Laboratory testing of residential heat pump controllers for demand response using pricing profiles

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Keywords

demand response, domestic energy efficiency, smart grid

Abstract

The modern power system needs to be increasingly flexible to efficiently integrate abundant intermittent renewable energy within a complex network comprising a growing number of distributed energy resources (DERs) and electrical loads. A cost-effective approach to provide grid flexibility is the adjustment of demand-side electric consumption profiles. In European Union (EU) households 79 % of total energy use is due to space conditioning and domestic water heating, so residential heat pumps can play a major role for providing flexibility to energy grids.

A residential water-to-air heat pump was evaluated in a laboratory setting to quantify electric load flexibility when controlled based on demand response (DR) curtailment signals and day-ahead pricing. Experiments were conducted using a hardware-in-the-loop setup where heat pump thermal loads were estimated by building energy computer simulations for a typical single-family apartment located in Madrid. The outdoor section of the heat pump was installing in a climate chamber to apply the outdoor temperature profile for the simulated test days.

DR signals were sent using OpenADR 2.0b requesting different levels of load curtailment. A rule-based controller used the signals to reduce heat pump electric power usage as requested. In addition, a day-ahead price profile was sent and both rule-based and model-predictive controllers were used to modify heat pump operation to minimize customer energy charges while seeking little-to-no impact on occupant comfort. The resulting electrical load profiles were compared to baseline days where no DR events were initiated.

Test results indicated that the load curtailment strategies were effective in achieving the target power limits for both space heating and cooling without a negative impact on comfort, cost or consumption. In addition, the predictive and rule-based price controllers efficiently shifted loads from high demand to low-price periods. The rule-based controller achieved 48 % cost savings in heating mode and 58 % savings in cooling mode. For the scenarios tested, power rebound effects after completion of the DR event were not significant.

Introduction

The European Union (EU) is aiming to be climate neutral by the year 2050 by reducing greenhouse emissions by 80–95 % (European Council, 2019). There are two critical aspects in achieving this goal: using energy very efficiently and increasing the penetration of renewables. The Energy Efficiency Directive, 2012/27/EU (The European Parliament and the Council of the European Union, 2012) is the European regulation that proposes minimum obligation measures to enhance energy efficiency and renewable energy targets in the Member States to meet the energy efficiency objectives established by the EU. Increased penetration of intermittent renewable energy and higher electricity demand, due to the electrification of households and transportation, may result in the inability to meet the energy grid needs for balancing and ancillary services. Under the scenario of a rapidly changing power grid with increasing renewable energy and complex distribution of resources, a new model is gradually being adopted for effectively integrating flexible energy generation and consumption resources under the concept of grid flexibility.

There are two aspects to grid flexibility – generation-side flexibility and demand-side flexibility. The latter, also known as flexible demand response, is one of the solutions proposed to enhance grid performance on the end use side by shifting power consumption to periods of the day with excess renewable energy, limiting consumption during high peak demand and optimizing energy use. In the United States, Demand Response (DR) is defined as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (U.S. Department of Energy, 2006). Flexible DR enhances this definition to include increase in power consumption when excess electricity is available on the grid. European Commission policies support the participation of consumers in the energy market through flexible DR services.

With growing interest in employing DR through end-use equipment in homes, the purpose of this project was to evaluate the capabilities, communications, and controls in smart controllers for residential heat pumps. While space conditioning and water heating together represent more than 75 % of final energy consumption in the EU residential sector (eurostat, 2018), the extension of smart controllers for heat pumps to include lighting, appliances and other end uses can also be investigated. For this project, two commercially available residential communication gateways were evaluated for connectivity with heat pumps.

These gateways utilize OpenADR 2.0b, an open communication standard that includes enhanced DR event and price scheduling as well as robust reporting services (OpenADR Alliance, 2015). Open Automated Demand Response (OpenADR) is an open and interoperable information exchange model and emerging Smart Grid standard. OpenADR standardizes the message format used for Automated DR so that dynamic price and reliability signals can be delivered in a uniform and interoperable fashion among Transmission System Operators (TSOs), Distribution System Operators (DSOs) and energy management and control systems. The 2.0b enhancements to the OpenADR specification enable TSOs, DSOs and aggregators to better monitor curtailment levels among DR event participants. Laboratory testing was conducted to quantify the flexibility that can be delivered when operating a residential heat pump under DR control.

