DEMAND RESPONSE OPTIMISATION OF ALL-ELECTRIC RESIDENTIAL BUILDINGS IN A DYNAMIC GRID ENVIRONMENT: IRISH CASE STUDY

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ABSTRACT

The current paper is concerned with a case study of a residential house, located in Ireland, which has been recently retrofitted from a conventional mixed fuel dwelling to a smart grid enabled all-electric dwelling. The aim of the specific case study is to examine the impact on the building retrofit measures on the dwelling carbon footprint, pre- and post- retrofit. The analysis was carried out using EnergyPlus. The baseline for the case study is the pre-retrofitted dwelling which was based on a mixture of energy supply sources including: fossil fuel for space heating, electricity for household equipment and a conventional gasoline car for transportation. Following the retrofit measures, space heating is provided by a ground source heat pump and transportation by an electric vehicle. Other retrofit measures include the installation of PV electric panels, heat recovery ventilation and increase in thermal energy storage capabilities. The retrofit measures were found to provide an overall reduction in carbon footprint from 43.3 to 30.8 $kg/m^2\ CO_2$.

INTRODUCTION

In Ireland residential buildings account for 34% of total electrical energy consumption as SEAI (2008) state. It is expected that in the future electricity demand patterns of the residential sector will change due to the development of smart grid initiatives and to the increasing deployment of renewable energy system (RES) installations. These measures are expected to result in an increase in the electrification of residential thermal loads, as well as other substitutions of conventional gasoline cars with electric vehicles.

Building performance simulation allows a very detailed and analytical assessment of the impact that the aforementioned changes are expected to have on different stakeholders including: householders, electricity utilities and governance through environment impacts. The imminent electric system upgrading to encompass smart grid technologies will require buildings able to adapt to dynamic pricing and high RES penetration in the electricity generation. Especially in Ireland, featuring a small and relative isolated system, the increasing wind penetration with all its associated stochasticity raises significant technical challenges Ibrahim et al. (2011). Energy storage and optimised energy management system can promote the integration of wind energy and balance the power system frequency.

In this context building simulation could lay the groundwork for the development of smart energy control systems for residential buildings in such a dynamic grid environment. As described in Erol-Kantarci and Mouftah (2010) smart grid energy management schemes contribute in decreasing the carbon foot print of the consumer,optimising the building energy systems operation and evaluating appropriate demand response schemes.

The present paper deals with a building simulation case study of an existing all-electric low energy house located in Ireland. This building has favourable thermal features, and furthermore, presents a series of energy systems that qualify it as an excellent example for a smart grid enabled house.

METHODOLOGY AND OBJECTIVES

The building was constructed in 1973 with increased thickness of insulation materials in its opaque elements. Up to now the owner has changed all its windows with double glazed systems while is currently implementing a plan of renovating all its energy systems. The aim of the retrofit is to maintain advanced levels of thermal comfort with low energy consumption and subsequent energy costs. To achieve this solar thermal collectors for DHW and PVs were installed and a ground water source heat pump for space heating and a heat recovery ventilation system were incorporated. In addition, since the summer of 2012, an electric car has substituted a conventional gasoline automobile for the household transportation needs. The electric car is charged from the household electricity system. . Overall, although being aware and considerate of the dwellings carbon footprint the motivation of the owner was not environmental but mainly economic. Following the installation of the technologically advanced energy systems several energy meters were installed to monitor the energy performance of the house as a whole and for different components.

The building was modelled using EnergyPlus Crawley

Figure 1: Real picture and 3D model of the house

et al. (2001) and was simulated for two discrete periods, years 2010 and 2012. The year 2012 was used for calibration purposes since for that particular period most of the metering equipment was in place providing data of actual energy consumption. The year 2010 was selected to compare the overall environmental and economic performance and additionally the impact to the power grid of the house in both its all electric and conventional version (kerosene boiler for space heating and DHW, no PVs, no HRV and no EV).
The 2010 was chosen because it was when the Irish Commission for Energy Regulation carried out the smart meter trial on 4000 residential buildings CER (2010) testing in parallel the effectiveness in demand modulation and energy saving of different Time of Use (TOU) tariffs. Those pricing schemes adopted for the smart meters trial and along with the weather data, the CO_2 intensity of the grid and the System Marginal Price for that period were used for the comparison between the two versions of the houses.

