VIRTUAL POWER PLANT FOR SMART GRID READY BUILDINGS AND CUSTOMERS

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VIRTUAL POWER PLANT FOR SMART GRID READY BUILDINGS AND CUSTOMERS

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Abstract

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Contents

1. Final report

1.1 Project details

Project title	Virtual Power Plant for Smart Grid Ready Buildings and Customers (VPP4SGR)
Project identification (program abbrev. and file)	Project Number: 12019
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Aarhus University, Department of Engineering Finlandsgade 22, 8200 Aarhus N
Project partners	Aarhus Kommune Alexandra Instituttet Grundfos Holding A/S Develco Products A/S DONG Energy A/S
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Date for submission	31-05-2016

1.2 Executive summary

The higher penetration of renewable energies is driving a change in the electrical grid, as we know it today. While more renewable energy is good for the environment, it raises some challenges, especially when balancing the electricity consumption with the available renewable energy production.

The Virtual Power Plant for Smart Grid Ready Buildings and Customers (VPP4SGR) project aims at making a large residential building and its residents ready for the new electrical grid, the *smart grid*. This is achieved by developing a minimalistic virtual power plant that monitors and controls distributed energy resources in a building and provides flexible consumption to the grid. We have investigate the flexibility potential of residential buildings as well as the extent we can engage residents in providing this required flexibility. A 12-storey student dormitory equipped with more than 3,000 sensors has been used as a test bed. The building was raised in 2012 and lives up to current standards of low-energy building design. It has been inaugurated as both a residence and a living lab.

During the VPP4SGR project, a prototype of the virtual power plant has been developed and evaluated in the test bed. The flexibility potential of the test bed has been assessed in several field trials considering different electricity loads and levels of involvement of the residents. We can conclude that while a minimalistic virtual power plant can enable flexibility consumption provision, the potential of a building like the studied one is small and aggregation of several buildings is required. Furthermore, engaging the residents on being flexible with their consumption is a very challenging task.

1.3 Project objectives

The main objective of this research project is to make a large residential building and all its residents ready for the new electrical grid, ready for the smart grid. This is done by means of a minimalistic virtual power plant that can monitor and control all energy resources in the building in an optimal manner while at the same time it provides demand response to third party aggregator. The residential consumers are key asset towards demand response provisioning. Therefore investigating how we can engage the consumers with the electrical grid is an important part of this project.

While the demand response potential of a single building is expected to be relatively low, pooling flexibility from a portfolio of buildings can generate a successful business case. Hence, in this project we also aim at analysing the demand response potential of aggregating several residential buildings. The project also aims at making recommendations on how to build future buildings (and retrofit older ones) to be ready for the smart grid.

Two singularities of the VPP4SGR project make it unique. First, the interdisciplinary approach and second the use of an impressive test bed. The challenges raised towards the smart grid are commonly addressed from a technical perspective. The VPP4SGR project takes advantage of a cross-disciplinary team and provides an interdisciplinary approach to research residential energy consumption and possible flexibility offered. In the VPP4SGR project, we have put large effort into doing a feasibility study by developing prototypes and testing them in a unique test bed located in Aarhus – the Grundfos Dormitory Lab. This test bed is equipped with a larger sensor network thus being an excellent resource to validate our research.

The objectives of this project are listed below:

1) Create overviews of energy consumption and action possibilities, useful for building control over/interaction with their energy systems and component.
2) Identify effects of user behaviour on the demand response potential of the building.
3) Investigate the correlation between weather and air quality forecast from prognosis models and local weather observations.
4) Develop an analytical model for demand response potential of a large building including its interplay with external factors such as market and weather data/information.
5) Development of a virtual power plant prototype.
6) Investigation of smart grid demand response scenarios based on smart grid model of the building.
7) Extension of the analytical model to include the behaviour of the residents.
8) Simulation of the smart grid potential of a city by scaling the model from one building to an ensemble of buildings.
9) Recommendations for an energy-friendly retrofitting of existing buildings to increase its demand response potential.

1.4 Project overview and results

1.4.1 The Grundfos Dormitory Lab

The Grundfos Dormitory Lab has been used as a main case study to evaluate the different research activities within this project. The Grundfos Dormitory Lab, also known as the Grundfos Kollegiet[1], is a student dormitory built in 2012 at the harbour of Aarhus. This test bed has 159 small-sized apartments (less than 40 m^2) for one or two people. These apartments have their own kitchen and bathroom but are not generally equipped with any large white appliance (e.g., dishwasher). The building has different common facilities, like a laundry room in the basement and a common kitchen in the top floor. The dormitory hosts around 200 students in their twenties with an almost equal gender distribution.

At the beginning of this project, the Grundfos Dormitory Lab was equipped with a large sensor network that enabled the monitoring of indoor climate conditions, water usage and heat usage at apartment level. Furthermore, this sensor network also enabled monitoring on common facilities like different pumping solutions and a weather station on the roof. The sensor network is composed by more than 3,000 sensors, where most of the sensors report measurements every five seconds.

Figure 1 - The Grundfos Dormitory Lab.

1.4.2 The building as an energy consumption facility

According to the Danish Energy Agency, residential buildings accounted for 33.5% of total electricity usage in 2014[2]. Additionally, Danish household also use a considerable amount of energy for heating purpose. Around 60% of this heat is provided through district heating, which is mainly co-produced together with electricity[3]. The Grundfos Dormitory Lab is no exception and is also heated through district heating.

During the VPP4SGR project the sensor network infrastructure has been extended with the following elements:

- A meshed ZigBee network implementing more than 140 ZigBee interface cards (MEP) in the installed smart meters in the apartments
- A ZigBee gateway on each floor connected to the LAN infrastructure of the building.
- ZigBee enabled door sensors on the stairwell of all floors
- ZigBee based prosumer meters installed at the laundry machines and the tumble dryer in the common laundry room.
- ZigBee enabled pulse-counting meters for electricity submeters to monitor the electricity of the ventilation system.
- A Bechhoff embedded PC to run the virtual power plant prototype controlling the ventilation system.

[1] URL: http://www.grundfoskollegiet.dk/

[2] Energistyrelsen. Energistatistik 2014 – Data, Tabeller, Statistikker og Kort. Technical report, 2015.

[3] URL: http://www.ens.dk/en/supply/heat-supply-denmark/ (Accessed 10-05-2016)

An overview of the electricity usage of the Grundfos Dormitory Lab has been obtained. The averaged power profile is shown in Figure 2 and the daily electricity consumption is shown in Figure 3. The data shown in both figures has been extracted from the metering infrastructure deployed in the test bed, which provides one-minute resolution on instantaneous power and electricity consumption.

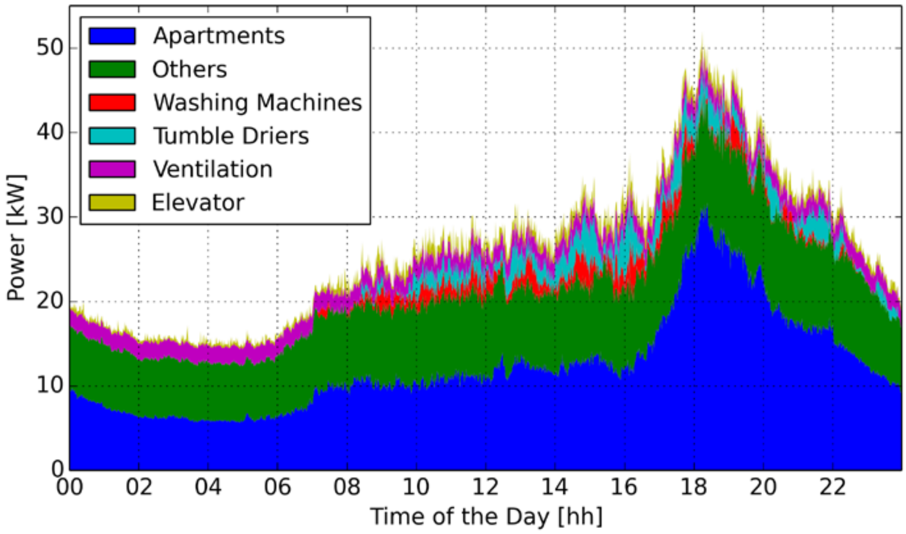

Figure 2 - Average power profile of the Grundfos Dormitory Lab from the 18-02-2016 until the 08-03-2016.

In Figure 2, it can be observed that the test bed presents the typical Danish power peak at 18:00. The ventilation system in this building is always on and uses an almost constant 2 kW power usage. This graph also shows the laundry room activity, which is concentrated in the period when the residents are allowed to wash their clothes (laundry room is closed during the night).

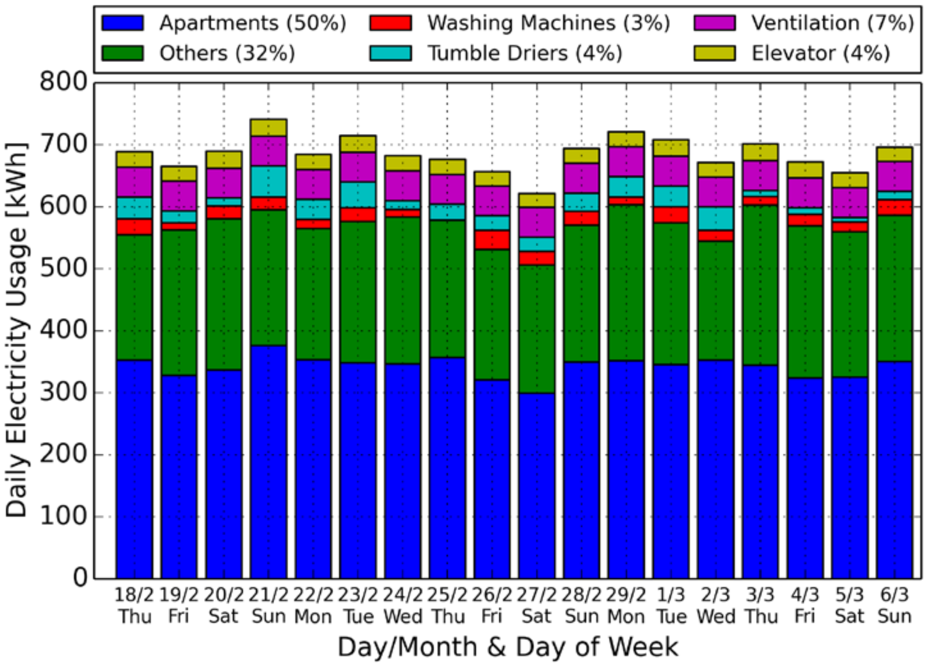

Figure 3 - Daily electricity usage of the Grundfos Dormitory Lab from the 18-02-2016 until the 06-03-2016.

