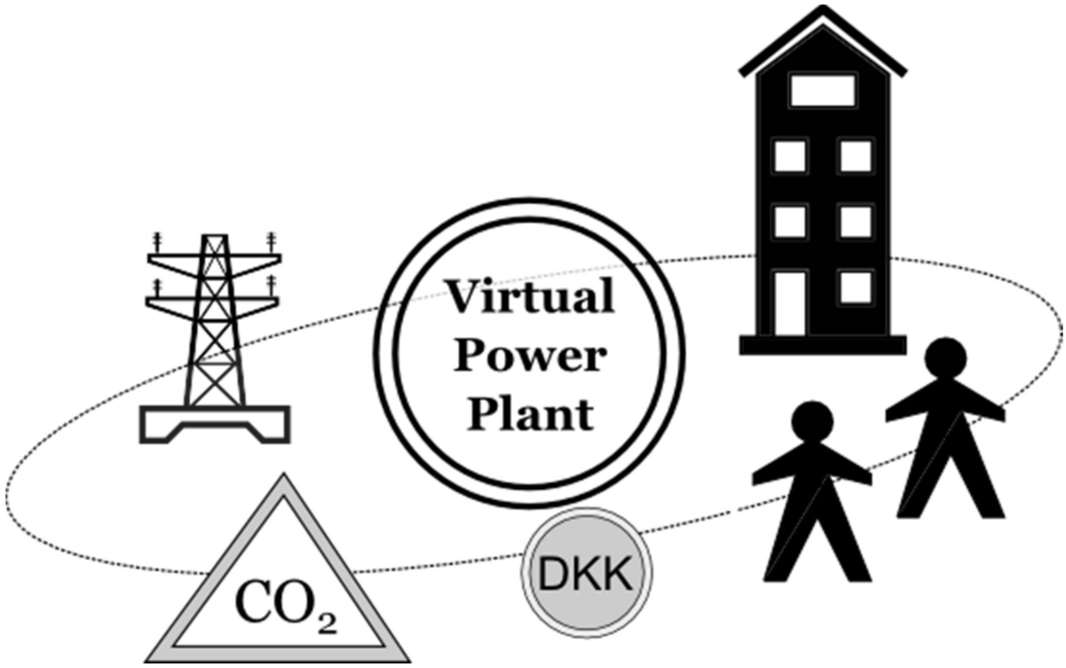
VIRTUAL POWER PLANT FOR RESIDENTIAL DEMAND **RESPONSE**

Electrical and Computer Engineering
Technical Report ECE-TR-22



AARHUS UNIVERSITY
DEPARTMENT OF ENGINEERING

DATA SHEET

Title: Virtual Power Plant for Residential Demand Response

Subtitle: Electrical and Computer Engineering

Series title and no.: Technical report ECE-TR-22

Author: Sergi Rotger-Griful
Department of Engineering – Electrical and Computer Engineering, Aarhus University

Internet version: The report is available in electronic format (pdf) at the Department of Engineering website http://www.eng.au.dk.

Publisher: Aarhus University©
URL: http://www.eng.au.dk

Year of publication: 2014 Pages: 28
Editing completed: October 2014

Abstract: This report presents the progress done in the first 1.5 years in relation to the PhD project "Virtual Power Plant for Residential Demand Response". The PhD project aims to gain insight on demand response provision in residential buildings by using a Virtual Power Plant (VPP) in a smart grid scenario. The document shows an architectural overview of the designed VPP and a prototype of the latter based on industrial automation equipment. Furthermore, the report introduces the control strategy of the VPP. This strategy is based on a model predictive control approach to locally optimise energy resources and to provide demand response to an aggregator. In addition, an initial study on prediction models for electricity consumption of residential buildings is presented. Load forecasting models like the ones described are used by the intelligence of the VPP for decision making. The report concludes by outlining the future work together with the planed publications that will lead to timely completion of the PhD study.

Keywords: smart grids, demand response, virtual power plant, residential buildings, model predictive control, load forecasting

Referee/Supervisor: Rune Hylsberg Jacobsen
Financial support: The work in this document has been funded by the Danish Energy Agency project: Virtual Power Plant for Smart Grid Ready Buildings and Customers (no. 12019).

Please cite as: Sergi Rotger-Griful, 2014. Virtual Power Plant for Residential Demand Response. Department of Engineering, Aarhus University. Denmark. 28 pp. - Technical report ECE-TR-22

Cover image: Sergi Rotger-Griful

ISSN: 2245-2087

VIRTUAL POWER PLANT FOR RESIDENTIAL DEMAND RESPONSE

Sergi Rotger-Griful
Aarhus University, Department of Engineering

Abstract

This report presents the progress done in the first 1.5 years in relation to the PhD project "Virtual Power Plant for Residential Demand Response". The PhD project aims to gain insight on demand response provision in residential buildings by using a Virtual Power Plant (VPP) in a smart grid scenario. The document shows an architectural overview of the designed VPP and a prototype of the latter based on industrial automation equipment. Furthermore, the report introduces the control strategy of the VPP. This strategy is based on a model predictive control approach to locally optimise energy resources and to provide demand response to an aggregator. In addition, an initial study on prediction models for electricity consumption of residential buildings is presented. Load forecasting models like the ones described are used by the intelligence of the VPP for decision making. The report concludes by outlining the future work together with the planed publications that will lead to timely completion of the PhD study.

Table of Contents

1 Introduction

The purpose of this report is to present the progress in relation to the PhD project "Virtual Power Plant for Residential Demand Response" carried out at the Department of Engineering at Aarhus University (AU). The document describes the work conducted during the first 1.5 years of the PhD and details the envisioned future plans for the remaining time.

This chapter is meant to introduce the reader to the PhD project. The chapter starts with an introduction to the research field followed by the aim of the PhD project. The chapter finalises outlining the structure of all the document.

1.1 Field of Research

The traditional electric grid is being re-engineered to tackle backbone problems. On one side, the worldwide electricity consumption is increasing every year [1]. This problem has traditionally been solved by investing in the distribution electric network to increase the maximum power of the grid. On the other side, the way electricity is produced nowadays is highly pollutant on CO_2 emissions [1], leading to the commonly accepted global warming. It is becoming increasingly difficult to ignore these issues and many governmental institutions are trying to face them by setting ambitious goals on climate and energy policies.