BUILDING DESCRIPTION

Location and architecture

The building, presented in Figure 1, is located in county Wicklow, Ireland and has a conditioned (heated) area of $208m^2$. Its architectural characteristics are that of a typical rural Irish bungalow of the 1970s. The U-Values of the different building components are nevertheless very close to the current Irish building regulation maximum values with the exception of the windows (Irish Government Publications and Government, 2011) as Table 1 illustrates. The overall window to wall ratio is 15% but at the south face is almost 55% higher than the north face of the building.

Table 1: Building element U-values compared with Irish building regulation standards 2011

Building Element	**U-Value** Test building	**U-Value** Irish Building Regulation 2011
	W/m^2K	W/m^2K
Walls	0.25	0.21
Roof	0.25	0.21
Windows	2.6	1.6
Floor	0.21	0.21

Therefore the building chosen is a suitable test case to represent a typical future residential retrofitted building.
For the modelling purpose the house was split into 13 thermal zones following an approach of making each separate room a thermal zone.

Occupancy profile and air exchange

The house is occupied by two adults. 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 following the process described by Neu et al. (2013) with the appropriate adjustments proposed by the occupants in order the model to better replicate their real life activities patterns. The building is naturally ventilated with 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. Seasonal (between winter and summer) and daily (between night and day) variations of both infiltration and ventilation were considered.

Thermostatic control

Following the space heating patterns of the occupants the heating period was set from the 1st of October to the 30th of April and the heating set point temperature was regulated to 20 C from 15:00 to 23:00 during weekdays and throughout the day during weekends.

Energy Systems

The energy systems used in the two versions (all electric and conventional) of the house are presented in Table 2. In the following paragraphs a short description of the different systems in both versions is provided.

Baseline House (Conventional)

The baseline house is heated with an 17 kW kerosene boiler based on a supply return of 80°C/70°C. The heat emitters are conventional radiators in all rooms except the bedrooms which are heated by electric fan convectors. Additionally, a 5 kW wood fired stove is located in the kitchen which the occupants use daily from 6 pm to 10 pm during the whole heating period. 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 remains usually opened increased air mixing was assumed. The DHW 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 $6.15m^2$. A 2 kW immersion resistance in the water tank provides auxiliary heating. The previously car of the owners before replacing it with the electric car was a 1998 cc gasoline car.

All-electric House

In the all-electric house the space heating system is a 12 kW (thermal output) ground water source heat pump. The heat pump uses as heat source water from a nearby open well. Measurement indicated that the temperature of the well water varied over the heating season between 8/6/8°C in Oct/Feb/May. For provision of thermal energy storage the heat pump was equipped with a large hot water tank. The initial preference of the householder was to operate the heat pump only during the night time, taking advantage of the low electricity tariff, and at a hot water supply temperature not higher than 50°C to achieve a high COP. Thus, during night time the heat pump would charge the hot water tank and during the day time the space heating load will be covered from the hot water tank.

Two issues were raised during the analysis of the initial simulation results regarding that control approach. Albeit the existing radiators are significantly oversized still they cannot cope with an inlet hot water temperature less than 55°C. Their heat transfer potential was severely low and thermal comfort conditions were not achieved in the house during most of the heating period. That is why the heat pump was regulated to operate at a 60°C hot water outlet temperature with a subsequent impact on the COP. The second issue had to do with the capacity of the hot water tank and the heat pump operation schedule. The results highlighted that with the limited heat pump capacity the latter need to operate for two periods daily from 23:00 to 07:00 (period of the initial operating schedule) and from 13:00 to 16:00 and charge a large tank of more than $2m^3$. It is noted that the wood fired stove was preserved and is going to still being used by the occupants with the same pattern.