In Figure 3, it can be observed that approximately 50% of the total electricity usage in the building originates from the apartments. It is expected that this percentage would be significantly larger if these apartments were equipped with large white appliances or were larger. Both the ventilation system and the laundry room in the test bed accounts for around 7% of the electricity usage while the elevator accounts for 4%. The 'Others' category accounts for almost one third of the building electricity usage and is originated from consumption in common facilities like the common kitchen, common lighting and different pumping solutions.

1.4.3 *The building as a flexible consumption provider*

One of the main objectives of this project is to investigate the flexibility potential of residential buildings. The technical term for this desired flexible consumption is demand response. Demand response is defined as a change in the normal consumption by the end-user of electricity in response to a signal, usually electricity prices[4].

During the progress of the project, we have developed a taxonomy to analyse the different characteristics of the demand response provision. This demand response taxonomy is shown in Figure 4 and is explained below.

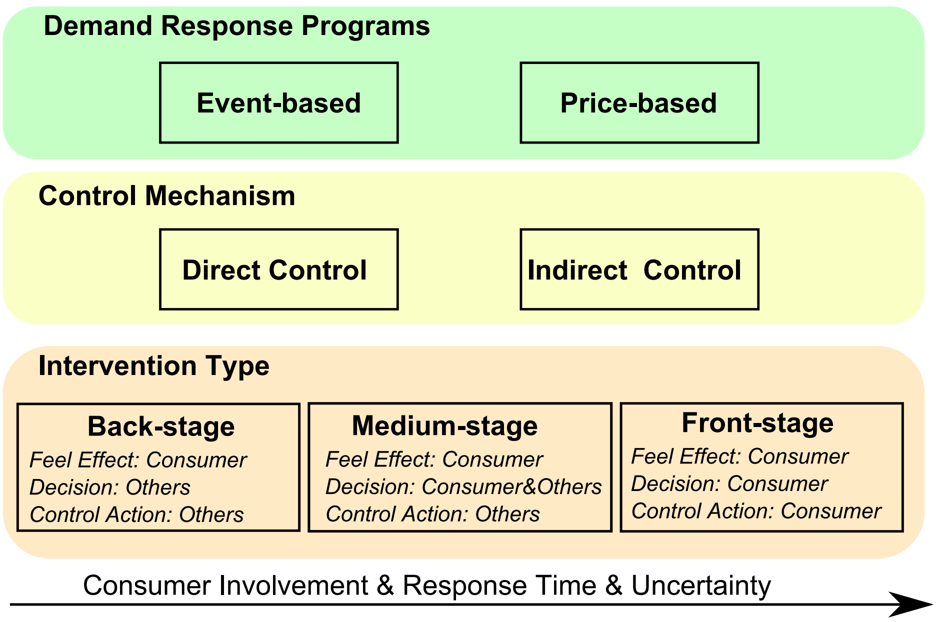

Figure 4 - Demand response/flexible consumption taxonomy.

Demand response is already a business case in the United States and is provided to the electricity markets through demand response programs. There are different types of programs. These mainly fall in two categories: price-based (or time-based) and event-based (or incentive-based) programs[5]. In price-based programs, a varying electricity tariff is shown to the electricity consumers to indirectly motivate a shift on electricity consumption from high price periods to low price periods. In event-based programs, the consumers directly participate in demand response events and receive some incentives in return. Usually, price-based programs rely on consumer involvement and their provision is more uncertain than event-based programs, where loads can directly be controlled by a third party.

Demand response is provided by controlling electricity loads like washing machines or ventilation fans. These loads can be either directly controlled by an Information and Communications Technology (ICT) system or indirectly controlled by displaying a signal to the end-user of the electricity load to motivate a desired behaviour. Direct load control usually presents a faster response time and higher provision certainty than indirect load control.

[4] URL: http://www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp

[5] URL: http://www.ferc.gov/legal/staff-reports/2015/demand-response.pdf

From a more practical perspective, demand response is provided in interventions. In this project, we proposed an intervention classification based on 1) who feels the effects of the intervention, 2) who takes the decision to carry out the intervention and 3) who does the final control actions. In *a back-stage intervention*, the electricity consumers may feel the effect of the actions carried out but they are not involved in the decision or the control actions (e.g., remote control of ventilation system). In a *medium-stage intervention*, the consumer still feels the effects of the interventions, is partially involved in the decision-making but does not take any control action (e.g., setting minimum and maximum accepted temperature of air conditioning). In a *front-stage intervention*, the consumers feel the effects of the actions taken and are involved in both the decision-making and control actions (e.g., consumer reacts on an external signal and modifies electricity usage).

The presented taxonomy is used to classify the demand response provision in different field trials explained below. Furthermore, this taxonomy can be used to assess demand response potential in buildings in a systematic way.

1.4.4 ICT to activate demand response provisioning

One of the main objectives of this project was to develop a prototype of a virtual power plant to monitor and control energy resources within the building while providing demand response. As the project progressed, we gained a better understanding of the system to developed and realised that rather than designing a virtual power plant we were conceiving an extended building energy management system.

A prototype of the building energy management system for residential demand response provisioning has been developed. This prototype is currently deployed in an embedded computer from the German manufacturer Beckhoff to collect data from the Grundfos Dormitory Lab. Different functionalities of this system (e.g., load control) have also been developed and tested as independent solutions. The integration of these functionalities with the building energy management system is left for future work. For more details on the design and prototype of this system, the reader is addressed to a scientific publication[6].

A large effort has also been put to improve the monitoring infrastructure of the test bed. This monitoring infrastructure has been used in several experiments and for the building energy management system prototype. The data provided from the existing monitoring infrastructure has been analysed to remove faulty data. The results of this process have led to a metering infrastructure in the Grundfos Dormitory Lab consisting of 3,168 different measurements, most of them reported every 5 seconds. 19 different measurements are provided from each of the 159 apartment level on indoor climate conditions, domestic water usage and district heating usage. The remaining 147 measurement provide data from common facilities: weather station in the roof, hot water recycling system, ventilation system, door openings etc.

On top of the existing wired monitoring infrastructure, we have added a wireless sensor network based on ZigBee devices. This sensor network was added to satisfy the needs that arose during the development of the project. The measurements obtained from this ZigBee devices enable electricity usage reporting at apartment level but also monitoring of door activity, temperature in the hallways, laundry electricity usage and many more. Having a comprehensive monitoring infrastructure has taken more effort than initially estimated but enables the possibility of future project to start with this infrastructure in place.

Additional ICT solutions have been deployed in the test bed for controllability purposes. The ventilation system in the Grundfos Dormitory Lab has been extended with a web API that enables remote control of the system. In order to interact with the residents, ZigBee devices have been used to influence the electricity usage in the building (e.g., blinking LEDs).

[6] Sergi Rotger-Griful, Ubbe Welling, and Rune Hylsberg Jacobsen. Multi-modal Building Energy Management System for Residential Demand Response. In the Proceedings of the 19th Euromicro Conference on Digital System Design (DSD). IEEE, 2016. pp 1-8

1.4.5 Field Trials

During the development of this 3-year project, we have deployed different field trials in the Grundfos Dormitory Lab to validate our research hypotheses. The original planned verification process of running a longer period to create a baseline consumption and hereafter do interventions was dropped due to the inherent problems of creating a reliable baseline in smart energy projects. In this section, you can find a description of the principal field trials.

The ***ventilation system control*** is a back-stage intervention where the demand response potential of the ventilation system at Grundfos Dormitory Lab was analysed. With that goal in mind, the ventilation system in the test bed has been extended to enable remote and secured controllability over the Internet (see Figure 5). Several experiments have been carried out to assess the potential of such system to participate in the ancillary service market defined by Energinet.dk.

Figure 5 - Equipment added at the ventilation system in the Grundfos Dormitory Lab. The green circle enclose the power supply used to power the embedded PC in the red circle.

The results of the direct control of the ventilation fans show that one ventilation system by itself can indeed react fast enough to satisfy time constraints of ancillary services in Denmark. However, the minimum power bids to be provided to the market make it infeasible for a single ventilation system to participate in the provision of ancillary services. Aggregating controllability over 50-300 systems is required to participate to the ancillary services with a minimum power bid of 0.3 MW which is required for a primarily reserve in Denmark. More details on this field trial can be read in this publication[7].

Green Lift is a front-stage intervention where the demand response potential of the elevator in Grundfos Dormitory Lab is analysed. The main idea was to provide the residents with information about “good” and “bad” periods to take the elevator, from a CO_2 emission intensity perspective. LEDs were deployed in a one-month intervention as shown in Figure 6. The LEDs flashed *red* when the electricity generation was pollutant and *green* when electricity came from renewable energy sources. In red periods, the residents were encouraged to take the stairs while in green periods they were encouraged to take the elevator. Electricity consumption in the elevator and door open-

[7] Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Dat Nguyen, and Gorm Sørensen. Demand Response Potential of Ventilation Systems in Residential Buildings. Energy and Buildings, vol.121, 1 June 2016, pp. 1–10. doi: 10.1016/j.enbuild.2016.03.061

ing were monitored during the field trial. This intervention is an illustrative example of indirect control.