In 2007, the European Council set three ambitious energy targets for 2020: 20% reduction of greenhouse gases, 20% electricity produced by renewable energies and 20% increase of energy efficiency [2]. On national level these policies are applied differently. For example, the Danish government strives to a 30% of electricity produced by renewable energy sources by 2020 and 100% by 2050 including transportation [3]. Satisfying all these needs will require a change in the electrical grid to overcome a set of new challenges. This forthcoming grid is known as the Smart Grid [4].

The Smart Grid is the future electrical grid that will use Information and Communication Technology (ICT) as a vehicle to handle a large amount of Distributed Energy Resources (DER) to increase the efficiency and reliability of the overall system. One of the many challenges towards the Smart Grid is the integration of renewable energies. These energy sources will enable the reduction of CO_2 emissions but at the cost of increasing the grid operation complexity. Compared to traditional power plants, renewable energy sources like photovoltaic panels or wind turbines cannot produce energy on-demand thus making it more challenging to balance the electricity production and the consumption. With high share of renewable production and in absence of cost-effective storage solutions, higher flexibility will be required from the demand side to adapt the consumption to the intermittent generation. Demand response is emerging as a key asset to provide this flexibility from the consumers in the Smart Grid [5].

The Department of Energy of the United States (US) defines demand response as a "change in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" [6]. In the US, demand response is already a business having around 40 curtailment service providers that are able to aggregate up to 10,000 MW of flexibility (peak demand reduction) of several consumers [6].

Demand response can be provided from different types of electricity consumers: large commercial and industrial, small commercial and industrial, residential, individual and fleet of plug-in Electric Vehicle (EV) [5]. Large commercial and industrial consumers are very attractive from a demand response point of view for having high and centralised loads. EVs will open new demand response opportunities as they are integrated in the market by shifting the load to alleviate grid congestion [7]. Small commercial and industries could be considered similar to residential consumers for having relatively low and distributed electricity usage. Small residential consumers have loads that can be limited from a demand response perspective, e.g., depending on the willingness of the consumer. Having low, distributed and somehow limited electricity loads in the residential domain makes demand response provision more challenging. However, the residential sector accounts to 30% of the electricity usage in the European Union (EU) [8], thus opening a wide range of demand response possibilities to be investigated.

The demand response potential of a single household is modest and by itself is not attractive when balancing the grid. Hence, it is commonly accepted the need of aggregating these low and decentralised electricity loads. Some studies aggregate loads at a building level [9], others at a neighbourhood level [10] and others at a city level [11]. When aggregating loads, ensuring a good coordination is a highly important task. One possible approach in this scenario is to use a Virtual Power Plant (VPP) [12]. A VPP can be defined as "a cluster of dispersed generator units, controllable loads and storages systems, aggregated in order to operate as a unique power plant" [13]. A VPP can be used to manage DER and to enable these to market participation [14, 15].

This PhD project aims to investigate the feasibility of using a VPP to manage the energy resources in a residential building. The envisioned VPP optimally regulates the electricity usage in the entities under control and provides flexible consumption through demand response.

1.2 Project Aim: Hypothesis and Purpose

The goal of this project is to provide insights to ease demand response provision in the residential sector by designing, developing and validating a VPP of a residential building. The underlying hypothesis of the PhD project is:

It is my hypothesis that a VPP deployed on an ICT platform, can efficiently coordinate a group of residential DER using adequate control algorithms and prediction models, enabling aggregated demand response provision to the electricity market through an aggregator in a smart grid context.

The term efficiently used in the hypothesis to describe the DER coordination entails the time responsiveness, the reliability of the communication and the quality of the service provided. The main idea is to analyse the concept of a residential VPP from an holistic perspective considering: the design and analysis of the ICT platform required, the control methods to manage electricity usage, the prediction models for the VPP operation and the interconnection with the electricity market. The approach followed in the PhD is illustrated in Figure 1.1, where each part is first considered independently and at the end all parts are assembled considering all the studied areas of the VPP as a whole.

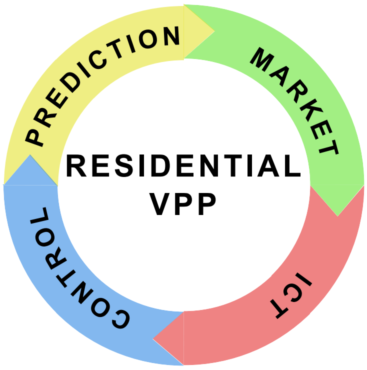


Figure 1.1: Overview of the research areas in the PhD.

The raised hypothesis will be validated by:

- Designing, developing and evaluating in a set of field trials an ICT platform of a VPP to monitor and control a residential building.
- Proposing and evaluating a suitable control strategy to be used by a VPP of a residential building to optimally regulate the local DER and to provide demand response.
- Studying the state of the art in methods for predicting residential electricity consumption, evaluating these methods and proposing a suitable model for the VPP operation.
- Analysing and evaluating the possibilities of providing ancillary services through flexible energy usage that a VPP of a residential building can provide through demand response bids to the electricity market via an aggregator.
- Evaluating a VPP of a residential building from a system perspective, considering the ICT infrastructure, the control algorithms, the prediction methods and the market interaction.

In the validation of the hypothesis, different evaluation metrics will be considered. Examples of this metrics are accuracy indexes in prediction models, execution time for control and prediction methods or demand response provisioning for control methods. In the first 1.5 years of the PhD project the contributions provided to the research field are:

1. A design of the ICT infrastructure of a VPP of a residential building considering all required stakeholders.
2. A methodology to evaluate demand response protocols along with demand response strategies.
3. A design of the control algorithm based on Model Predictive Control (MPC) for the VPP of a residential building to regulate local DER and to provide demand response.
4. An initial analysis on methods to predict electricity consumption in residential buildings.