Background

The concept of "energy efficiency/demand-side management" was introduced in the Electricity Directive – 2009/72/EC of the Third Energy Package (The European Parliament and the Council of the European Union, 2009) as a measure beneficial for reducing greenhouse gas emissions, limiting energy consumption, and providing security of energy supply. Furthermore, Energy Efficiency Directive 2012/27/EU requests the promotion of DR participation in balancing markets and for the provision of ancillary services. In this Directive, TSOs and DSOs are required to modify technical modalities and rules for DR market participation. Among the technical modalities, adjustments required by this directive are allowing consumers' flexibility to compete alongside supply and legalize aggregation in all markets.

Europe does not currently have a unified energy market; therefore, different countries have taken their initiatives for the implementation of DR in the context of their particular regulations and market situation. In Europe, existing aggregators engage mainly with industrial or commercial customers, with limited examples of DR in the residential sector. Household energy consumption represents 29.7 % of the total electricity consumption in Europe (eurostat, 2018), therefore the residential sector presents a significant opportunity to provide grid flexibility via DR (Gils, 2014). Access to the energy markets using DR technologies is progressing in Europe with new policies and regulations at the Union and Member States levels. Some European countries have accepted DR as legal to comply with EU policy requirements, but they have not yet established the required mechanisms for market participation and for enabling independent aggregation (e.g., Italy, Portugal, Croatia, Spain). Another group of countries has introduced a regulatory framework for DR market participation. Still, aggregators are only allowed to offer services at the retailer level (e.g., Netherlands, Germany, some Nordic countries). The most advanced group of Member States on this subject has introduced regulatory mechanisms enabling the provision of flexibility as a market service and the operation of independent aggregators (Grasset H., 2018). Hence, DR has access to almost all markets in France, Denmark, and the United Kingdom. Although not widely implemented, some examples of DR programs with residential customer's aggregation can be found in France, UK, Austria, and Finland.

Project Objectives and Research Questions

This project, sponsored and funded by Naturgy and EPRI, was focused on the development and testing of "smart" heat pumps for residential applications in Europe. The objective of the project was to evaluate the capabilities, communications, and controls in smart controllers for heat pumps to demonstrate demand-side flexibility and management to participate in DR programs. A major goal was to assess and demonstrate the end-to-end requirements for communicating signals to a heat pump and actuating a change in its operation. The OpenADR 2.0b open communication protocol was utilized to transmit DR request messages from a Virtual Top Node (VTN – also known as Demand Response Automation System or DRAS), through the internet, to a Virtual End Node (VEN) as this protocol is gaining acceptance worldwide as a highly secure two-way information exchange model and Smart Grid standard.

Another goal was to identify commercially available residential communication gateways and heat pump controllers that can receive such signals and be used for flexible DR control. If all requirements were not available, then document the technology gaps and identify potential options for addressing them. In addition to controlling heat pump operation, another goal was to identify a flexible option (hardware and software) that could also be used to also control other residential end uses (e.g., lights, appliances, etc.), thereby forming a unified, whole-house demand flexibility platform that could support the business needs of the utility and also provide cost savings to the customer.

Figure 1. Photograph of the air-source heat pump tested at IREC laboratory.

In summary, the research questions that needed to be addressed were as follows:

- What is the energy flexibility potential of an individual heat pump, especially in the context of Spain?
- What is the availability and performance of gateway hardware/software for communicating DR signals between grid operators and home devices using the OpenADR 2.0b communication protocol?
- What is the resulting heat pump performance based on several control algorithms responding to a variety of DR signals based on lab tests which mimic real conditions in Spanish context, both for heating and cooling?
- What can be expected when applying heat pump DR control at the aggregated level?
- What is the technological potential for deploying DR controllers on current heat pump products in the Spanish market? Can such controllers be used to control other equipment in Spanish houses?
- How can the results of this project be put into practice by an energy utility like Naturgy?
  - What is the value for the retail business of the utility (analytics & controllers/EMS)?
  - What is the value for the DSO and TSO (resiliency and reliability)?

This project aimed to answer several of these questions.