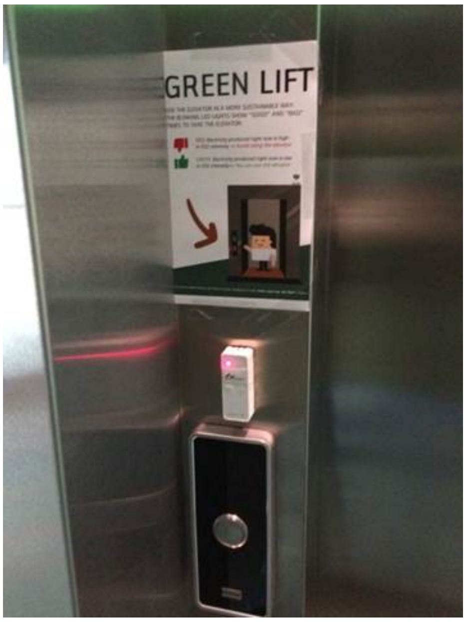

Figure 6 - Green Lift, blinking LEDs and posters were placed in the elevator to trigger behavioural change.

Green Lift was successful in motivating more staircase usage in general. The residents were quite positive about this intervention but found it a bit hard to understand that in some periods they were encouraged to take the elevator. Despite the higher door activity, no significant reduction was found on the electricity consumption of the elevator. More details on this field trial are provided in this publication[8].

ShareBuddy is a casual mobile game designed to engage the residents at the Grundfos Dormitory Lab in reducing or shifting their consumption. The overall concept of the game is that residents try to reduce or shift consumption in real life to earn resources for their buddy in the game, enabling the buddy to carry out different daily routines like showering, eating or tooth brushing and thereby earn points.

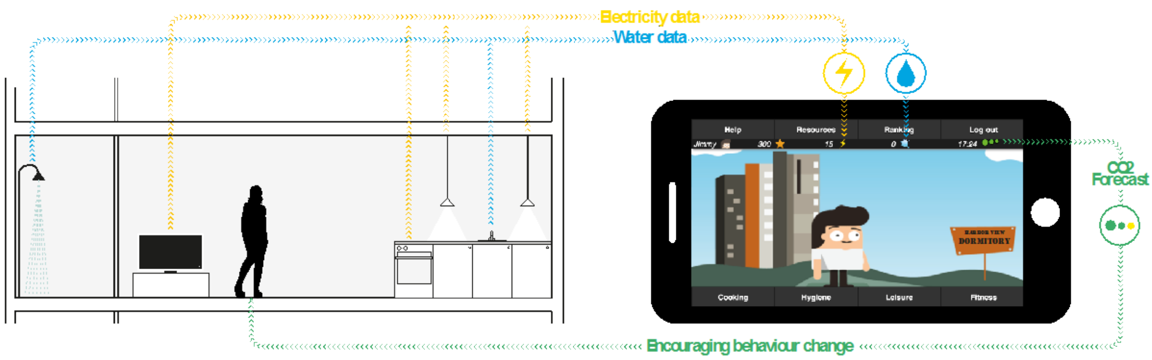

Figure 7 - ShareBuddy, a causal mobile game to increase energy awareness.

[8] Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Robert Stephen Brewer, and Mia Kruse Rasmussen. Green Lift: Exploring the Demand Response Potential of Elevators in Buildings. Energy Research & Social Sciences, 2016. Under review

ShareBuddy is a front-stage intervention that was deployed in the test bed. A total of 42 residents played this game during 3 weeks. This intervention increased energy awareness of the residents but residents found difficult to understand the concept of shifting energy usage.
More details on this intervention are provided in this publication[9].

The overall concept of the ***Clock Cast***[10] front-stage intervention was to try to make the energy forecast visible in a different way through the presence of a physical clock, showing the next "good" hour to consume energy. In addition to the physical clock, participants also had access to a web forecast, and we sent them text messages with suggestions for how to match their consumption to the forecast.

Figure 8 - Clock Cast, mobile app and physical clock.

Clock Cast was tested with three participants in the Grundfos Dormitory Lab and two families outside the dorm. The main findings of this intervention were that shifting requires the ability to plan, thus limiting the activities to be shifted to doing laundry, dishwashing and tumble-drying. Therefore, more information than the next good hour is needed. Having the physical clock raised energy awareness but by itself is not enough to shift energy. More details are provided in this publication.

1.4.6 Models and Simulations: Ventilation, Heating and Domestic Hot Water

The development of analytical models for demand response assessment is also another important goal of this research project. Rather than having a comprehensive model of the building as a whole, we have developed a set of models to assess the demand response potential of different parts of the building (e.g., ventilation system).

Ventilation system

A simple model of the ventilation system fans was created and validated using sensor data from the Grundfos Dormitory Lab. This model enables the assessment of demand response provisioning of ventilation system. A simulation environment that uses that model has been developed in Python and is publically available on GitHub[11].

[9] Robert Brewer, Nervo Verdezoto, Thomas Holst and Mia Kruse Rasmussen. Tough Shift: Exploring the Complexities of Shifting Residential Electricity Use Through a Casual Mobile Game. In CHI PLAY '15, 2015, pp. 307-317. doi: 10.1145/2793107.2793108

[10] Majken Kirkegaard Rasmussen, Mia Rasmussen, Nervo Verdezoto, Robert Brewer, Laura Nielsen, Niels Olof Bouvin. Sustainable Sinning: Sustainable Sinning: a Design Strategy for Shifting Energy Consumption. Under review

[11] URL: https://github.com/comsyslab/VentSysSimulator

The demand response potential of the ventilation system has also been assessed in a comprehensive manner by using a co-simulation environment with hardware-in-the-loop. The ICT platform developed to remote control the ventilation system has been used to enable a hardware-in-the-loop component. The low-voltage distribution grid was modelled up to the first transformer. The network communications were also modelled using a demand response communication protocol. Using this co-simulation environment, it was possible to assess the effect of remote controlling the ventilation system in the test bed for demand response purposes. This work was a joint effort with Lawrence Berkeley National Laboratory. More details can be found in the respective publication[12].

Space Heating

The Grundfos Dormitory Lab is connected to district heating. Hence, in its current configuration, space heating cannot provide any significant demand response to the electricity system. However, it is still interesting to study the demand response potential for a number of reasons. First, district heating can benefit from load shifting to reduce morning peaks. Second, district heating is expected to be an integrated part of the so-called smart energy system in which electricity and heat production is closely related; and third, the study is useful for other buildings with electrified space heating such as heat pumps.

Space heating can be controlled centrally by adjusting the supply water temperature or decentralized through thermostats in each apartment. The decentralised approach is proposed here, because it can utilize a larger part of the inherent demand response potential without violating comfort constraints.

A mathematical model of the space heating has been developed to assess the demand response potential of this system. This system can be controlled using and economic model predictive control thus shifting space heating in time to reduce energy costs, CO_2 emissions and consumption in peak periods. A simulation study show that the energy costs for space heating in test bed can be reduced by up to 14%, CO_2 emissions can be reduced up to 9% and the consumption can be reduced by as much as 80 % through load-shifting in the period where the grid experience the maximum load.

Another finding is that the goal of minimizing energy consumption might need to be reconsidered as the dominant objective in the design and control of heating systems. Results show that using more energy can sometimes lead to reduced energy costs and CO_2 emissions and shift reduce consumption in peak periods. Night setback is a control strategy, which is designed to minimize energy by lowering set points at night, but this does not utilize the low prices at night and can lead to significantly higher costs compared to a night boosting strategy. Night setback will also lead to higher consumption in high and peak load periods.

Most research on price-based demand response adopts the assumption that the electricity spot price reflects conditions in the electricity grid, but this is not necessarily the case. Simulations show that an economic model predictive control that applies spot price for load-shifting can cause an increase in CO_2 emissions compared to a traditional controller because spot price and the CO_2 intensity associated with electricity production is not strongly correlated. We therefore propose to supplement the price signal with a CO_2-intensity signal such that the load can be shifted to periods with both low prices and CO_2 intensities. For more details on this model predictive control of space heating the reader is addressed to the respective publication[13].

A paper has also been dedicated to show how taxes and levies affect the demand response potential related to space heating. The results show that constant taxes reduce the incentive to perform load shifting. If taxes on the other hand were constructed to vary according to the load on the elec-

[12] Sergi Rotger-Griful, Spyros Chatzivasileiadis, Rune Hylsberg Jacobsen, Emma M. Stewart, Javier Matanza Domingo, and Michael Wetter. Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response. In 19th Power Systems Computation Conference (PSCC). IEEE, 2016, pp. 1-7. doi:10.1109/PSCC.2016.7540828

[13] Michael Dahl Knudsen and Steffen Petersen. Demand Response Potential of Model Predictive Control of Space Heating based on price and Carbon Dioxide Intensity Signals. Energy and Buildings, vol 125, 2016, pp. 196-204 doi:10.1016/j.enbuild.2016.04.053.

tricity system and the CO_2 intensity then they would increase the incentive for demand response. More details on this study are provided here[14].

Domestic Hot Water

The domestic hot water system in the Grundfos Dormitory Lab is connected to district heating via a tank-less instantaneous heat exchanger and does therefore not contain any significant demand response potential. A paper has instead been dedicated to investigate the demand response potential if the building had been connected to low-temperature district heating, which is expected to be the next generation of district heating. In this setup, the district heating supply temperature needs to be boosted by a heat pump and stored in a hot water tank. Simulations show that this system would provide a significant demand response potential resulting in reduced energy costs and reduce the heat load both in the morning peak periods of district heating and in the evening peak of the electricity system. More details on this analysis are provided in this publication[15].

1.4.7 Engaging the residents

During the development of this project, we have engaged the residents through questionnaires, workshops and interviews to try to get a better understanding of their energy consumption, the flexibility potential, and what it implies for them in their daily lives. During 2013, a study of the residents of the Grundfos Dormitory was conducted by the Alexandra Institute. The study was a result of a joint effort between the Ecosense and the VPP4SGR project and results have been published in the paper entitled: Understanding Energy Consumption at the Grundfos Dormitory Lab as Situated Practices. This report summarizes the main findings of the interviews carried out with residents of the Grundfos Dormitory as part of the qualitative baseline in the fall of 2013, and provides an analytical framework for understanding these insights in a wider context as socially situated practices.