1.3 Document Structure

The document is organised in four chapters and three appendices. The first and second chapter are meant to introduce the reader to the field of research and the PhD project to better understand the whole document. The third chapter introduces the concept of the VPP of a residential building and all the different approaches considered: ICT, control, prediction and market. The fourth and last chapter synthesises the conducted work in the first 1.5 years of the PhD, deepens on the future plans for completion of the project and concludes the document. The appendices document the publications done and planned, the courses taken and the acronyms used in the report.

Chapter 1 - Introduction: Introduces the reader to the research field, presents the purpose of the PhD project here described and outlines the structure of the document.

Chapter 2 - Background: Presents the necessary background for comprehension of the rest of the document and describes the case study used to validate the research.

Chapter 3 - Residential VPP with Demand Response: Describes the work conducted in the first 1.5 years of the PhD and briefly outlines future work plans.

Chapter 4 - Current Status and Future Plans: Summaries the contributions done so far and details the future plans for completion of the PhD project.

Appendix A - Publications: Outlines the publications accepted, submitted and planned related to the PhD project.

Appendix B - Course: Describes the courses carried out during the first 1.5 years of the PhD.

Appendix C - Acronyms: Lists the acronyms being used in the document.

2

Background

This chapter provides the basic background for better understanding of the remaining of the document. First, an overview of the electricity system is provided. Second, basic concepts of demand response are presented. Finally, the chapter describes the case study being used to validate the research.

2.1 Electricity System Overview

This section provides a common understanding on the naming and roles of the actors involved in the physical delivery of electricity and the electricity market. In Figure 2.1 an overview of the all the stakeholders and their relationship is displayed. The figure represents the Danish grid system and has been inspired from [16, 17, 18]. All the actors shown in Figure 2.1 are described hereafter. Please note that for simplicity the figure considers the most generic case omitting some singular ones (e.g., consumers buying electricity to large producers through a bilateral contract).

- **Bulk generation:** Entity producing large amounts of electricity and trading them into the market.
- **Transmission System Operator (TSO):** Entity responsible of the high-voltage transmission of electricity that operates the whole gird system.
- **Distribution System Operator (DSO):** Entity responsible of the distribution of electricity at low-voltage grid.
- **Consumer:** Entity using electricity that can buy electricity in the market, through a retailer or in a bilateral contract.
- **Distributed Energy Resources (DER):** Entities that can generate, store and/or consume small amounts of electricity, i.e., typically less than 250 kW [15].
- **Balance Responsible Party (BRP):** Entity responsible of providing flexibility (production or consumption) to the grid in communication with the TSO.
- **Retailer:** Entity defining contracts with the consumers on electricity supply that trades in the electricity market.

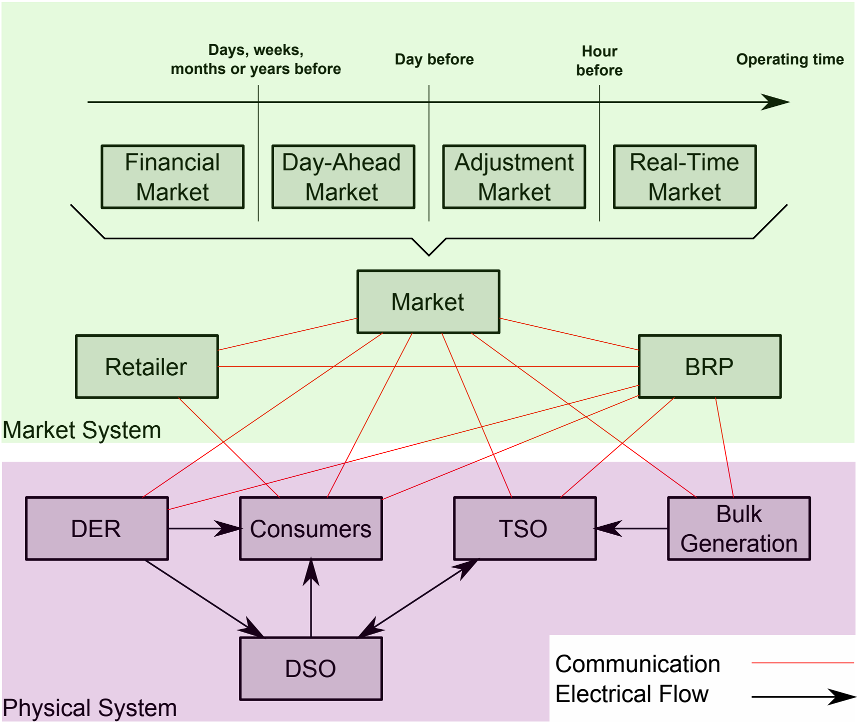


Figure 2.1: Present Danish Electricity System [16, 17, 18]

- **Market:** Entity representing the electricity market. In Denmark there are two markets depending on the time of delivery: future or financial markets and short-term markets. The short term market is regulated by *Nord Pool Spot* and is divided in day-ahead market (*Elspot*), adjustment market (*Elbas*) and real-time market. The financial market is regulated by *Nasdaq OMX Commodities*.

2.2 Demand Response Basics

Demand response can provide flexibility in the electricity usage to migrate from a paradigm where the generation follows the consumption to one where consumption follows generation. Demand response comprises all intentional alterations on consumers' consumption patterns of electricity usage in response to external signals [19]. Demand response presents a main difference with Demand-Side Management (DSM). The former implies a consumer-to-grid approach where the consumer becomes an active asset by managing its own consumption thus achieving monetary benefits. On the contrary, DSM implies a grid-to-consumer approach where a DSO decides activities to improve the efficiency of the energy system. DSM has been already implemented in the industry the past decades [20].

The benefits from demand response are vary depending on the stakeholders point of view. The consumers benefits from bill savings and energy usage awareness. DSOs and TSOs have the opportunity to relieve grid constraints, increase the grid performance and decrease grid investment for system expansion [5, 20].

Demand response resources in the residential sector mainly fall in one of these three categories: Heating, Ventilating and Air Conditioning (HVAC), lighting and plug-loads.