Approach and Experimental Setup

The project aimed at demonstrating control of a residential heat pump in the Spanish context using DR signals. For the laboratory demonstration, an inverter-driven heat pump (model HITACHI Yutaki S combi RAS-4WHVNPE+RWD-4.0NWE) was locally controlled based on DR signals received from a remote server (VTN) that acted as a proxy for a demand response automation system (DRAS) at a DSO using OpenADR2.0b communication. Figure 1 shows the heat pump inside the environmental chamber at IREC's laboratory in Tarragona, and the domestic hot water (DHW) tank outside the chamber. Based on this methodology, the project's focus was to assess:

- Reliability of a DR communications platform based on the OpenADR2.0b standard
- Flexibility potential that can be delivered with diverse heat pump DR control strategies

The tests were conducted using a hardware-in-the-loop configuration, shown schematically in Figure 2, which is a technique that allows testing real equipment integrated within a simulation environment in real-time. Using this configuration, the heat pump was operated under the dynamic thermal loads of a virtual building model (developed with the software TRNSYS). For the tests, the outdoor section of the heat pump operated inside a climate chamber that conditioned the temperature and humidity of the air surrounding the equipment to emulate varying weather conditions in Spain. The heat pump was operated dynamically by reproducing the building's thermal loads at each time step with a thermal test bench. This test bench emulated the temperature of the water returning to the heat pump from the building heating and cooling distribution system, as calculated by the building simulation model.

The project aimed at estimating the maximum flexibility achieved by controlling a heat pump in space heating, space cooling and DHW modes for the climate of Madrid. Two days representative of extreme load conditions in the heating and cooling seasons were selected by means of clustering k-means analysis. The outdoor temperature profiles for these two days were used to perform laboratory experiments under quasi-realistic conditions. DR signals were generated by a remote OpenADR server, transferred via the internet, and received locally by two different DR client gateway products via Wi-Fi communication, which transferred the DR messages received to a heat pump local controller. The specifications and DR applications for both gateways are summarized in Table 1[1], and the communication architectures are shown in Figure 3.

Representative of explicit or implicit DR programs, the DR signals tested (summarized in Table 2) consisted of:

- Load limitation requests for general curtailment (named as SIMPLE 1), critical curtailment (SIMPLE 2) and emergency curtailment (SIMPLE 3). The curtailment signals were applied according to specifications contained in the AHRI 1380-2019 technical standard (Air-Conditioning, Heating, & Refrigeration Institute, 2019). This standard provides requirements for the implementation of OpenADR Demand Response signals for variable capacity HVAC systems for light commercial and residential applications. For this project, curtailment periods with a duration of 1 to 3 hours were

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[1] Intwine gateway also includes the capability for communication via cellular modem.

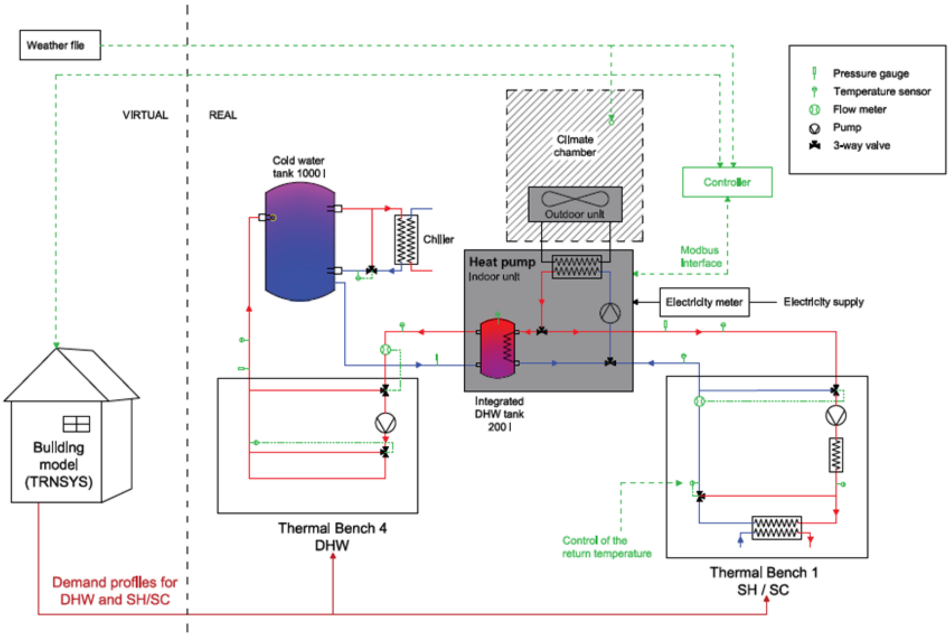

Figure 2. Hydraulic schematic of experimental set up.

Table 1. Specifications and application of OpenADR2.0b gateways (Virtual End Nodes) tested.