Two of the main findings that affect the flexibility potential in the Grundfos Dormitory Lab are:

1. Residents view their consumption in a holistic perspective.
2. They consider their own flexibility potential to be limited.

All residents feel they use only the energy that is necessary, and that they are not able to change much without making big sacrifices. What their consumption amounts to in kilo-watt-hours (kWh) varies greatly despite very similar apartments, but even people with a relatively high consumption, compared to the average, view their own consumption as necessary and find it difficult to pinpoint areas for saving or shifting.

Nobody wants to waste energy. Instead, they want to be able to do the things they want and need to do, and they want to be able to choose where to save or be flexible. Many of them value cooking and feel that they can ”afford” to spend the energy required, without feeling guilty, because their overall consumption is relatively low. They also see it as very difficult for them to move the time of cooking. They cannot just move dinnertime a couple of hours because this will affect other practices like exercising or hanging out with friends.

In a master’s project it was investigated how a weekly planning element for household activities could be introduced in the study of user’s flexibility. A conceptual framework for demand response load shifting was developed. Based on this framework, a prototype: *ForecastAway* was subsequently made and validated with a selection of potential end-users. The study showed that some activities such as laundry and dishwashing could potential be shifted while other activities are “sacred” and would likely not result in any significant demand response[16].

[14] Michael Dahl Knudsen, R.E.Hedegaard, T.H.Pedersen and S.Petersen. Model Predictive Control of Space Heating and the Impact of Taxes on Demand Response: A Simulation Study. 12th REHVA World Congress (CLIMA2016)

[15] M.D.Knudsen, S.Petersen, M.S.Jensen, M.Kjer and R.Juul, Demand Response Potential in Domestic Hot Water Preparation Supplied by Low-Temperature District Heating. Energy and Buildings. Under review

[16] Jung Min Kim, Rune Hylsberg Jacobsen and Robert S. Brewer, CoFELS: Conceptual Framework for Electricity Load Shifting System Design, In 19th Euromicro Conference on Digital System Design (DSD). IEEE, 2016. pp. 1-8.

When it comes to laundry, there are infrastructural obstacles that make this practice difficult to reduce or shift: the laundry room is closed at night and there is no room in the building to air-dry clothes. So typically residents have to dry their clothes in the tumble-dryer.

With the interventions: *ShareBuddy*, *Green Lift, ForecastAway* and *Clock Cast* we have engaged residents/end-users to try to shift some of their consumption. Based on our findings from these interventions we learned that:

- Shifting is a difficult concept for people to understand and even more difficult for them to accommodate to their different everyday practices
- If given the option: People will try to reduce rather that shift their consumption
- Residents feel that flexibility requires planning.

One of the things that make shifting especially difficult is the lack of clear consistent guidelines for how to act sustainably. You can never really tell how the wind will be blowing, so shifting consumption to match fluctuating production requires people to pay attention. This requires a lot of effort, and when we also know that most people do not really care that much about energy, and do not even see themselves as energy consumers, this poses a substantial challenge for the flexibility potential of people's everyday practices.

1.4.8 Overall demand response potential of the Grundfos Dormitory Lab

The Grundfos Dormitory Lab is a high efficient building equipped with the state of the art pumping solutions, lighting, ventilation systems, etc. High efficient buildings generally present lower electricity consumption than other facilities thus limiting the demand response potential. The Grundfos Dormitory Lab is no exception and presents a low demand response potential. The demand response potential of several different electricity loads in the building has been evaluated in field trials and simulations.

Table 1 lists the estimated share of electricity and total energy consumption based on the measuring program conducted during the course of the VPP4SGR project.

Table 1: Estimated flexibility potential for the Grundfos Dormitory Lab

	Share of electricity consumption	Share of energy consumption	Max. flexibility potential [kWh/h]	Realistic flexibility potential [kWh/h]	Assessed shifting potential
Ventilation system	8%	2%	1.5 - 4.5	1.5	44%
Circulation pump	0.2%	0.06%	0.05	0.03	0%
Elevator usage	5%	1.4%	1.0	1.0	2%
Laundry room	9%	2%	3.0	2.0	8%
Apartment appliances	57%	15%	14.6	0	0%
Others	21%	6%	--	--	0%
Space heating*)	--	73%	30	23	7% **)

*) Space heating is supplied by district heating.

**) The shifting potential is estimated from the MPC controller's ability to shift to other sources than wind power cf. Knudsen and Petersen 2016[17].

The Table lists the maximum and a realistic flexibility potential are given. In the right-most column, we give our estimate on the shifting potential based on experiences from our field trial experiments. It is seen that sources, which can be automated, such as the ventilation system, have a

[17] M.D.Knudsen and S.Petersen. Demand Response Potential of Model Predictive Control of Space Heating based on price and Carbon Dioxide Intensity Signals. Energy and Buildings, 2016.

high shifting potential (44%) whereas sources that require residents to take decisions on shifting consumption, for instance laundry and elevator usage, have a relatively low shifting potential (8% and 2% respectively).

The ventilation system of the test bed is one of the loads that present a more appealing demand response potential. The performance of this system can be remotely controlled and provides a 1.5 kW for down regulation and a 4.5 kW for up-regulation in a relatively short time. Furthermore, this system is also capable of following a one-minute varying power profile. All this can be done without affecting significantly the comfort of the residents. The potential of one system alone is not very large but pooling a portfolio of several systems can be of high interest for the electrical grid. However, a demand response action from the ventilation system can be rather fast (on seconds time scale).

The demand response potential of the elevator in the test bed has also been assessed. Although this electrical load accounts for 4% of the total electricity consumption it was observed that it is hard to provide demand response through the elevator. The *Green Lift* intervention showed that it is possible to trigger a temporary behavioural change on the way people use the elevator but that translating this to load shift can be complicated.

If we look at the electricity consumed in the apartments this accounts for 50% to 60% of the building's electricity consumption. Providing demand response on apartment level seems a bit complicated since residents are quite inflexible in their practices. This lead to consider the possibility of controlling the cooling cycles of the fridges in the apartments. In such small apartments, this consumption accounts for around 20% of the electricity usage within an apartment. We did try to engage residents in a field trial controlling their fridges but very few participants joined.

The only practise, which seemed that the residents were willing to change, was their laundries. No intervention was done in the laundry room but we did installed sensors at appliance level that will enable future project to study this potential. It should be highlighted that the consumption in the laundry room accounts for 7% of the whole building.

Simulation analyses have been done to assess the demand response potential of the heating system of the building. Results show that if the temperature could be controlled at apartment level, it is possible to reduce up to 80% of the heat load during peak periods. We would therefore recommend decentralised temperature regulation at apartment level rather than the centralised option. Furthermore, we also recommend considering different strategies than energy consumption minimisation because this strategies do not exploit the low electricity prices during night times.

Overall, the demand response potential arising from regulating electricity consumption amounts to 7.4 MWh/year. The demand response potential of the Grundfos Dormitory Lab is limited to control of ventilation system and potentially to modify the laundry habits. In case the building had electric heating that could be controlled at apartment level, this heating system would enable a large demand response provisioning. In this particular test bed, it seems unfeasible to engage the residents in shifting their electricity consumption (providing demand response) but residents seems to be more receptive in permanent energy reductions.

The largest potential for demand response in the building arises from the consumption of district heating. We estimate that building operation can be optimized to follow the energy markets and thereby contributing with a shifting potential of around 7%. Since district heating is by far the largest energy source for the building's total energy consumption (approx. 73%) and demand response potential of around 14.1 MWh/year can be obtained. This obviously depends on the season with the largest potential during wintertime and almost no potential during summertime.

1.4.9 Progress towards the objectives

In this section, we assess the progress achieved during this project towards meeting the objectives stated in section 1.3. In each of the nine following paragraph, we discuss to which extend we have achieve each of the nine project objectives.

Objective 1 – Energy Overviews

During the development of this project we have generated an overview of energy consumption in the building (e.g., Figure 2 and Figure 3) and analysed possible actions to carry out to achieve demand response.

Objective 2 – User Behaviour Effects

Analysing electricity consumption data, we have seen how different the consumption profile can be despite the similarities between apartments. We have considered different interventions that involved the residents in the test bed in different levels. We have observed that engaging the residents with demand response provisioning is hard mainly because residents are quite inflexible with their practices and they find difficult to comprehend the demand response concept.

Objective 3 – Forecast-Measurement Correlation

The weather and air quality forecast obtained with the available models has been correlated with the available sensor data on the Grundfos Dormitory Lab. It has been observed that the predictions of these models present good accuracy.

Objective 4 – Demand Response Analytical Model

During this project, we have developed different models to assess the demand response of different systems within the test bed. We have developed models on heating as well as ventilation systems. In the heating model, we have analysed the interplay of our model with different external factors like solar irradiation, electricity prices, CO_2 emission intensity from electricity generation etc.

Objective 5 – Virtual Power Plant Prototype

In this project, we have designed and implemented a prototype of a minimalistic virtual power plant. The prototype has been deployed in hardware and tested in the Grundfos Dormitory Lab. Different functionalities of the system have been developed and tested as an independent solution rather than integrating them in one product.

Objective 6 – Demand Response Scenarios

Using the developed models, we have been able to consider different demand response scenarios for specific systems (i.e., heating and ventilation). Examples of these scenarios are a load following or ancillary service provisioning.

Objective 7 – Behaviour in Models

The consumer behaviour was to some extend added in the ventilation system model by modelling the indoor CO_2 level in the apartment over time. Similarly, the developed heating model enables the possibility to consider different temperature settings that the residents could potentially set.

Objective 8 – City Potential

We have simulated a scenario where all buildings in the city of Aarhus with similar size as our test bed were equipped with a similar ventilation system. Simulation results showed that by aggregating almost 800 buildings we could achieve 1.5 MW of flexible consumption. This is discussed in one of our publications[18].

[18] Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Dat Nguyen, and Gorm Sørensen. Demand Response Potential of Ventilation Systems in Residential Buildings. Energy and Buildings, Energy and Buildings, vol. 121, 2016, pp. 1–10. doi: 10.1016/j.enbuild.2016.03.061

Objective 9 – Retrofitting of Buildings

We have also proposed several measures to enable/increase demand response provision from existing buildings (e.g., enable apartment level temperature control).