HVAC appliances present an interesting demand response potential for consuming large amounts of electricity and for providing a storable commodity (i.e., thermal energy). Lighting have low energy consumption highly correlated with the consumers behaviour. Plug-loads present a large range of electricity consumption from a few W to a few kW highly linked with consumers behaviour. The demand response potential of different appliances in a EU are widely discussed in [21]. The consumers loads can also be classified on how they provide service to the consumers: storable load (e.g., EV and HVAC), shiftable load (e.g., laundry), curtailable load, non-curtailable or base load and self-generation [22]. The distinction between curtailable and non-curtailable is defined by the consumers priorities. The European Committee for Electrotechnical Standardization (CEN-ELEC) has decided to adopt this naming for classifying flexibility sources [23].

Demand response is usually provided through demand response programs. The penetration of these programs is different in the US and in the EU. In the US, demand response programs are a reality being the business of 40 companies [6]. In the EU, demand response programs penetration is lower due to the regulatory barriers that are limiting the possibility of third parties to enter to electricity markets [24]. Demand response programs fall in one of these three categories: price-based programs, incentive or event-based programs and demand reduction bids [5]. In price-based programs, the electricity price variation motivates the consumer to change its consumption pattern. In event-based programs, DSOs send requests to the consumers to provide demand response to support the reliability of the grid. In demand reduction bids, the consumers send bids to inform about possible load to be shifted or curtailed. From the described programs three demand response triggers are identified: electricity price, demand response requests and demand response offers.

2.3 Case Study: VPP4SGR Project

The PhD project here described is fully funded by a research project under the ForskEL program named ”Virtual Power Plants for Smart Grid Ready Buildings and Customers (VPP4SGR)” and uses the framework provided by the later as a case study. This ongoing project started in spring 2013 and aims to develop a VPP to monitor and control the energy usage of a residential building while providing demand response. To provide electricity flexibility to the grid the active participation of the residents in the building is crucial. The VPP4SGR project tackles the problem from a multidisciplinary perspective, having as partners industry, academia and a governmental institution with large variety of members including anthropologist, engineers and computer scientists among others.

The VPP4SGR project uses as a test bed a student dorm constructed in 2012 placed in the harbour of Aarhus named Grundfos Dormitory Lab (GDL). This building is the home of 180 students and has 159 apartments divided on 12 floors. The building is equipped with a metering infrastructures having more than 3,300 sensors reporting data every 5 seconds on electricity consumption, indoor climate conditions, domestic water and district heating usage for each of the apartments and common areas.

The VPP4SGR project expects to provide recommendations on the construction of future buildings and the retrofitting of the existing ones to be ready for the Smart Grid. Furthermore, the project strives to develop models to better understand the energy behaviour of residential consumers and to gain insight and provide recommendations on means to involve individuals to a larger degree. The presented PhD project contributes to the VPP4SGR project by designing and developing the ICT platform of the VPP.

3

Residential VPP with Demand Response

This chapter presents the research conducted during the first 1.5 years of the PhD project and outlines future contributions. The chapter frames the current and planned contributions in the different aspects of the VPP. The chapter starts by presenting the overview of the VPP of a residential building followed by the ICT platform design and prototyping. The chapter follows by introducing control methods for demand response provision and prediction models for residential electricity consumption. The chapter finalises with a brief introduction to demand response biding in electricity market that will be studied in the future.

3.1 Residential VPP Overview

The higher penetration of renewable energy sources in the grid is driving a shift from a generation-oriented grid system towards a consumption-oriented. To enable this change, higher flexibility of the consumers can be provided by demand response. In this PhD project a VPP is proposed as tool to provide aggregated demand response from a residential building. The VPP act as a bridge between the residential consumers and the DSOs and is crucial that it's operation benefits both. In such scenario, the VPP interacts with a large number of different stakeholders and interoperability problems can easily arise. The VPP has direct control to some of the DER placed in the building and uses sensitive information about the consumer. It is therefore very important to ensure the secure operation and privacy concerns of the individuals.

Aiming to benefit both consumers and DSOs the VPP operation considers a twofold objective: optimally regulate local energy resources and provide demand response. This control problem entails keeping consumers comfort, using the thermal inertia of the building and handling disturbances like external weather conditions among others, thus being complex to solve. To support the VPP operation, accurate prediction models of electricity consumption are needed. Achieving good accuracy in these models is not easy for a single residential consumer due to the different behaviour of individuals, however the task eases when aggregating a group of consumers [25]. For the success of a product like the proposed VPP, the interaction with electricity markets is highly important. To these markets the VPP can offer flexible consumption, local storage and production from the building DER. Providing this flexibility with guarantees is a challenging task since part of it relies on the consumers behaviour. All the mentioned challenges should be considered in the design of a VPP of a residential building.

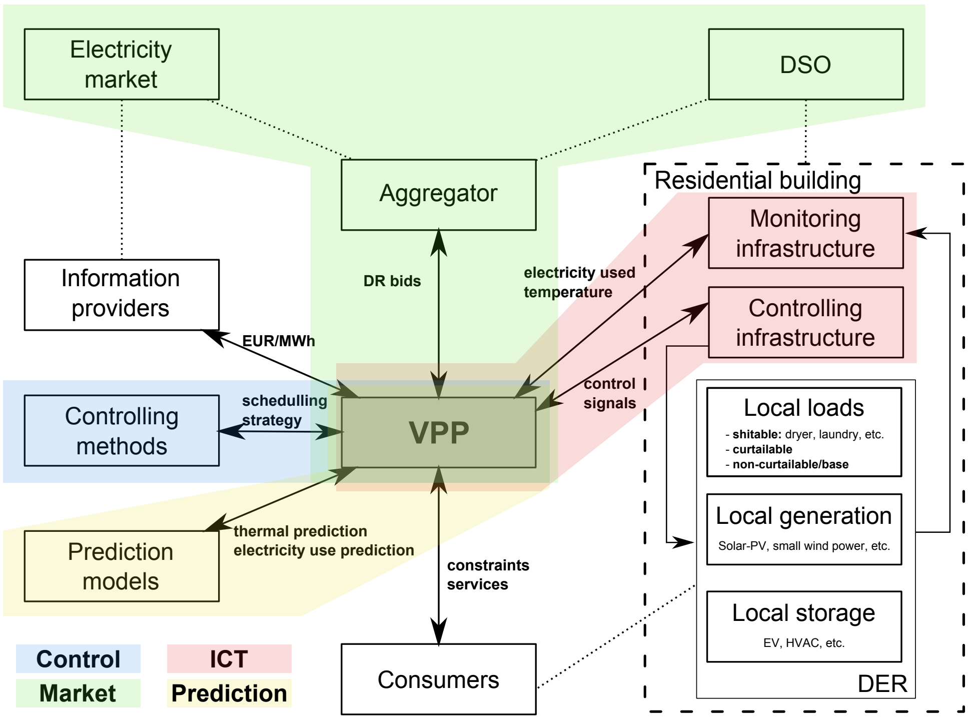


Figure 3.1: Residential VPP overview with studied research fields.