OpenADR2.0b gateway	Specifications for the project	DR Application
Intwine Connected Gateway (Intwine Connect, n.d.)	Local OpenADR VEN gateway connected to heat pump controller	• Load curtailment requests • Price tariff information • Day-ahead notification with users choosing to join the DR event
SkyCentrics SkySnap 200 (SkyCentrics, n.d.)	Cloud-based OpenADR VEN communicating with local gateway connected to heat pump controller	• Load curtailment requests • Automatic user enrollment

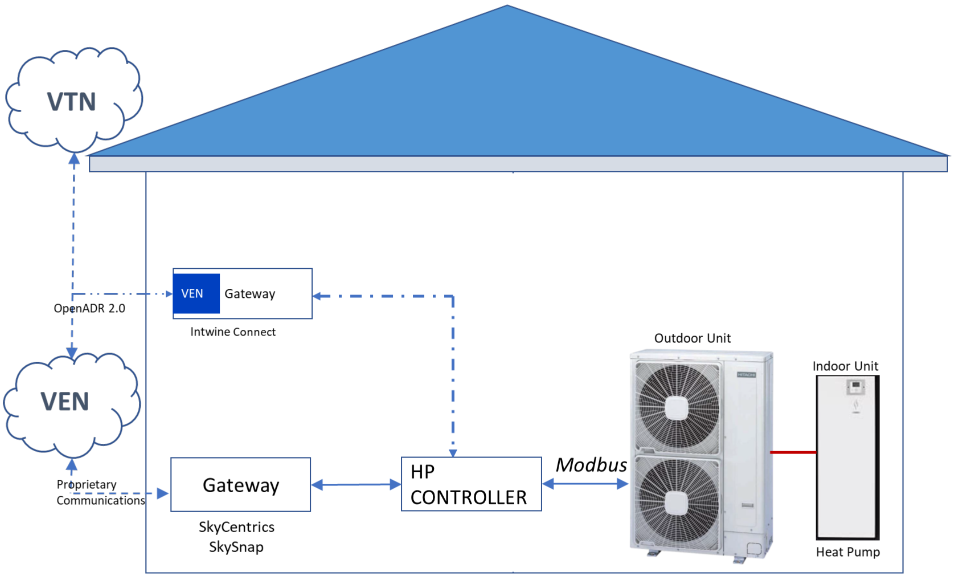

Figure 3. Communication architectures for a local and a cloud based OpenADR VEN and gateway.

specified considering typical Spanish electric grid load profiles for summer and winter, and common duration practices by energy utilities.

- Time-of-use tariffs based on the two-period VPSC Spanish regulated tariff profile (PVPC tariff in Spanish).

Depending on the test case and gateway, notification was sent either the day ahead assuming users can opt-in to the DR event, or with automatic user participation. Automatic participation is representative of DR programs based on contract agreements with consumers allowing direct load control access by the DR provider.

Three types of heat pump control algorithms, with control logic simulated using a desktop computer with Modbus communication to the heat pump, were tested for implementing the received DR signals:

- Standard thermostat control with power limitation capability (Rule-Based Control, RBC)
- RBC responding to a price signal (RBC-Price)
- Model Predictive Control responding to a price signal (MPC-Price)

Further description of the heat pump controller logic is provided in Table 3. In all cases the measured heat pump response to each DR control strategy was assessed by comparison with a reference case without DR. Key performance indicators were calculated to characterize different aspects of the electric power flexibility achieved with each strategy. The performance indicators used were the daily energy consumption, heat pump efficiency, daily energy cost and the operative temperature as a comfort indicator, among others. Indicators were chosen to reflect: 1) the flexibility delivered in terms of power limitation, load shifting, energy and cost savings, 2) the impact on occupant comfort and heat pump efficiency, and 3) potential rebound effects.

Project test results

The delivery and processing of DR signals, as well as the implementation of heat pump control responses, were largely effective for achieving the power limitation, cost or comfort optimization objectives particular to each test case. The primary results regarding the flexibility achieved from the tests performed are the following:

- Load curtailment DR strategies (RBC control) were effective in achieving space heating and cooling load power targets of 60 %, 40 % and 0 % with respect to power rating conditions (Table 4 and Table 5). This strategy proved to be successful in attaining the required power limitation with accuracy and without a negative impact on comfort, cost or consumption (Figures 4 and 5, RBC SIMPLE tests).

Table 2. Summary of DR signals tested.