1.4.10 Progress per work package

WP1 – Management

This work package has been led by Aarhus University, Department of Engineering and consisted on three main tasks: project coordination, project monitoring and quality assurance.

A consortium agreement was signed between all project partners. Once the project started, Green Wave Reality, who was a partner in the original consortium, dropped out of the project and was replaced by Develco Products.

To ensure good communication and coordination of activities, the key stakeholder met on regular basis. In case of need, special meetings were set to discuss topics that are more specific. Every six months all project partners reported their progress in writing to the coordinating institution. This latter wrote a document, which was sent to Energinet.dk together with the financial report.

In the project, we dealt with data from the test bed that raised some privacy concerns. The residents signed agreements consenting to share their data to us for research projects. When this data was used by people outside the consortium agreement (i.e., students doing research projects) a confidentiality contact was signed by individual students.

It was identified that some of the work published could potentially generate conflict of interest within the project partners. An approval procedure was established between Aarhus University and Grundfos to ensure that the published work did not interfered with Grundfos interests.

WP2 – Analysis and Specifications

This work package has five key tasks: requirements analysis, consumer behaviour requirements, weather and air quality models, ICT specifications and field trial specifications. Department of Engineering and Department of Environmental Science from Aarhus University led this work package together with Alexandra Institute.

The work carried out in this work packaged has been described in three deliverables: System Requirements, IT Specifications and Field Trials Specification. The System Requirements defines the needs of the designed virtual power plant from a system engineering approach. The IT Specification defined the ICT design of the virtual power plant. The Field Trial Specification defined the interventions to be carried out at Grundfos Dormitory Lab. Alexandra Institute wrote a technical report describing an analysis on the residents in the Grundfos Dormitory Lab and how we could potentially engage them in demand response provisioning.

WP3 – Modelling and Simulations

This work package consists of four main tasks: building modelling, forecast models, model integration and simulations. The work package was led by the Department of Engineering and the Department of Environmental Science of Aarhus University.

Rather than generating a comprehensive model of the building as a whole, we took the approach of defining a set of models of systems within the building. The weather forecast and air quality models where extended to enable predictions at very high resolution (1 km x 1 km).

WP4 – IT Platform Development

This work package includes five key tasks: monitoring support, load control strategies and algorithms, load control support, platform operation and user interfaces. This work package was led by all three departments within Aarhus University together with Develco Products.

The existing monitoring platform when the project started was still a bit immature and we required the installation of additional equipment to have the enough data to deploy the planned field trials. These unexpected larger efforts lead to a change on the initial plans and rather than having the virtual power plant controlling the whole building for a long period we decided to carry out independent test that would evaluate different characteristics of the virtual power plant.

A data acquisition platform Karibu[19] designed by the Department of Computer Science was used to collect all test bed data and send it to virtual power plant. A prototype of the virtual power plant was implemented by the Department of Engineering.

WP5 – Integration and Field Trial
This work package includes four key tasks: apartment installation, baseline stage, load control stage and consumer research. The work package was led by Aarhus University Department of Engineering, Develco Product and Alexandra Institute.

In this work package, we deployed the required equipment in the Grundfos Dormitory Lab. Develco Product equipment was used to provide the additional sensors required and Beckhoff controller to enable ventilation control. In this work package, we carried out the planned field trials.

WP6 – Dissemination and Exploitation
This work package includes three main tasks: dissemination plan, dissemination activities and exploitation plan. All partners have been involved in this work package.

The project has led to results that have been disseminated in conferences, journal articles, lectures at the university, online videos and many more. Department of Engineering has been leading the development of the project web site[20], where all project dissemination is listed. We also went through the process of patenting an invention but it was decided not to proceed with the invention. With respect to the exploitation plan, each project partner identified the possible plans from their perspective (detailed below).

1.4.10.1 WP7 - Evaluation
This work package includes four key tasks: evaluation of demand response potential of buildings, qualitative evaluation, evaluation of forecast models and evaluation of smart city potential. All partners at Aarhus University and Alexandra Institute led different tasks within this work package.

The overall demand response potential of the building was assessed. The developed ventilation system model was used to assess the potential of several systems in a smart city context. The weather and air pollution forecast models were evaluated with sensor data.

1.5 Dissemination of results
In VPP4SGR project, we set ambitious goals on disseminating our research by publishing in high quality journals, presenting our work in conferences, in guest lectures and many more. This section outlines the different dissemination actives carried out during the development of the project. For a comprehensive list of dissemination activities, check the project web site: vpp4sgr.dk.

1.5.1 Project internal deliverables
During the development of the project, we generated periodic project progress reports that were sent to Energinet.dk for evaluation together with financial updates. We also generated three project deliverables shared within the project partners:

[19] Henrik Bærbak Christensen, Henrik Blunck, Niels Olof Bouvin, Robert S. Brewer, and Markus Wüstenberg. 2014. Karibu: a flexible, highly-available, and scalable architecture for urban data collection. In Proceedings of the First International Conference on IoT in Urban Space (URB-IOT '14). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, 2014, pp. 96-98. DOI:10.4108/icst.urb-iot.2014.257253

[20] URL: www.vpp4sgr.dk

- System requirements: This document details the requirements of the designed virtual pow-power plant.
- IT Specifications: This document details the ICT design of the virtual power plant.
- Field Trials specification: This deliverable detailed the field trials to be deployed in the Grundfos Dormitory Lab.

1.5.2 Scientific dissemination

During this project, we have produced a large amount (22) of scientific contributions ranging from high ranked journal publications, to flagship conference articles, and book chapters. The scientific publications are listed in Annex 2.1. We have provided a brief description of the content of each scientific publication.

1.5.3 Other Public Dissemination

We have created a website that contains the main information of the project: www.vpp4sgr.dk. In this website, you have a comprehensive list of the dissemination activities. These activities include online videos, guest lectures, online news, conference presentations and more.

1.6 Utilization of project results

In the following subsections each of the project partner has detailed their respective exploitation plans with respect to the VPP4SGR project.

1.6.1 Department of Computer Science, Aarhus University

The results from the VPP4SGR project have demonstrated how big data from building sensors and ethnographic enquiries can be collected and handled efficiently in a cloud service, the Karibu backend. The results also show how the data can be used for interventions with inhabitants to influence their energy behaviour. One example of an intervention is the *ShareBuddy* game, where the user's resource consumption in the real world has a strong influence on the amount of resources that the inhabitant/player has in the ShareBuddy virtual game universe. Another example is the *Clock Cast* experiment, where data from the energy net is utilized to develop a clock physical as well as on iPad/iPhone that shows the next green slot in the grid stimulating the user to place his/her electricity usage in that green slot. Finally, the data from test bed has been used to experiment on visual analytics[21] for patterns in resource consumption at the building. An example of an analysis result is that there is a very varying usage of domestic heating resources, showing even some extreme usage numbers. This is the case at the same time as the inhabitants claim that the building is very heating efficient. Their own understanding from interviews generally is that they do not use district heating because the building is very well isolated. Thus, the general understanding of the default thermostat settings seems to be misunderstood. Demonstrations of visual analytics for the Grundfos Dormitory Lab have led to many requests for the analysis tools developed.

1.6.2 Department of Engineering, Aarhus University (ECE)

The scientific effort in the VPP4SGR project has led to an improved understanding of the trade-off between *low-energy* and *flexible-energy* operations of modern buildings. From an ICT point of view, the project has resulted in an improved understanding of how to build a control system that integrates well with the existing building automation infrastructure using state of the art in communication protocols and web services[22]. This infrastructure has shown its potential to deliver direct control as in the ventilation case[23], along with indirect control as demonstrated in the *Green Lift* exper-

[21] Nielsen, Matthias; Grønbæk, Kaj; ,Towards Highly Affine Visualizations of Consumption Data from Buildings,"6th International Conference on Information Visualization Theory and Applications, Berlin, Germany", 247-255,2015,"ISBN: 978-989-758-088-8, ScitePress"

[22] Sergi Rotger-Griful, Ubbe Welling and Rune Hylsberg Jacobsen; Multi-modal Building Energy Management System for Residential Demand Response, Proceedings of the 19th Euromicro conference on Digital System Design (DSD 2016), IEEE 2016, pp. 1-8.

[23] Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Dat Nguyen, and Gorm Sørensen. Demand Response Potential of Ventilation Systems in Residential Buildings. Energy and Buildings, 2016. doi: 10.1016/j.enbuild.2016.03.061

iment[24]. Moreover, it has been demonstrated how the test bed can be integrated into a co-simulation environment for the studies of the impacts of demand response on the power grid infrastructure.

Selected scientific problems and development tasks from VPP4SGR project have been subject to a number of master and bachelor student projects. Furthermore, VPP4SGR will in the future be used as a case study in courses in computer engineering.

Finally, the activities in the VPP4SGR project have also identified many interesting opportunities for Ph.D. level research in smart energy. Accordingly, such research problems will be proposed as topics for future Ph.D. projects.

Aarhus University will investigate the potential of maturing the building automation systems integrated to the virtual power plant concept through its recent spin-out company eGuard IVS. The estimated technology readiness level is TRL5 and a further increase of product maturity could possible increase this to TRL9. This development is challenged by the fact that most control solutions in buildings need a large portion of customization, which drives up the cost of deployment, operation and maintenance. A business case study will be conducted in collaboration with eGuard IVS.

1.6.3 Department of Engineering, Aarhus University (CAE)

The results from the VPP4SGR project have demonstrated that smart control of building energy systems has a significant potential to reduce energy use and CO_2 emissions while providing energy flexibility to the grid. As such, VPP4SGR has provided valuable insights that already are exploited in new research projects focusing on flexibility in the case of building energy retrofit. The Grundfos Dormitory Lab may be equipped with a vast amount of sensors collecting data for investigation of various issues. However, reliable data collection is only one of the important aspects of making a building *smart grid ready*. The building does not become *smart grid ready* unless the automation system is able to send control signals to the energy-using systems such as space heating, domestic hot water and ventilation. The results from VPP4SGR provides insights on this matter and is an excellent platform for defining new and necessary research steps towards realising this potential in actual building operations. This involves the research-driven development of components (actuators, smarter sensor technology, and *intelligent* automation systems) and design guidelines for energy flexible buildings. Finally, the VPP4SGR results can be a platform for suggestions and discussions of building regulations that reflects the need for a balance in investments in energy savings, production and flexibility.