Figure 3.1 shows the context diagram of the designed VPP and the interaction with the different actors. In colour the reader can see the different research areas that have been investigated or that are meant to be investigated before completion of the PhD project.

The residential building has a set of DER that fall in one of the already mentioned five categories: local storage, local generation, shiftable loads, curtailable loads and non-curtailable/base loads. These DER are being monitored by a sensor network, controlled by some home automation devices and being used by the consumers. The building monitoring infrastructure also measures non-electrical values like indoor climate conditions and water usage. Furthermore, the VPP collects data from external data sources like electricity prices and grid status. The intelligence of the VPP digests all these data to regulate the energy resources by means of controlling algorithms and prediction models. Please note that both controlling methods and prediction models have been placed outside the VPP system for illustrative purposes but from a product point of view they would be placed inside. Finally, the VPP interacts with the consumers by providing services to them or by setting performance constraints (e.g., temperature thresholds) and with an aggregator by exchanging demand response bids. The role of the aggregator is still not well defined in the current Danish grid system. The following sections deepen in each studied area in this projects.

3.2 VPP ICT Design and Prototype

VPPs open a new horizon of benefits in a Smart Grid scenario but also raise some challenges to be tackled. VPPs are seen as a vehicle for DER integration in the power grid and electricity market. For that purpose a VPP needs to collect and digest data from many different sources and send control signals to the DER under regulation presenting interoperability issues to be solved by using standards. Furthermore, the VPP needs to interact with the consumers providing them services and allowing them setting operation characteristics.

In [26] the authors present an architecture of VPP for both commercial and technical operations identifying the different stakeholders involved. A service oriented architecture of a VPP using the IEC 61850 standard principles with Object Linking and Embedding for Process Control (OPC) Unified Architecture is described in [27]. In [28] the authors introduce a VPP to coordinate a fleet of EV considering the following modules: data storage, forecasting models, optimisation methods, customer interaction and communications. VPPs have also attracted the attention of big companies like *Siemens* or *Schneider Electric* which are already designing and developing VPPs for their customers.

The VPP here considered differs from the previously mentioned for being used in a residential building. The proposed architecture is divided in 6 different modules as depicted in Figure 3.2. The monitoring module is responsible of gathering information from different data providers using different protocols and sending these data to the data storage module. The data storage module handles all actions involving the collected data having an internal light-weight database for near-real time monitoring and controlling. Additionally, this module sends all collected data to an external data warehouse for historical data analysis (omitted for simplicity in Figure 3.1). The controlling module act as the brain of the VPP using direct and indirect control for optimal regulation and demand response provision. The VPP also uses prediction models like electricity consumption or presence detection placed inside the prediction module. The interaction with the aggregator shown in Figure 3.1 is administrated by the bidding module. Other functions like data validation or consumer interaction are encapsulated in the support functions module of the VPP.

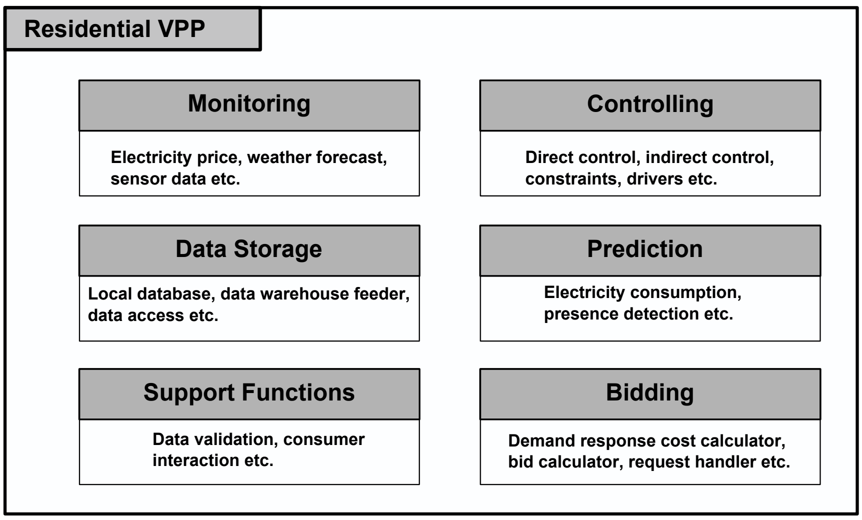


Figure 3.2: Residential VPP component diagram.

3.2.1 VPP Prototyping

The proposed VPP is envisioned as an Energy Management System (EMS) to be deployed in a residential building through home automation equipment, run as a service on top of the existing building control system. This needs to be considered on the prototyping because these hardware devices may be constrained in resources (e.g. limited storage). The VPP prototype is being developed for the VPP4SGR project. In the project test bed, the GDL, the installed sensor network uses industrial automation equipment from *Beckhoff*. Each of the 159 apartments contains a BC9191, Beckhoff Programmable Logic Controller (PLC), to gather information from all the sensors. The VPP4SGR project has purchased two BC9191 to develop a realistic laboratory set-up. For interoperability purposes an embedded computer from *Beckhoff* (CX2030) has been purchased aiming to host the VPP. Ideally the developed VPP (hardware and software) could be deployed in the GDL to be tested.