Type of DR signal	Information	Notification and User Enrolment
Load limitation requests (Explicit DR)	*General curtailment*: limit to 70 % of rated power (SIMPLE 1) – 3 hr. duration: Summer 11.00–14.00, Winter 19.00–22.00 *Critical curtailment*: limit to 40 % of rated power (SIMPLE 2) – 2 hr duration: Summer 12.00–14.00, Winter 10.00–12.00 *Emergency curtailment*: 100 % power rating reduction (SIMPLE 3) – 1 hr duration: Summer 18.00–19.00, Winter 20.00–21.00	Day-ahead with users choosing to join the DR events, or Automatic user participation
Time-of-use Tariffs (Implicit DR)	Daily (24 hour) price profile based on two-period Spanish VPSC tariff (PVPC)	Day-ahead with users choosing to join the DR program (opt-in) Automatic enrollment, for all events or based on user-selected participation days

Table 3. Summary of heat pump DR control logic tested in the project.

Controller Type	Objective	Method
Standard thermostat control with power limitation capabilities (Rule-based control, RBC)	Limit power level during pre-defined time periods	Power modulation by modifying supply water temperature based on performance correlation method
Rule-based control responding to a price signal (RBC-Price)	Reduce energy costs	Modify indoor thermostat temperature set point depending on current price with respect to daily price distribution
Model predictive control responding to a price signal (MPC-Price)	Reduce energy costs and maximize comfort	Learns building thermal properties and optimizes heat pump operation considering forecast of load and prices to achieve objectives

Table 4. Energy flexibility achieved with power curtailment strategies (RBC) in heating mode.

KPI	Standard thermostat without DR (reference)	General curtailment (RBC SIMPLE 1)	Critical and emergency curtailment (RBC SIMPLE 2 and 3)
Power target (kW)	–	1.9 kW	1.1 kW and 0 kW
Measured power during curtailment periods (kW)	1.4–2.1 ± 0.5 %	1.9 kW	1.0 kW and 0 kW
Power target (% power rating)	–	70 %	40 % and 0 %
Measured power during curtailment periods (% power rating)	75 %	69 %	36 % and 0 %

Table 5. Energy flexibility achieved with power curtailment DR strategies (RBC) in cooling mode.

KPI	Standard thermostat without DR (reference)	General curtailment (RBC SIMPLE 1)	Critical and emergency curtailment (RBC SIMPLE 2 and 3)
Power target (kW)	–	1.54 kW	0.88 kW and 0 kW
Measured power during curtailment periods (kW)	1.4 ± 0.5 %	1.38 kW	0.58 kW and 0 kW
Power target (% power rating)	–	70 %	27 % and 0 %
Measured power during curtailment periods (% power rating)	64 %	63 %	40 % and 0 %

- Price-based strategies based on rule thermostat control (RBC-Price control) proved to be very effective in reducing heating and cooling costs by preventing heat pump operation during the high price period of VPSC tariff profiles. The strategy reduced the energy load during the high price period by 5.4 kWh/day in cooling mode and 7.0 kWh/day in heating mode, with energy and cost savings of 61 % and 48 %, respectively, in heating operation, and 45 % and 58 % in cooling mode. The strategy did not cause a loss of energy efficiency while comfort was maintained between medium and moderate levels (Figures 4 and 5, RBC-Price tests).
- Price-based strategies based on model predictive control (MPC-Price control) achieved 7 % and 25 % reductions in energy use and cost, respectively, in cooling mode, without a negative impact on comfort levels (Figure 5, MPC-Price test). This particular strategy was successful in shifting electric load from the high price to the low demand period by applying precooling during the low-price period as in Figure 6. The MPC control was not effective in reducing cost and energy in heating mode during this lab test, but in other applications it has been shown to achieve significant load shifting and cost reductions (Péan, 2019). The price-based RBC controller in this study outperformed the price-based MPC control in terms of energy and cost savings. However, MPC provided better comfort conditions than RBC control in cooling mode as shown in Figure 5. In cases where RBC performs equal to or better than MPC, RBC should be the preferred option due to its simplicity regarding implementation and adjustment.

The results presented here are based on a virtual building model representative of a typical Spanish apartment (circa 1991–2007), with wall insulation U-value of 0.625 W/m^{2}K, window U-value of 2.5 W/m^{2}K, high thermal mass due to the wall, roof and floor construction materials, and fan-coil units as emitters. High levels of insulation and thermal mass reduce space heating loads and tend to reduce impacts on occupant comfort during DR events when heating system operation is curtailed. The opposite is true for "light weight" construction with less insulation. Thus, high-performance construction with adequate levels of insulation and thermal mass provides excellent opportunity for energy efficiency and demand response benefits for both homeowners and utility energy providers.