The heat recovery ventilation system uses the heat from the exhaust air of the kitchen and living room to warm up the fresh air into the bedrooms and living room displaying an average sensible heat transfer effectiveness of 80%. It is operating only during the heating period. The array of photovoltaic panels has a nominal power of 6 kWp. It is placed 30 m 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.

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

Weather and simulations period

The closest weather station is that of the Dublin airport about 35 km away from the house. To generate the climatic files with the actual weather data of the two years used in calculation for the particular location the Real Time Weather Converter 2.1 software Lundström (2012) was used. The particular tool retrieves data from the Integrated Surface Database and modelled solar radiation data from STRANG. However, for the latter database it should be mentioned that the validation data for the island of Ireland reveal a quite significant negative bias. The two actual weather years 2010 and 2012 are being compared with the typical meteorological year (International Weather for Energy Calculations - IWEC) ASHRAE (2001) for Dublin airport in Figure 2 for two climatic variables, air temperature and global horizontal radiation. The negative bias on the modelled solar radiation data is apparent when

Table 2: Conventional house and all-electric house equipment

System	Baseline house (Conventional)	All electric house (Electrical)
Space heating	kerosene boiler (17 kW) + wood stove 5kW	GSHP (12 kW) + wood stove 5 kW
DHW	solar thermal + immersion (2 kW)	solar thermal + immersion (2 kW)
DHW tank	$0.2m^3$	$0.2m^3$
Thermal storage	None	$2.2m^3$ water tank
Heat recovery	None	Heat Recovery Ventilation
Electric microgeneration	None	PV System (6 kWp)
Car	Gasoline car (1998 cc)	Electric Car (24 kW)

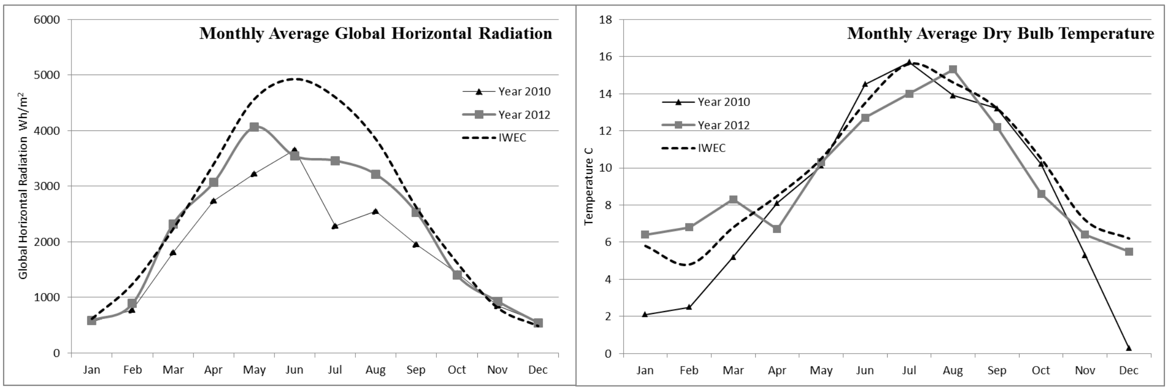

Figure 2: Air temperature and solar radiation for the three weather years

the values of the actual years are compared with that of the typical.

Table 3: Energy consumption figures from simulation and recorded data(2012)

Fuel	Conventional	Electrical	Recorded
	kWh/m^2	kWh/m^2	kWh/m^2
Kerosene	88.6	-	89.6
Gasoline	44.9	-	46
Electricity	13.9	75.8	13.3

RESULTS

The COP of the ground source heat pump is a function of the outlet temperature, which is set to 60 °C, so that comfort levels were similar to that provided by the kerosene boiler. This lowers the seasonal COP of the heat pump to less than 1.5 which sacrifices the overall efficiency of the system for the comfort requirements. This situation is typical for many installations in UK and Ireland's according to the heat pumps test trial described in (Roy et al., 2010) .