The full laboratory set-up is depicted in Figure 3.3. A light-weight VPP collects grid CO_2 emissions forecast and day-ahead electricity prices from external information providers (i.e., *Energinet.dk* and *Nord Pool Spot*). Additionally, the VPP gathers electricity consumption from a *Kamsptrup* smart meter using Kamstrup Meter Protocol (KMP) protocol [29]. The consumer puts clothes in the dryer and sets through a web-based user interface the desired completion time and decides between a green program (CO_2), economic program (electricity price) or a weighted combination of the latter two. The control algorithm inside the VPP makes a decision on when to run the dryer and sends a control signal to BC9191 using Automation Device Specification (ADS) protocol [30]. Finally, the BC9191 sends a pulse to start the tumble dryer. At the moment of writing this report the lab set-up is nearly operative. This lab set-up has been developed in collaboration with a group of master students.

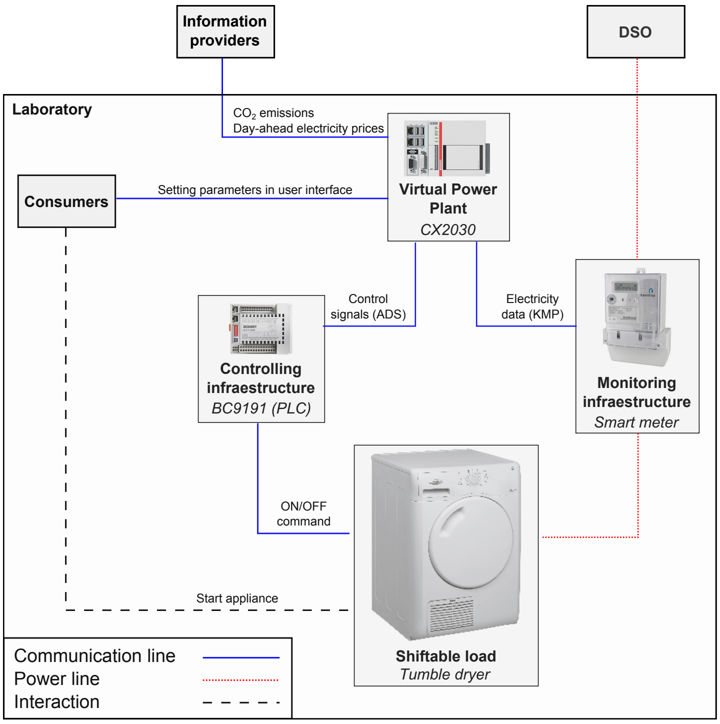


Figure 3.3: Laboratory set-up.

The lab set-up currently consists on a light-weight version of VPP containing the strictly necessary components to do a demonstration. A more complete, but not finalised, version of the VPP is implemented in a server in the laboratory. This server contains all the monitoring and data storage modules previously described. The monitoring infrastructure collects data from five different data providers and stores it in the internal database. The internal database consists on a rolling window database that keeps data corresponding to a time window of one week thus erasing old data to keep the size of the database small. The storage module sends all the data to an external data warehouse. At the moment of writing this report a mechanism for data validation is being developed by two bachelor students.

3.2.2 Evaluating Demand Response Protocols

A key enabler for the success of smart grids and demand response is the existence and use of standards. The use of standards ensures the seamless interoperability between different stakeholders. Several smart grid standards have emerged and are being developed by different organisations in different regions. In the US the National Institute of Standards and Technology (NIST) is leading the standardisation and in the EU the organisation responsible of it is CEN-ELEC [4]. From the communication perspective there is a need for standard protocols to build strong business cases around new topics like demand response.

There are currently two industrial alliances working on the standardisation, automation and simplification of demand response. The *OpenADR* alliance has developed an application layer protocol named OpenADR 2.0 to ease demand response integration [31]. In contrast, the *ZigBee* and *HomePlug* alliances have recently published the Smart Energy Profile 2.0 (SEP2) application protocol to be used for demand response applications [32]. In the literature there have been big efforts on evaluating different demand response strategies and demand response programs, however these often neglect the performance of the communication protocol being used.

A novel methodology to evaluate the performance of demand response protocols together with a demand response strategy is proposed. This methodology can be used to assess a strategy together with a protocol and iteratively tune parameters in either the protocol or the strategy to achieve desirable performance. The methodology consists of three steps:

1. A model is obtained by formalising a household scenario description (previously described in natural language), a demand response strategy and a protocol using existing specifications (e.g., SEP2 specification [32]).

2. The developed model is synthesised into executable code and the described scenario with the strategy and protocol are simulated.

3. The results are evaluated according to some performance metrics on both the protocol and the strategy. Monitoring performance metrics enable to tune parameters on the protocol and the demand response strategy.

The proposed methodology has been validated with a case study, describing a real household scenario, using SEP2 as a protocol, adopting a simple upper threshold limit as a strategy, choosing a protocol parameter as a tuning parameter and considering a set of performance metrics on both protocol and strategy. The proposed strategy can be used for the VPP to evaluate different strategies together with a demand response protocol thus choosing a good combination.

3.3 Control Methods

The control module of the VPP aims at optimising the local energy resources of the building while providing flexibility to the grid by means of demand response. Building automation systems can decrease the costs on electricity usage by shaping the load profile. This shaping can be done by using local storage, local production and flexible loads in a smarter manner. For that purpose, information about the current and future states of variables like weather conditions, electricity prices and building states is needed. During the VPP operation the comfort in the building shall not be jeopardised. Additionally, one must add in to the problem the presence of disturbances like external weather conditions. Last but not least the behaviour and presence of the consumers living in the building must be taken into account.

There are mainly two control approaches for the problem faced by the VPP: direct control and indirect control. Direct control is usually done by a centralised EMS that automatically regulates DER after an agreement with the consumer. Indirect control consist on providing some information to the consumers, like electricity prices or grid CO_2 emissions to affect their electricity consumption. The typical control approach for a VPP is to use direct control, however the combination of both direct and indirect control is suggested to be beneficial [33]. The proposed VPP considers both direct and indirect control but just the former is described hereafter.