The performance of the OpenADR2.0b communications and control platform tested in the project was satisfactory. In summary:

- Communication via OpenADR2.0b protocol between the remote DR server and the local OpenADR gateways was reliable, fast and stable in most cases.
- Translation and transference of signals from the OpenADR gateways to the lab heat pump controllers was always correct, with minor adjustments needed to expand the capability of gateways to handle additional DR signal information.

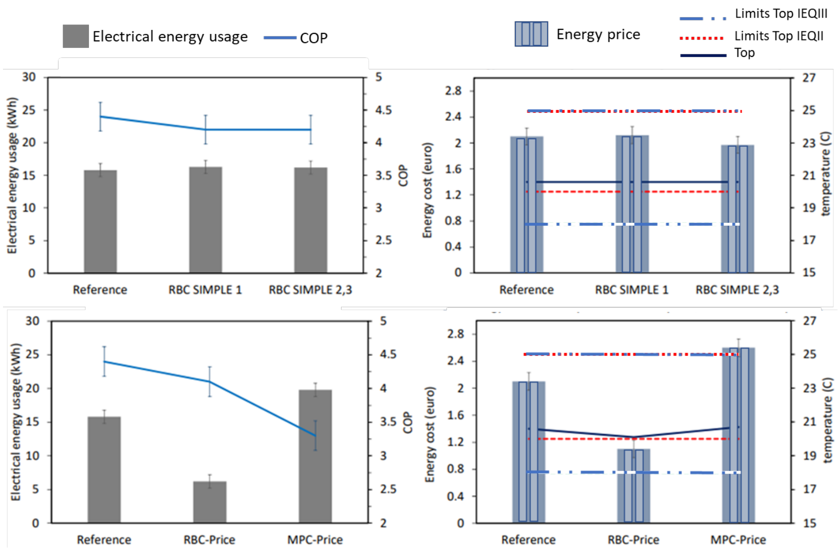

Figure 4. Comparison of heating mode strategies. T_{op}: operative temperature during curtailment for RBC SIMPLE cases and during high price period for RBC-Price and MPC-Price cases. T_{op} comfort categories IEQII (medium comfort) and IEQ III (moderate comfort): limits according to EN16798 (UNE, 2020).

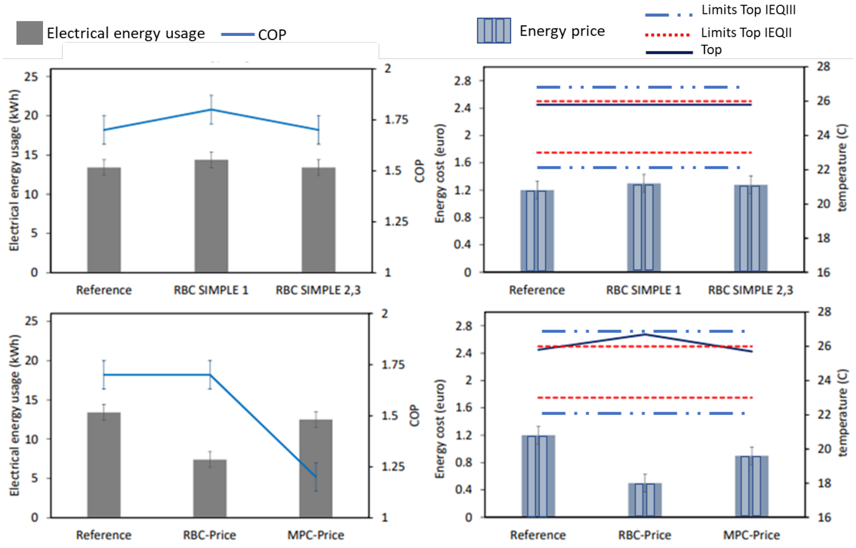

Figure 5. Comparison of cooling mode strategies. Top: operative temperature during curtailment for RBC SIMPLE cases and during high price period for RBC-Price and MPC-Price cases. T_{op} comfort categories IEQII (medium comfort) and IEQ III (moderate comfort) limits according to EN16798(UNE 2020).

