENERGY BALANCE BASED MODEL AND ITS OPTIMIZATION.

Handbook, A., 2001. Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.*

Hasnain, S., 1998. Review on sustainable thermal energy storage technologies, part I: heat storage materials and techniques. *Energy Conversion and Management,* 39(11), pp. 1127-1138.

Hedegaard, K., Mathiesen, B. V., Lund, H. & Heiselberg, P., 2012. Wind power integration using individual heat pumps--Analysis of different heat storage options. *Energy*.

Hewitt, N. J., 2012. Heat pumps and energy storage--The challenges of implementation. *Applied Energy,* 89(1), pp. 37-44.

IEA, 2011. *Energy-efficient Buildings: Heating and Cooling Equipment,* s.l.: s.n.

Lundstrom, L., 2012. Weather data for building simulation: New actual weather files for North Europe combining observed weather and modeled solar radiation.

Marra, F., Yang, G. Y., Traholt, C. & Larsen, E., 2012. *Demand profile study of battery electric vehicle under different charging options.* s.l., s.n., pp. 1-7.

Neu, O., Flynn, D., Pallonetto, F. & Donal, F., 2013. High Resolution Space-Time Data: Methodology for Residential Building Simulation Modelling. *IBPSA Building Simulation Conference 2013,* Volume 0, p. 0.

Nuytten, T. et al., 2013. Flexibility of a combined heat and power system with thermal energy storage for district heating. *Applied Energy,* Volume 104, pp. 583-591.

O Gallachoir, B., Gardner, P., Snodin, H. & McKeogh, E., 2007. Wind energy and system security--the grid connection moratorium in Ireland. *International Journal of Energy Technology and Policy,* 5(5), pp. 633-647.

O'Connell, A., Flynn, D., Richardson, P. & Keane, A., 2012. *Controlled charging of electric vehicles in residential distribution networks.* s.l., s.n., pp. 1-7.

SEAI, 2011. *Residential Energy Road Map.* s.l.:s.n.

SEAI, 2012. *Renewable Energy in Ireland.* s.l.:s.n.

Six, D., Desmedt, J., Vahnoudt, D. & Bael, J., 2011. *„Exploring the flexibility potential of residental heat pumps combined with thermal energy storage for smart grids “.* s.l., s.n.

Smith, W. J., 2010. Can EV (electric vehicles) address Ireland’s carbon emissions from transport?. *Energy,* 35(12), pp. 4514-4521.

Tahersima, F., Stoustrup, J., Meybodi, S. A. & Rasmussen, H., 2011. *Contribution of domestic heating systems to smart grid control.* s.l., s.n., pp. 3677-3681.

Veldman, E., Gibescu, M., Slootweg, H. & Kling, W., 2011. Impact of electrification of residential heating on loading of distribution networks. *PowerTech, 2011 IEEE Trondheim,* pp. 1-7.