In the literature logic based EMS are commonly used [34]. These systems make decision based on tree rules (e.g., if-then-else). One important issue of these methods is that they rely on a reactive control meaning that control actions are taken considering the current state. On the contrary, predictive control considers both the current states and the future ones usually leading to better solutions. MPC has been used in many application domains and also in similar problems to the one faced by the VPP. Several studies have been done on regulating HVAC systems, lighting in building and also on local storage production facilities [35, 36, 37, 38]. MPC has also been considered to manage local storage, local production and loads on a residential building in [39]. One important advantage of MPC is the ability to handle complex dynamics and system constraints.

The proposed control method used by the VPP is based on a MPC. This controller will regulate the DER in the building: generation, storage, shiftable loads and curtailable loads. The non-curtailable loads will be tackled by an indirect control. The direct control will be done solving a multi-objective optimisation problem: maximise comfort in the building, minimise electricity cost and provide demand response. This later optimisation parameter will be considered by minimising the difference between baseline electricity consumption and electricity consumption with a demand response event. Multi-objective functions in complex systems like the one introduced can present the problem of conflicting goals. To tackle this problem in a MPC framework one can consider soft-constraints thus enlarging the solution space. Adding soft-constrains imply increasing the complexity on the problem to solve because for each soft-constraint one new variable is considered in the optimisation function. Another parameter to consider is the length of the MPC horizon and the resolution on each time step.

In Figure 3.4 the proposed MPC in the VPP framework is displayed. The MPC gets information on the electricity prices and the weather forecast from external information providers. The bidding module interacts with the aggregator and provides the MPC with a curve of the desired electricity load with a demand response event. The consumers interact with the building, the DER inside the later and the MPC by introducing comfort

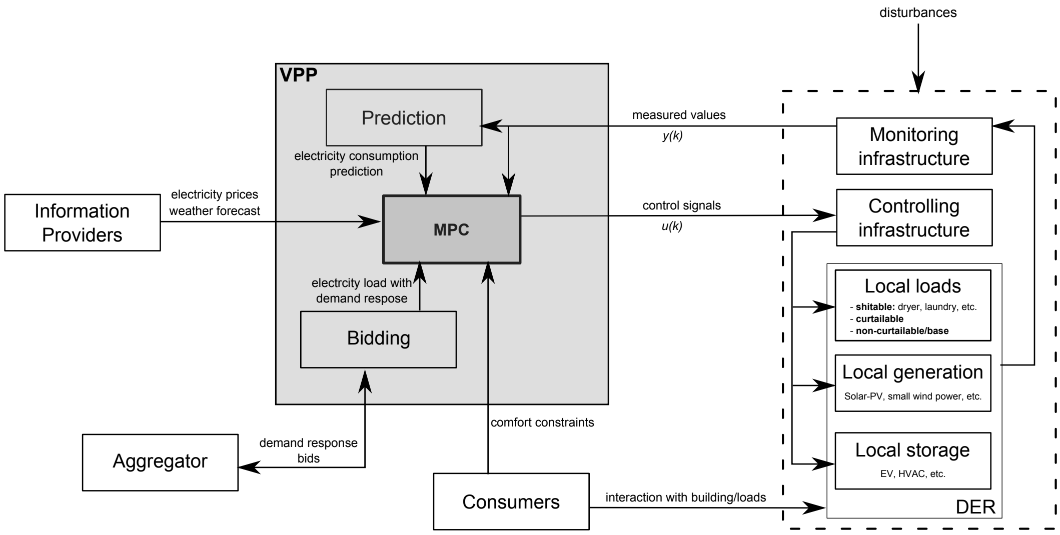


Figure 3.4: Model Predictive Control of a Residential Building.

constraints. The prediction module of the VPP uses forecasting models to provide predicted baseline electricity consumption. The MPC optimises according to the parameters later stated and sends control signals to the local controlling infrastructure placed in the building, which actuate to the different DER. The monitoring infrastructure closes the control loop by providing measurements on the states of the DER and the building back to the controller.

The mathematical formulation of the optimisation problem to be solved by the VPP controller is:

$$\begin{aligned} min \sum_{k=1}^{N} & w_1 \rho_{EL}(k) C_{EL}(k) + \ w_2 \Phi(T(k), CO_2(k), H(k)) \\ & + w_3 \parallel C_{EL}(k) - C_{DR}(k) \parallel + w_4 \parallel \epsilon(k) \parallel \\ s.t. \ \ & h_{\text{model}}(x(k), u(k)) = 0 \\ & g_{\text{hard}}(x(k), u(k)) \leq 0 \\ & g_{\text{soft}}(x(k), u(k), \epsilon(k)) \leq 0 \end{aligned} \tag{3.1}$$

The optimisation problem minimises the cost function for a time horizon N considering different weights for each parameter w_1, w_2, w_3 and w_4. Normalisation should be evaluated when having weighted multi-objective optimisation. Following standard control nomenclature $x(k)$ represents the system states and $u(k)$ the control variables. ρ_{EL} is the electricity price, C_{EL} is the base electricity consumption, Φ is a index on discomfort that depend on indoor climate conditions (temperature, CO_2 levels and humidity). C_{DR} is the electricity consumption with demand response provision and $\epsilon(k)$ are the variables linked to soft-constraints. h_{model} is the function that models the system while g_{hard} and g_{soft} are the constraints. An example of hard-constrains could be energy balance whereas a soft-constraint could be the indoor comfort:

$$\Phi_{\text{min}} - \epsilon(k) \leq \Phi(T(k), CO_2(k), H(k)) \leq \Phi_{\text{max}} + \epsilon(k) \tag{3.2}$$

The MPC is based on an iterative process where a model of the building is optimised in a finite time horizon. For each instant k, the building states are sampled and the cost function is computed for a determined time horizon $k + N$. Then the first step in the control signal $u(k+1)$ is sent to the building controllers and the process is started all over again shifting the time horizon.

The envisioned control algorithm of the VPP is based in a MPC. A control design has been outlined, but not implemented. When implementing the MPC some considerations should be taken into account like the non-linearities of the system and the presence of binary variables. Future work in this area will consist on implementing a MPC and test it in a simulation environment evaluating different parameters like computational performance.