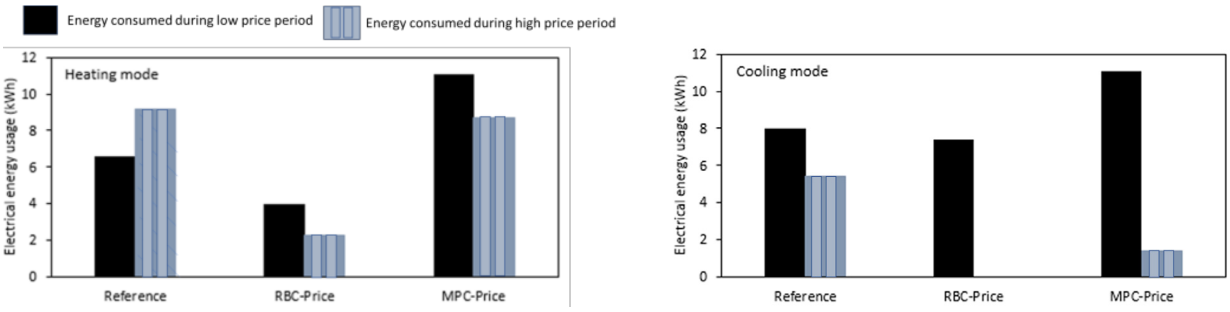

Figure 6. Load shifting produced by RBC- and MPC-Price strategies.

- The local communication methods tested in the project to implement DR signals were based on Modbus messaging (Intwine) and direct voltage signals (SkyCentrics), but the tested gateways have the capability of using multiple protocols to communicate with home devices, smart sensors and appliances.

Leveraging project results for electric utility applications

Generally, energy utility strategies to shape residential electric demand aim to derive mutual benefits from users modifying their consumption patterns, including space conditioning, lighting and other home appliances. Exploiting the results of this project for potential applications by a utility like Naturgy, two main strategies related to demand-side management for residential customers are considered: smart home solutions and DR programs for grid flexibility (Table 6). Two potential business models are proposed for each of these models.

SMART HOME SOLUTIONS

The models considered to supply smart home solutions are a) supply of smart home energy management systems (HEMS), and b) household energy analytics and recommendation service.

The OpenADR gateways tested in the present project could be used to create HEMS systems for communicating with external OpenADR servers and controlling a range of home devices including heat pumps. A gateway provides the opportunity for an all-in-one solution to implement a HEMS system that is highly flexible for using different protocols to communicate and control home devices as shown in Figure 7. This solution would be comprised of a local communications gateway, an energy management system, and a heat pump controller in a single package product that could be provided to the home user.

The second model proposed within the Smart Home Solutions category is the provision of a household consumption analytics and recommendations service. This model consists of a service offered by energy utilities to customers providing personalized advice on users' energy usage with the aim of improving their energy consumption habits. The energy utility may collect measurements of energy consumption with smart meters or smart thermostats by means of a HEMS to provide reports and recommendations to users regarding their energy consumption patterns. This service can be combined with the deployment of DR programs since a recommendation service can improve awareness on the environmental and technical benefits derived from improving energy consumption habits. In such cases, the customers may pay a fee for this service.

DR PROGRAMS FOR GRID FLEXIBILITY

This type of business model is adopted by energy utilities to enhance their grid operations and derive benefits through the implementation of DR programs for residential customers. Since

Table 6. Potential business models regarding demand response for energy utilities.

Solutions	**Potential Business Models**
Smart home solutions	• Supply smart home energy management systems (HEMS) • Household consumption analytics and recommendations service
Demand response programs for grid flexibility	• Explicit DR for grid flexibility • Implicit DR for optimal time-of-use contracts

Figure 7. Example of HEMS serving as DR gateway, energy management system and controller.

space conditioning represents the highest energy demand in the residential sector and due to the increasing uptake of heat pumps in Europe, the inclusion of heat pump control to provide grid flexibility through DR programs is key to this type of model.

Regarding heat pump operation based on tariff information, it has been shown in this project that price-based control algorithms (RBC-Price and MPC-Price) can provide daily energy cost savings between 25 and 58 %. Laboratory tests confirmed that 4–6.2 kWh energy per heat pump could be removed from the high price period thanks to the price-based heat pump controller algorithms. Furthermore, field tests reviewed in the project demonstrate that bills reductions of 10 % can be attained when using smart management systems to optimize heat pump operation according to pricing information (Nyborg, 2013).