1.6.4 Department of Environmental Science, Aarhus University (ENVS)

In the project, the Urban Background Model for air pollution has been extended to cover the whole of Denmark at a very high resolution (1 km x 1 km). The model has furthermore been coupled to the weather forecast model, Eta, which provide meteorological data for driving the air pollution models as well as the regional model, DEHM, to account for long-range transported air pollution. The whole system has been validated against all available data from the Danish monitoring program[25].

The development has founded our capability to provide operational weather and air pollution forecast products for the whole country at a very high spatial and temporal resolution as well as the capability to produce retrospective model runs for the last 35 years.

The forecast products and the capability of producing time series of weather and air pollution will be exploited in offering a large variety of operational data to public and private customers. The products that we can now offer within the scope of the VPP4SGR project are e.g.:

[24] Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Robert Stephen Brewer, and Mia Kruse Rasmussen. Green Lift: Exploring the Demand Response Potential of Elevators in Buildings. Building and Environment, 2016. Under review

[25] U. Im, J. H. Christensen, M. Ketzel, T. Ellermann, C. Geels, K. M. Hansen, O. Hertel, O.-K. Nielsen, M. S. Plejdrup, and J. Brandt, 2016. Validation of the integrated THOR air pollution forecast system. Atmospheric Chemistry and Physics. In preparation.

1. 3-days weather and air pollution forecasts, updated four times every day for intelligent building control of indoor environment, including ventilation and heating.
2. Retrospective time series of weather and air pollution as a basis for building design and decisions on building technology application.

The data can be applied for many other purposes, as e.g., weather and air pollution forecasts for countries or cities not only in Denmark but also abroad, if high-resolution emission data are provided, since the methodology is generic and can in principle be applied all over the world. Furthermore, weather forecast products can be used for planning of energy production, where the production from renewable sources, like wind energy is forecasted. Also assessments of emission reduction strategies and policies for public authorities are already conducted.

ENVS is already selling forecast products on a smaller scale. The strategy is to expand this business by finding a private partner, which can handle the marketing and the customer contact and support, both in Denmark and abroad. Preferably a partner, who is already represented in different countries abroad, where we can take advantage of an already existing marketing and customer contacts support infrastructure.

1.6.5 Alexandra Instituttet

The interdisciplinary research at the Grundfos Dormitory Lab has given Alexandra Instituttet a chance to explore the relationship between energy consumption and different everyday practices, in particular cooking and laundry. The qualitative studies in combination with the quantitative consumption data has enabled us to gain valuable new knowledge on the different elements that affect energy consumption in private homes and helped to better understand some of the main challenges of engaging residents in different ways to support flexible consumption.

Based on this knowledge we have developed new frameworks to help us communicate this more holistic view on energy consumption and the different elements that shape people's behaviour in relation to energy consumption.

One of these frameworks is The Contextual Wheel of Practice (COWOP) that was developed based on our findings from the qualitative analyses at the dorm. It was presented and published at CHI 2015[26], drawing on empirical examples from our studies and interventions at the Grundfos Dormitory Lab. We already use this framework, and the knowledge it represents, widely in our teaching and dissemination activities and will continue to build on the findings in future projects and explorations of energy consumption to investigate how we can work to engage people in the sustainable transition, taking both behavioural, social, infrastructural and material elements into account.

[26] Johanne Mose Entwistle, Mia Kruse Rasmussen, Nervo Verdezoto, Robert S. Brewer, and Mads Schaarup Andersen. 2015. Beyond the Individual: The Contextual Wheel of Practice as a Research Framework for Sustainable HCI. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, pp. 1125-1134. Doi:10.1145/2702123.2702232

Figure 9 - The Contextual Wheel of Practice.

1.6.6 Aarhus Kommune

The City Council of Aarhus Municipality will consider its new climate plan in the course of 2016. One of the key points of the plan is partnerships between businesses and academic institutions, because overall CO_2 emissions in the city cannot be brought down by the council alone. Businesses and residents need to take the next important step, and be able to see the value in doing so. The 2016-2020 Climate Plan aims at creating a strong platform for partnerships across skill, areas and sectors. The VPP4SGR project is an excellent example of how that can be done.

The council will use the experience gained and results from VPP4SGR project to inspire and facilitate future partnership projects under the auspices of the Climate Plan. VPP4SGR is an excellent example of how varied result requirements can act as individual drivers for a joint project. Everyone involved achieved specific results from the project, whilst a common platform for communicating them was developed. The City Council also wants to use the halls of residence as a physical example of what we can do in Aarhus and Denmark within the cleantech industry. The building itself is a fine example of a *living lab*, in which technology is tested with respect to human behaviour. The fact that habits can be hard to change has also been taken into account, making the need for smarter technology greater – and rapidly accelerating in response.

1.6.7 Develco Products A/S

The exploitation potential from the VPP4SGR project is huge for Develco Products. The partnership with researchers, industrial partners, municipalities has resulted in valuable market knowledge that will help us learn how we can improve the design of our products concerning functionalities, aesthetics and technology.

The field trials at the Grundfos Dormitory Lab have given us a high degree of literacy concerning the meeting between technology and man. The study of a living lab together with anthropologists has expanded our market knowledge and provided valuable insight in user behaviour.

Develco Products participates actively in national and international research projects focusing on the smart grid. Through the VPP4SGR project and the synergy with the other research projects, we get access to the newest knowledge from pilot tests and project results/experience within the fields of smart grid and demand response – knowledge that we include in our strategic work as well as in the technical development.

Besides all the activities directly performed in the project, Develco Products also considers VPP4SGR as an important channel of visibility. Furthermore, it has provided the possibility of testing future products and configuration set-ups.

Our product portfolio is widely based on the open wireless standard: ZigBee. In VPP4SGR, we have developed a ZigBee network analysis tool that makes us capable of debugging and extracting information about the wireless network quality. Together with this, we have improved other software tools in the project. We have further been working on these so they have now reached the proper level of maturity. Today, these tools constitute an important part of our Squid.link Starter Kit and we recently launched our support forum where the buyers of the starter kit can access the tools developed in VPP4SGR at commercial conditions.

Overall, the project results will become an integral part of Develco Products' market understanding and will – together with input from customers and smart grid stakeholders – compose the basis for decisions on which products to develop and bring to market in the future.

1.6.8 Grundfos Holding A/S

Grundfos has been represented in the pump market for nearly 70 years and we contribute to global sustainability by pioneering technologies that improve quality of life for people and care for the planet. We add value by decoupling growth from CO_2 emissions, reducing energy consumption and making clean water available.

Grundfos' history of sustainability dates back to the establishment of the company in 1945 and our organization and employees continue to live this value. High on the agenda is our aim to be active in improving the environment, both in terms of the changing world around us, but also our own footprint. We therefore support the *Caring for Climate* initiative and accordingly, we have committed ourselves never to emit more CO_2 than we did in 2008.

We continuously aim to strengthen our leading position within energy and environmental friendly solutions and strong marketing of our most energy saving solutions has generated positive results. Today pumps account for no less than 10% of the world's electricity consumption, and distribution of water and energy to and from buildings account for a significantly part.

Building services is an import business area for Grundfos. We deliver pump solutions for all water applications in residential and commercial buildings for instance heating, cooling and domestic hot and cold water. High efficient pumps exist today but the future energy challenges lies in new solutions for optimal production, distribution and consumption of energy.

The research results developed in the VPP4SGR project are an important contribution to future intelligent products that consider energy consumption in a more holistic way where consumption of energy in a building is a part of a larger energy optimal solution on a city level. However, investments in energy-optimised pumping systems must be profitable for the customers. A natural next step is therefore to transform the research results from VPP4SGR to prototype units that can be field tested in the Grundfos Dormitory Lab so that the potential and business value can be examined.

1.7 Project conclusion and perspective

During the past three years research activities at the Grundfos Dormitory Lab has focused on improved understanding of the energy consumption in the building. The project has been leveraged on the common building installation and the residents with the aim of determining the flexibility potential of the building – including its residents – and the measures needed to provide a proper demand response. As a result, the VPP4SGR project has created overviews of energy consumption and action possibilities, useful for building control over/interaction with their energy systems and component. To better understand the flexibility potential of the building, the project has invented a taxonomy for demand response control actions that embraces direct and indirect load control. The direct control implements automation actions to shift electricity consumption whereas the indirect control uses control signals to stimulate human behaviour.

A minimalistic virtual power plant prototype has been built and integrated with the installed building automation system to demonstrate effects on demand response. The proposed system has offered a unique possibility to study the mix of technically achievable control systems and the anthropological and sociological effects of human behaviour on energy consumption in an interdisciplinary set-up. For instance, gamification (ShareBuddy) and notching (Clock Cast) approaches are examples of means to study the latter. In contrast, automated control of the ventilation system can provide a fast a predictable demand response. However, this response need to be pooled with many similar responses to have any significant impact on the power grid.

Another aspect of the project is the assessment of the potential use of weather and air pollution forecast as possible triggers of demand response. This has presented a progress beyond the state of the art in high-resolution forecasting models.

A significant effort of the project has been devoted to acquisition and handling of energy data. The project has benefited from a shared infrastructure, the Karibu cloud platform. The project has shown that handling a vast amount of data and securing quality of data is a manageable but also a somewhat cumbersome task. Furthermore, the ICT infrastructure of the building has been extended with for instance ZigBee wireless sensor and actuator network. To our knowledge installed ZigBee mesh network in Grundfos Dormitory Lab is among the largest ZigBee networks to date.

From a civil engineering perspective, the project has developed and analytical model for the study of smart energy concepts in large residential buildings. Preliminary results from simulations have for instance shown that in some periods, there can be an economic benefit of increasing energy consumption at night; and hence store thermal energy; and let the building cool off during daytime. This operation mode has the potential of a better utilization of renewable energy.