The energy consumption of the conventional and all electrical building was evaluated for the year 2012 as illustrated in Table 3. Simulated results are being compared in that table with the recorded energy consumption of the building. As the building (conventional house) was modelled following its real features (thermal characteristics, occupancy data, electric equipment, HVAC system characteristics, thermostatic control), simulated under real weather data and by and large calibrated using real monitored data its thermal performance is very close to the actual. It should be mentioned that the results of Table 3 do not include the contribution of the PV system. The generated electricity from the latter is about 30% of the overall electricity consumption of the conventional house

Carbon footprint

The buildings carbon footprint is calculated with the data from the Irish system operator, Eirgrid. The data contains the Irish power grid fuel mix and the wind generation at time step of 15 minutes. 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.

CO_2 emissions due to the kerosene boiler are calculated by using a value of 257 g/kWh according to SEAI (2012). The annual CO_2 emissions were calculated for year 2010 and are being depicted in Figure 3. According to Kondratenko et al. (2006) a typical Irish dwelling, constructed as per 2002 building regulations, releases 28.55 kg CO_2/year per square meter and consumes 97.22 $kWh/m^2/year$ for space heating. For the year 2010 the carbon footprint of the conventional test house was 26.24 kg/CO_2 per square meter which compares with other results from literature. To evaluate the CO_2 emission of the gasoline car an average value of 200 g/km of CO_2 was used assuming a four years old vehicle according to Sullivan et al. (2004). Overall, during 2010 the carbon footprint of the conventional house was about 9000 kg of CO_2 (43.3 kg/m2 CO_2) while the all electric house emit-

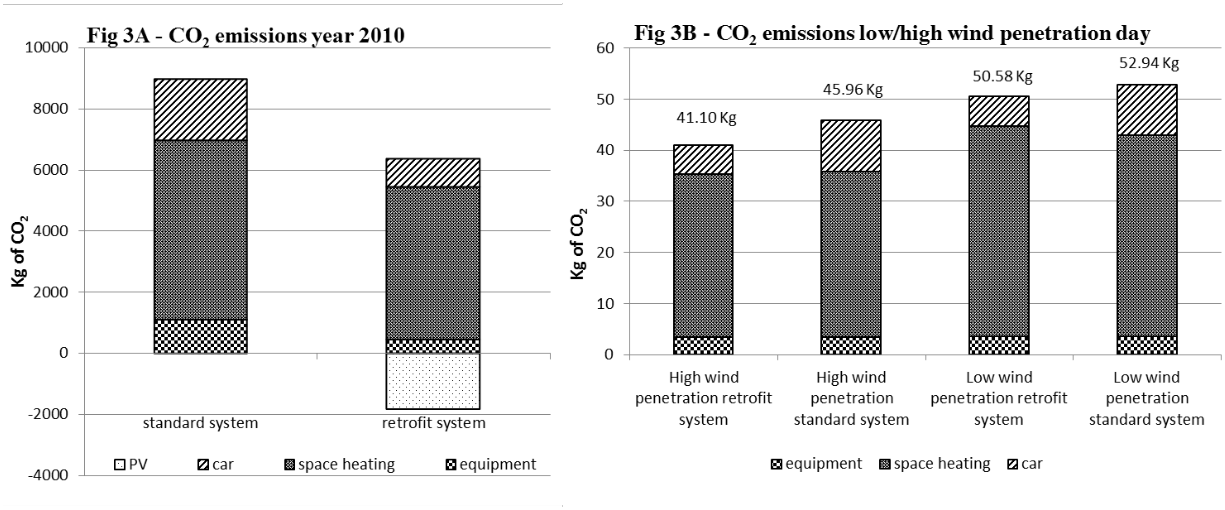

Figure 3: Carbon footprint comparison between conventional and all-electric system