Conclusions and Recommendations

This project sought to demonstrate the application of heat pump demand response control to deliver flexibility to the electricity grid. Results from the project show that flexibly controllable heat pump loads can potentially support an electricity grid system with intermittent, renewable resources. The overall conclusions and lessons learned from this project are the following:

- Heat pump control is an extremely promising technology for implementation in DR programs. In this project, load curtailment strategies achieved space conditioning power limitation targets with accuracy and in a reproducible manner, while the price-based predictive and rule controllers efficiently shifted loads from high demand to low energy cost periods. These price-based controllers can achieve important cost savings under an appropriate pricing scheme.
- Project test results indicate that the OpenADR 2.0b protocol for transferring DR signals from a remote server to home devices is a highly secure communication standard that can be deployed in DR programs. The OpenADR gateway and controllers tested in this project provided good response in terms of signal reception and transference to heat pump controllers.
- Energy and power rebound effects were not significant for the tested heat pump. However according to field studies, it is expected that crowding will occur at the aggregation level as a result of synchronous dynamics of multiple heat pumps; an aspect that should be addressed with the application of supervisory aggregation mechanisms.
- According to information from field campaigns, strategies for customers' engagement and DR program adaptation to users' preferences are critical to enhance customer acceptance. The development of clear and concise customer engagement and awareness programs are necessary for the successful deployment of DR services.
- Energy utilities in Europe are increasingly engaging in businesses related to the supply of smart home energy management solutions. Most HEMS products in the market provide modular solutions ranging from simple lighting control to complex smart thermostats. The OpenADR gateway (Intwine and SkyCentrics) and controller logic tested in this project (Rule-based and Model Predictive Control) can be further developed to provide an integrated HEMS solution with OpenADR communication and additional capability to control heat pumps and other home devices.
- Energy utilities in Europe are increasingly adopting the deployment of DR programs as part of their business portfolio, particularly DR programs for direct load control based on customer incentives and implicit services using time-of-use tariffs. The values and revenues of each of these models are being explored to determine the best pathway for each utility and their customers.

This project demonstrated that heat pumps under demand response control can provide energy flexibility while maintaining energy efficiency and consumer comfort for typical Spanish housing. Applying the tested DR strategies to a pool of heat pumps installed in multiple residential buildings is expected to provide significant benefits for grid operations. While the controls and communication system components tested in the project are at an advanced technology readiness level, additional development is required before demonstration in the field.

As future work, the project team proposes field tests for deployment of HEMS and DR program services, as follows:

- Scaled field tests with 10–20 households using the HEMS solution to test/verify performance in actual residences. The tests may include the deployment of a scaled aggregation architecture for control of heat pumps and other appliances in individual homes. This testing allows for 1) validating control operation by the configured HEMS with home devices and heat pumps from different manufacturers, 2) validating DR bidirectional communication under TLS security protocols, 3) verifying applicability of DR programs in real settings, and validating value to the grid and 4) validating user's preferences, engagement and overall value to the customer. The objective of this testing is to make the transition from "proof-of-concept solution" to "field-deployable solution" in preparation for a large-scale pilot program.
- Large-scale field pilot. Testing may be extended to a large number of residences (e.g., 100–200 homes) after required aggregation architecture and HEMS refinements are implemented based on lessons learned from the scaled field tests. Such a field pilot program is designed to validate appropriate utility business plans related to a potential DR program. The pilots may also include a phase to test supervisory control aggregation to enhance flexibility and dampen rebound effects caused by the synchronous operation of multiple heat pumps.

Abbreviations

AHRI	Air-Conditioning, Heating, and Refrigeration Institute
DER	Distributed Energy Resources
DHW	Domestic Hot Water
DR	Demand Response
DRAS	Demand Response Automatic System

EMS	Energy Management System
EU	European Union
DSOs	Distribution System Operators
HEMS	Home Energy Management System
MPC	Model Predictive Controller
OpenADR	Open Automated Demand Response
PVPC	el Precio Voluntario para el Pequeño Consumidor
RBC	Rule-Based Controller
TLS	Transport Layer Security
TSOs	Transmission System Operators
VEN	Virtual End Node
VPSC	Variable Price for Small Consumer
VTN	Virtual Top Node

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Acknowledgments

The authors would like to acknowledge Naturgy S.A. for its support and co-funding of this study. The team would like to acknowledge the following Naturgy Technology Innovation Group personnel – Silvia Sanjoaquin Vives, Alezeia Gonzalez Garcia, and Nuria de Lucas – for providing guidance throughout the course of this project. The team would also like to acknowledge Ryan May, Intwine Connect, and Tristan de Frondeville, SkyCentrics, for their support of the project. Finally, the team would like to acknowledge Elena Fuentes Lopez's participation, formerly head of IREC's thermal laboratory in Tarragona, and all the other IREC laboratory personnel who worked tirelessly on this project.