During the project lifetime a significant number of scientific publications (22) as well as other dissemination activities including video recording, public interviews, invited talks etc. have been carried out. Communication with the residents has been through yearly Grundfos events as well as direct mail and use of the Facebook group for the residence.

In summary, we conclude that the potential of a building like the studied one is small and aggregation of several buildings is required. Furthermore, engaging the residents to become flexible with their consumption is a very challenging task, although not completely impossible.

Today, at the end of the VPP4SGR project the Grundfos Dormitory Lab is in a good shape to support future research, development and demonstration activities in smart energy. In isolation, the building may not provide enough flexibility to provide a response that can be traded on an energy market; but it has provided an improved understanding in the flexibility potential of buildings, the operation of buildings as well as the response of residence living in buildings. The Grundfos Dormitory Lab offers a unique opportunity to further study smart energy also taking into account the heterogeneous mix of energy sources i.e., electricity, district heating, solar irradiation and thermal heat exchange.

1.7.1 Acknowledgements

All project partners would like to express their gratitude to all external parties that have made it possible to get so far with this project. We would specially like to thank all the students that have decided to work with us. We would also like to offer a special thanks to DEAS for their friendly and professional support of the project. Thanks also go to Energinet.dk for making data available for renewable energy generation and the CO_2 emission intensity forecasts. Furthermore, we would like to thank Nord Pool for providing information related to energy markets.

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2. Annexes

2.1 Scientific Dissemination List

1. *Sergi Rotger-Griful and Rune Hylsberg Jacobsen. Chaos Modeling and Control Systems Design. Ed. by Ahmad Taher Azar and Sundarapandian Vaidyanathan, chapter Control of Smart Grid Residential Buildings with Demand Response, pp. 133–161. Springer International Publishing, 2015. doi: 10.1007/978-3-319-13132-0_7*

   This book chapter presents an overview of the Virtual Power Plant of a residential building for smart grid purposes.

2. *Emad Ebeid, Sergi Rotger-Griful, Søren Aagaard Mikkelsen, and Rune Hylsberg Jacobsen. A Methodology to Evaluate Demand Response Communication Protocols for the Smart Grid. In IEEE International Conference on Communication Workshop (ICCW), pp. 2012–2017, 2015. doi: 10.1109/ICCW.2015.7247476*

   This conference paper describes a methodology to evaluate the demand response communication protocol under different control strategies and scenarios. The article is supported with simulations using Smart Energy Profile 2.0 protocol, which could potentially be used by the virtual power plant.

3. *Michael Dahl Knudsen and Sergi Rotger-Griful. Combined Price and Event-based Demand Response Using Two-stage Model Predictive Control. In IEEE International Conference on Smart Grid Communications (SmartGridComm), pp. 344-349, 2015. doi: 10.1109/SmartGridComm.2015.7436324*

   The publication is a conference article that presents a control strategy, based on model predictive control that can be used to provide both price-based and event-based demand response. The controller design is evaluated in a co-simulation environment.

4. *Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Dat Nguyen, and Gorm Sørensen. Demand Response Potential of Ventilation Systems in Residential Buildings. Energy and Buildings, vol. 121, pp. 1-10, 2016. doi: 10.1016/j.enbuild.2016.03.061*

   This journal article analyses the demand response potential of ventilation systems. The article presents a model and a simulation environment to assess the flexibility of aggregating a portfolio of ventilation systems. Additionally, the paper describes the system extension and experimental result carried out using the ventilation system in the Grundfos Dormitory Lab.

5. *Sergi Rotger-Griful, Spyros Chatzivasileiadis, Rune Hylsberg Jacobsen, Emma M. Stewart, Javier Matanza Domingo, and Michael Wetter. Hardware-in-the-Loop Co-simulation of Distribution Grid for Demand Response. In 19th Power Systems Computation Conference (PSCC). IEEE, pp. 1-7, doi:10.1109/PSCC.2016.7540828, 2016*

   The work described herein was presented in a conference article that extends a co-simulation platform with a Hardware-in-the-Loop to assess the demand response potential of ventilation systems in a holistic manner.

6. *Emad Ebeid, Sergi Rotger-Griful, Søren Aagaard Mikkelsen, and Rune Hylsberg Jacobsen. Smarter Energy: from Smart Metering to the Smart Grid. Ed. by Hongjian Sun, chapter A Model-Driven Evaluation of Demand Response Communication Protocols for Smart Grid, pp. 1–35. Institution of Engineering and Technology (IET), 2017. Under review*

   The book chapter presents a methodology to evaluate demand response communication protocols under certain direct control strategies and deterministic user scenarios.

7. *Sergi Rotger-Griful, Rune Hylsberg Jacobsen, Robert Stephen Brewer, and Mia Kruse Rasmussen. Green Lift: Exploring the Demand Response Potential of Elevators in Buildings. Energy Research & Social Sciences, 2016. Under review*

   Journal article under review that analyses the demand response potential of elevators in residential buildings by providing feedback information to the residents. The results are supported with a one-month field trial in the Grundfos Dormitory Lab.

8. *Sergi Rotger-Griful, Ubbe Welling, and Rune Hylsberg Jacobsen. Multi-modal Building Energy Management System for Residential Demand Response. In Proceedings of the 19th Euromicro Conference on Digital System Design (DSD). Limassol, Cyprus, 30 August – 1 September 2016, IEEE, pp. 1-8.*

   Conference article that present the design and prototype of a building energy management system to provide demand response. The article was given a best paper award.

9. *Robert S. Brewer, Nervo Verdezoto, Mia Kruse Rasmussen, Johanne Mose Entwistle, Kaj Grønbæk, Henrik Blunck, Thomas Holst. Challenge: Getting Residential Users to Shift Their Electricity Usage Patterns. The sixth ACM International Conference on Future Energy Systems (ACM e-Energy). Association for Computing Machinery, 2015. pp. 83-88. doi:[10.1145/2768510.2770934](10.1145/2768510.2770934)*

   Based on lessons learned from interventions at the Grundfos Dormitory Lab, the paper discusses the challenges of getting residents to shift consumption.

10. *Johanne Mose Entwistle, Mia Kruse Rasmussen, Nervo Verdezoto, Robert S. Brewer, Mads Svhaarup Andersen. Beyond the Individual: The Contextual Wheel of Practice as a Research Framework for Sustainable HCI. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, (CHI 2015). Association for Computing Machinery, 2015. pp. 1125-1134. doi:[10.1145/2702123.2702232](10.1145/2702123.2702232)*

    This paper presents the COWOP framework and discusses how a more holistic and practice-oriented understanding of energy consumption can help us develop better interventions to try to reduce or shift consumption.

11. *Mia Kruse Rasmussen. People, Technology, and Energy: Configurations of Practices and Place. CHI workshop "Smart For Life: Designing Smart Home Technologies that Evolve with Users", 18 April 2015. URL: http://zpac.ch/smartforlife/CRsubmissions/Mia%20Kruse%20Rasmussen%20CR.pdf.*

    This workshop paper further explores the potential of COWOP as a way to understand energy consumption in the home and how we can work to change it.

12. *Robert Stephen Brewer, Nervo Verdezoto, Thomas Holst, Mia Kruse Rasmussen. Tough Shift: Exploring the complexities of Shifting Residential Electricity Use through a Casual Mobile Game. Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play (CHI Play 2015), pp. 307-317, 2015. doi: [10.1145/2793107.2793108](10.1145/2793107.2793108).*

    This paper presents the ShareBuddy intervention; how the game was designed, the main findings from the field trials, and discusses the potential of using this type of casual game as a way to engage residents in shifting consumption.

13. *Michael Dahl Knudsen and Steffen Petersen. Demand Response Potential of Model Predictive Control of Space Heating based on price and Carbon Dioxide Intensity Signals. Energy and Buildings, vol. 125, pp. 196-204, 2016. doi:10.1016/j.enbuild.2016.04.053*

    This paper investigates the demand response potential of space heating when controlled by a model predictive controller that minimizes a weighted sum of energy costs and CO_2 emissions.

14. *M.D.Knudsen, S.Petersen, M.S.Jensen, M.Kjer and R.Juul, Demand Response Potential in Domestic Hot Water Preparation Supplied by Low-Temperature District Heating. Energy and Buildings, 2016. Under review.*

    This paper investigates the demand response potential of a domestic hot water system connected to a low temperature district heating network and a micro-booster heat pump controlled by an economic model predictive controller.

15. *S.Petersen, T.H.Pedersen, K.U.Nielsen and M.D.Knudsen. Method for detection of room occupancy based on trajectory of sensor data. Part I: Getting the ground truth, 2016. Under review.*

This paper present a method to accurately determine the number of people in a room based on a Kinect camera.

16. *M.D.Knudsen, R.E.Hedegaard, T.H.Pedersen and S.Petersen. Model Predictive Control of Space Heating and the Impact of Taxes on Demand Response: A Simulation Study. 12th REHVA World Congress (CLIMA2016). 22-25 May, Aalborg, Denmark 2016.*

Conference article that investigates the effect taxes and levies have on the demand response potential based on a case where space heating is controlled by an economic model predictive controller.

17. *T.H.Pedersen, M.D.Knudsen, R.E.Hedegaard and S.Petersen. Handling Stochastic Occupancy in an Economic Model Predictive Control Framework for Heating System Operation in Dwellings. 12th REHVA World Congress (CLIMA2016). 22-25 May, Aalborg, Denmark 2016.*

Conference article that presents a simple method to handle occupancy in a case where space heating is controlled by an economic model predictive controller.

18. *R.E.Hedegaard, T.H.Pedersen, M.D.Knudsen and S.Petersen. Identifying a comfortable excitation signal for generating building models for model predictive control: a simulation study. 12th REHVA World Congress (CLIMA2016). 22-25 May, Aalborg, Denmark 2016.*

Conference article that investigates how a suitable excitation signal used for system identification of a thermal building model can be constructed such that it reveals enough information about the building without violating comfort constraints.