ted just 6400 kg of CO_2 (30.8 $kg/m^2/CO_2$). That is a reduction in CO_2 emissions of 28.9%. It should be noted here that the Irish electric system has a significantly high penetration of wind energy that promotes, from an environmental and power grid perspective, the electrification of residential loads (e.g. electrically driven heating systems, electric vehicles). The space heating contributes 800 kg savings of CO_2 emissions while the presence of the EV allowed a reduction of 1000 kg of CO_2. An overall reduction of the emission is also credited to the PV system that generates almost 4000 kWh for the year. The carbon foot print of the two versions of the house was calculated and compared for 2010 and for additionally two days with different shares of wind generated electricity and presented in figure 3b. These two days have similar average ambient temperature (2.5 °C) but different shares of wind generated electricity in the Irish system. Considering January 12^{TH} the wind penetration was 20% (average wind speed 11.9 m/s) and the average CO_2 emission was 477 g/kWh, whereas for February 12^{TH} the wind penetration was 4% (average wind speed 3.7 m/s) and the average CO_2 emission was 524 g/kWh. The retrofit building displays for both days a lower carbon emission than the conventional, ranging from 11% for the high wind to 5% to the low wind day. That clearly indicates how electrification of loads can have significant environmental benefits as we moving forward to higher participation of RES in the electricity generation fuel mix.

Economic evaluation

During the 2010 the Irish Commission for Energy Regulation initiated a smart meter trial CER (2010) introducing several Time of Use tariffs (Table 4) to the dwellings enrolled. Those tariffs were used to evaluate the responsiveness of the electricity end users to a price difference between peak and off peak time. In this analysis the 4 different static pricing schemes were used to assess the economic performance of the two versions of the house. The objective was to adapt automatically the heating system to the tariff in order to maximize the economic saving.

The heating system of the electrical building was controlled in such a way as not to operate during the Irish system's peak load (and peak pricing time period). In addition the electric car was charging with cheap off peak electricity during the night while of course the PVs were generating electric energy during the daytime period at higher electricity prices. Therefore the economic performance of the all electric house was expected to be better than the conventional house.

The simulation outcomes, presented in the graph of Figure 4 reveal that the economic benefits could lead to a yearly net saving dependent on the electricity price difference between the off-peak and peak. Even using the existing flat tariff the energy cost is dramatically reduced in the electrical house but by applying any of the TOU tariff results in more than halving the energy cost. Specifically, the savings range from 2000€ for tariff A to 2300€ for tariff D, which includes very low off peak and very high on peak prices.

Regarding the breakdown of the cost savings to the different energy systems, a saving of 84% was calculated comparing the EV and the gasoline car, while a saving of 34% derived from the heating system considering the 2010 kerosene price for space heating. On these figures by adding the economic contribution of the PV system an overall result of more than 50 per cent lower cost for energy products is achieved compared to the old system.

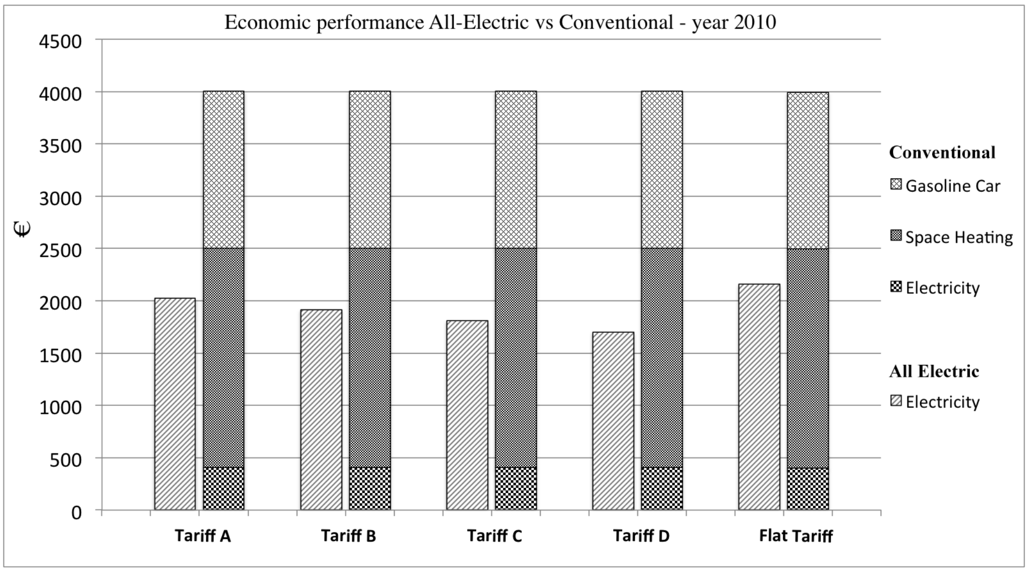

Figure 4: Economic analysis using Time of Use tariffs, conventional building expenses against all-electric

Table 4: Residential time of use tariff

Tariff type .	**Night** 23.00-08.00	**Day** 08.00-17.00 19.00-23.00 weekdays 17.00-19.00 weekends and holidays	**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

Impact on the power grid

The energy demand of the building was also compared to the power grid energy demand and the System Marginal Price (SMP) which is the wholesale single island-wide price for each half hour trading period in a typical day. The result is illustrated in Figure 5. The peak demand of the building was shifted an hour before the system peak demand. From the point of view of the electricity operators, during peak time, the building has a lower electricity demand. Consequently the overall electricity cost is decreased significantly.

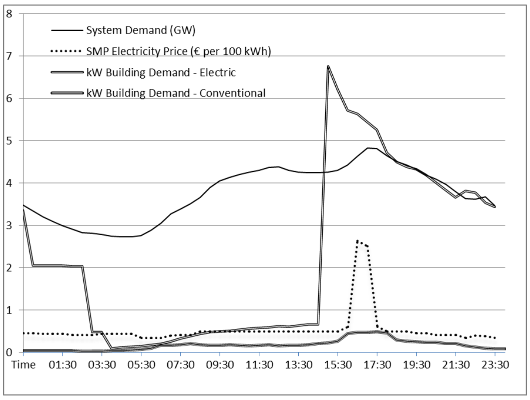

Figure 5: Global electricity demand vs SMP price vs building electricity demand

DISCUSSION

There are several issues arising from this study related to the use of building simulation for addressing issues of demand response in smart grid all electric residential buildings. One refers to the EV, which although EnergyPlus facilitates the modelling of an electric battery, the latter can only be used in combination with a microgeneration system. Thus an EV that is discharged separately of the building is currently not a modelling option using EnergyPlus. The approach used in the present work was to model the EV as external electric load. However, the anticipated penetration of high number of EVs in the market necessitates the incorporation of an appropriate electric battery that can be discharged both externally according to a schedule following the travelling pattern of the car and internally providing another electricity source in the building at times of high electricity prices. The second option is of great importance if sophisticated control schemes are going to be developed for smart houses.

Regarding the importance of using building simulation to assess the dynamic performance of the all electric house it can be easily said that it was invaluable. Accurate environmental indexes were calculated that provided insight to the performance of its energy systems. 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 outcomes were used to tune the operational features of the different systems.

All the generated information can be used from all the involved parties (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 microgeneration) suggested by IEA (2011) as those with the greatest long-term potential for reducing CO_2 emissions. From a research point of view the next step is to explore and develop more advanced control strategies for the electric systems of the house that can be easily incorporated in a future scenario of dynamic grid environment. Model predictive control options accommodating next day weather and electricity price forecasting can be evaluated through building simulation to allow users of such smart grid enabled buildings to determine the operational features of their equipment.

CONCLUSIONS

The work described in the present paper revealed that under the particularities of the Irish electric system, with the high wind penetration, the performance of an all electric dwelling presents essential advantages over even highly efficient conventional systems. Albeit, the COP of the water source heat pump was moderate to low, due to high hot water outlet temperature, the overall building with its EV and PVs displayed a far more benign environmental performance than the conventional. When taking into account the already decided and announced roll out of smart meters at a national level, anticipated to be escorted by flexible pricing schemes by the utilities, the economic benefits of an all-electric with energy storage capacity building are more than significant.

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ABBREVIATIONS

COP	Coefficient of performance
DHW	Domestic hot water
EV	Electric vehicle
HRV	Heat recovery ventilation
HVAC	Heating Ventilation and Air Conditioning
PV	Photovoltaic system
RES	Renewable energy sources
TOU	Time of use tariff

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