19. *A.Heller, A.Wyckmans, G.Zucker, S.Petersen, C.Haider. Buildings interaction with the Energy Systems – A Research Agenda. Seventh PHN Sustainable Cities and Buildings conference (Passiv Hus Norden). Copenhagen, Denmark. 2015*

The paper describes the research agenda to support energy-efficiency goals through smart city efforts for a few European cases as examples (VPP4SGR being one of them) with a focus on the impacts of buildings in the overall energy system.

20. Henrik Bærbak Christensen, Henrik Blunck, Niels Olof Bouvin, Robert Stephen Brewer, and Markus Wüstenberg. 2014. Karibu: a flexible, highly-available, and scalable architecture for urban data collection. In Proceedings of the First International Conference on IoT in Urban Space (URB-IOT '14). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, Belgium, pp. 96-98. doi:10.4108/icst.urb-iot.2014.257253

This paper describes the KARIBU big data backend for collecting data from the Grundfos Dormitory Lab.

21. Matthias Nielsen and Kaj Grønbæk. Towards Highly Affine Visualizations of Consumption Data from Buildings, Proceedings of the 6th International Conference on Information Visualization Theory and Applications (VISIGRAPP 2015), ISBN 978-989-758-088-8, pp. 247-255. doi: 10.5220/0005315102470255

This paper described the AffinityViz visual analytics tool developed to analyse the Grundfos Dormitory Lab data.

22. Jung Min Kim, Rune Hylsberg Jacobsen and Robert S. Brewer, CoFELS: Conceptual Framework for Electricity Load Shifting System Design, Proceedings of the 19th Euromicro Conference on Digital System Design (DSD). Limassol, Cyprus, 30 August – 1 September 2016, IEEE, pp 1-8.

The paper introduces a conceptual framework for electricity load shifting applications aimed for systems designers. A prototype implementation of a demand response application is developed and used to study the user’s flexibility based on a weekly planning.

2.2 Dissemination activities

Dissemination activities have been divided by the categories: REPORT, PRESENTATION, INTERVIEW, and OTHER.

2016:

- Mia Kruse Rasmussen "Energiforbrug og praksisteori" Guest lecture on IT-Universitet "Sustainable Futures" course 25.02.16. [PRESENTATION].
- Mia Kruse Rasmussen "How hard can it be? – experiences on changing energy consumption at a dormitory in Aarhus" – EcoSense closing seminar 18.03.16. [PRESENTATION].
- Mia Kruse Rasmussen "Engaging Energy Consumers in the Smart Grid" – ICCI Danish Panel 27.04.16. [PRESENTATION].
- Mia Kruse Rasmussen Forståelser af (unges) energiforbrug. Smergy ungdomsråd i Aarhus 4.05.16. [PRESENTATION].
- Mia Kruse Rasmussen: mennesker, adfærd og energiforbrug. Intelligent Energi 10.05.16. [PRESENTATION].
- Mia Kruse Rasmussen "Hvorfor er det så svært for folk at gøre det rigtige i forhold til indeklima?" – Indeklimadag 31.05.16. [PRESENTATION].
- Project group: Video presentation on AAK's YouTube channel: https://youtu.be/DQ6cSrFAE7M (Danish) and https://youtu.be/L9meg6l94Ag (English). [OTHER].

2015:

- Johanne Mose Entwistle Smart Energy Conference, Vejle 26 March 2015 [PRESENTATION].
- Johanne Mose Entwistle, Rådet for sundt indeklima "Energiforbrug og indeklima i hjemmet". Hindsgavl 17 March 2015 [PRESENTATION].
- Johanne Mose Entwistle. Part of the Danish Panel. ICCI Istanbul 2015, 30 April [PRESENTATION].
- Steffen Petersen and Michael Dahl Knudsen, CITIES project - internal meeting on Flexible Buildings, Technical University of Denmark, 19 August 2015 [PRESENTATION].
- Steffen Petersen and Michael Dahl Knudsen, CITIES project - workshop on Flexible Buildings, Technical University of Denmark, 7 September 2015 [PRESENTATION].
- Michael Dahl Knudsen, Extended Partner Meeting at Grundfos, 8. May 2015 [PRESENTATION].
- S. Rotger-Griful, Guest lecture at the Bachelor course Databaser-I4DAB-01 at Aarhus School of Engineering – Aarhus University (ASE AU). [OTHER]
- S. Rotger-Griful, Interview with the communication officer of the Department of Engineering Kim Harrel about Green Lift (elevator field trial) [11-03-2015] [OTHER].
- S. Rotger-Griful, Guest lecture at Master course Data Management at the Department of Engineering at Aarhus University (ENG AU). [OTHER].
- Rune Hylsberg Jacobsen, Presentation of Green Lift experiment at the AU-ESM kick-off Workshop Event, Aarhus University, 20 February, 2015. [PRESENTATION].
- Rune Hylsberg Jacobsen, "To shift or not to shift? Towards an Urban Demand Response", Invited talk at the AU Smart Cities Symposium, 3 March 2015. [PRESENTATION].
- Steffen Petersen, Kick-off Event AU Energy Systems and Markets, Lecture (including simulation results from VPP4SGR), "Smart Energy and Buildings", 17 February 2015. [OTHER].
- Steffen Petersen, Conference on Healthy Indoor Climate (CISBO), Lecture (including simulation results from VPP4SGR), "Energi i boliger" [OTHER].

2014

- Sergi Rotger-Griful, Guest lecture at the Bachelor course Databaser-I4DAB-01 at Aarhus School of Engineering – Aarhus University (ASE AU). [OTHER].
- Sergi Rotger-Griful, 2014. Virtual Power Plant for Residential Demand Response. Department of Engineering, Aarhus University. Denmark. 28 pages - Technical report ECE-TR-22. [REPORT]

- Gorm Sørensen and Dat Nguyen, Energy Consumption-aware Home Automation System Using Industrial Hardware Components, Engineering Research Project (5 ECTS), fall 2015. Supervisors: Rune Hylsberg Jacobsen and Sergi Rotger-Griful. Video presentation available at YouTube: https://www.youtube.com/watch?v=789MopOAVek [OTHER].
- Martin Kobberø. ”Undersøgelse af Demand Response strategier implementeret med Smart Energy Profile 2”, Master's Thesis, Aarhus University. Supervisor: Rune H. Jacobsen, June 2014. [REPORT].
- Johanne Mose Entwistle. Elforsk strategi seminar - Dansk Energi, Kbh, April 2, 2014. [PRESENTATION].
- Johanne Mose Entwistle. Suitable for Business - Green Incorporated - KU, March 28, 2014. [PRESENTATION].
- Johanne Mose Entwistle. Energifondens Summer School. 22 August, 2014 (Presentation). [PRESENTATION].
- Speaker at 'Anvendt Antropologi' Aalborg University. 15 December 2014. [PRESENTATION].
- Johanne Mose Entwistle. Speaker and chair at Fremtidens Energi (Energy of the Future), Navitas, Aarhus, 22 September 2014. [PRESENTATION].
- Johanne Mose Entwistle. P4 Østjylland - September 2014 (Radio interview). [INTERVIEW].
- Johanne Mose Entwistlem, "Ecosense", presentation at the klimapartnerseminar 7 January 2014, Teknologisk Institut, Aarhus. [REPORT].
- Jung Min Kim (Jenny), Demand response survey study, 5 ECTS R&D project, Aarhus University, December 2014. Supervisor: Rune Hylsberg Jacobsen. [REPORT].
- Lasse Balmer Hansen and Jesper Gilbert Lausen, Virtual Power Plant Data Validation, Bachelor project, December 17, 2014. Supervisors: Rune Hylsberg Jacobsen and Sergi Rotger Griful. [REPORT].
- Michael Dahl Knudsen, Tour guide at the Grundfos dormitory. [OTHER].
- Michael Dahl Knudsen, Guest lectures at the Master´s degree programme in Architectural Engineering (ASE). [OTHER].
- Michael Dahl Knudsen, Speaker at the conference "Fremtidens Energy" (Energy of the future) at Navitas, Aarhus, 22 September 2014. [PRESENTATION].
- Rune Hylsberg Jacobsen, Demand Response i Smart Grid. Speaker at the conference "Fremtidens Energy" (Energy of the future) at Navitas, Aarhus, 22 September 2014. [PRESENTATION].
- Peter Harling Lykke, Co-organizing the conference "Fremtidens Energi" (Energy of the future) at Navitas Aarhus, 22 September 2014. [OTHER].
- Peter Harling Lykke. ”Virtual Power Plant”, presentation at the Klimapartnerseminar 7 January 2014, Teknologisk Institut, Aarhus. [PRESENTATION].
- Sergi Rotger Griful, Søren Aa. Mikkelsen, and Rune H. Jacobsen, Smart Buildings as Demand Response Providers Presentation in Smart Cities Workshop held in Aarhus in April 2014 available at prezi.com. [PRESENTATION].
- Sergi Rotger Griful. "Energi Positiva. Aarhus". Interview to Catalan TV. Available at blog.tv3.cat. [INTERVIEW].

2013

- Johanne Mose Entwistle, Oplæg for Organisation for Vedvarende Energi, 16th of December 2013. [PRESENTATION].
- Mia Kruse Rasmussen, Johanne Mose Entwistle, Laura Lynggaard Nielsen. Working Paper 1: Understanding Energy Consumption at the Grundfos Dormitory Lab as Situated Practices, Initial Qualitative Report 2013. Available from http://alexandra.dk/sites/default/files/working_paper_1-energy-consumption-as-situated-practices.pdf, pp. 1-60 [REPORT]
- Peter Harling Lykke, presentation for REMT 20 December 2013. Rådet for Region Midtjyllands megasatsning på Vedvarende Energi. [PRESENTATION].

2.3 List of project contributors / members

In the table below, you can see a comprehensive list of all people that have contributed in this research project.

Table 2- VPP4SGR project members.

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Henrik Blunck	Department of Computer Science, Aarhus University (former employee)	
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Sergi Rotger-Griful and Rune Hylsberg Jacobsen, Virtual Power Plant for Smart Grid Ready Buildings and Customers, 2016

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