3.4 Prediction Models for Electricity Consumption

Demand response programs are already a reality in the US in commercial and industrial consumers, however the implementation in the residential sector is still in an early stage. A major challenge in these programs is to estimate the normal or baseline electricity consumption without a demand response event [40]. The difference between the electricity load with and without demand response may be used to calculate the monetary remuneration for the customer. Current methods are various, from previous day matching to regression methods [41]. There are many methods used to estimate the baseline however none of the presented methods are shown to be precise enough at household level [40].

Many studies have been done on the residential sector using machine learning techniques like support vector regression and neural networks [42, 43]. Some methods present promising results however it seems unlikely they may be implemented in real life because some utilities are not allowed to use black-box models [40]. Additionally, a large amount of the proposed methods are built with data from the US, country with a high correlation with temperature and electricity consumption due to air conditioners. However, there are not many methods used in cold countries where the presence of air conditioners is low.

A model to estimate the baseline electricity consumption can be used by the EMS of a residential building to optimally regulate energy resources while providing demand response using MPC. In a VPP framework, such model could be used for controlling DER and bidding demand response with an aggregator. Using as a case study the dataset from the VPP4SGR project an initial investigation of different models to predict electricity consumption in a residential building has been done. It is important to highlight that this initial study has been developed as an assignment for one PhD courses thus constraining a bit the techniques considered to the syllabus of the course. The aim has been to benchmark different models to predict the electricity consumption of a residential building.

The data available for the VPP under the VPP4SGR project, at the time of writing this document, comes from 5 different sources: sensor network in test bed GDL, weather forecast from model developed by the *Department of Environmental Science* from AU, *Energinet.dk* (Danish TSO), *Nord Pool Spot* and *NRGi* (Danish DSO). In total there are 64 possible predictors to estimate the response variable; however 16 variables have been preselected with domain knowledge to simplify the analysis. Among the selected variables there are commonly used variables in the literature like *hour of the day*, *day of the week* or *previous consumption*. Other data has been considered, like data regarding *indoor climate conditions* and *water usage* (reflect human activity) provided by GDL sensors, *external weather conditions* provided by the forecast model and *grid CO_2 emissions.* All these data is provided with different frequencies and it has been transformed to have 15 minutes resolution as the electricity data provided by *NRGi.* The electricity consumption data has been shifted by one hour for the response variable as proposed in [44]. For each of the predictors given to the model, the corresponding electricity consumption output fed in the model is the electricity consumption in the building one hour into the future.

In order to have a manageable dataset one month of data has been considered (i.e., 2,689 observations). The first step has been to divide the data on time in two groups: the initial 75% for cross validation and the 25% for testing. Before analysing different models three different performance indexes have been considered: Mean Square Error (MSE), Mean Absolute Percentage Error (MAPE) and Coefficient of Variance (CV). The statistics MAPE and CV are commonly used in the literature for evaluating prediction models of electricity consumption [42, 43, 44]. Eleven different models have been trained, some of them using cross-validation, and benchmarked (see Table 3.1).

Model	**MSE**	**MAPE [%]**	**CV[%]**	**Complexity**	**Transparent**
Ordinary Least Squares	4.53	22.57	34.11	16	Yes
Step Regression	4.43	22.64	33.82	7	Yes
Ridge Regression	4.58	22.54	34.46	16	Yes
Elastic Net	3.21	22.32	29.73	6	Yes
Bias Expansion	2.55	20.16	27.13	12	Yes
Principal Component Regression	3.21	22.61	30.69	12	No
Partial Least Squares Regression	4.23	22.17	33.81	4	No
Regression Trees	1.17	11.62	18.54	16	Yes
Bagging Trees	1.02	10.65	17.21	150	No
Random Forest	1.08	11.13	17.82	100	No
Neural Networks	1.07	12.66	17.73	26	No

Table 3.1: Comparison of all Prediction Models Using GDL Dataset.

The selection criteria of a final model has considered the complexity of the model (i.e., variables used, number of trees in random forest and bagging trees and hidden layers in neural networks), the transparency of the model i.e. whether or not is a *black-box* model and the accuracy on prediction (MSE, MAPE and CV values). Regression trees have been decided as the most suitable method of the considered ones because of its transparency and good accuracy with MSE values of 1.17 kWh/15 min, MAPE of 11.62% and CV of 18.54% on the cross-validation dataset. Other models like neural networks or random forest offered better accuracy but have been discarded for complexity and transparency. The performance of the chosen model with the test dataset is shown in Figure 3.5, where each of the seven peaks corresponds to a day with the habitual maximum in the afternoon. As expected accuracy performance decreased slightly on the testing dataset leading to values of 1.58 kWh/15 min, 13.7% and 21.79% on MSE, MAPE and CV respectively.

The conducted study has benchmarked eleven different methods to predict electricity consumption and has decided the most suitable one based on model complexity, trans-

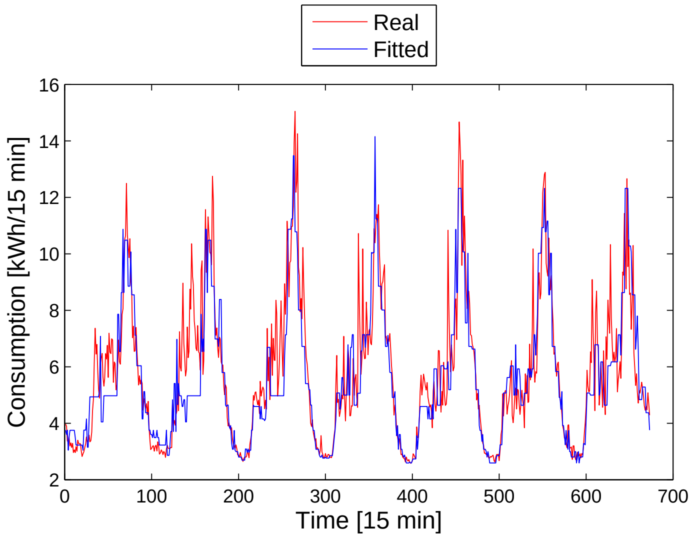


Figure 3.5: Regression Trees Model on Testing Dataset.

parency and accuracy. High importance has been given to transparency to satisfy the business needs of demand response, thus leading to discard more accurate but non-transparent models. From a VPP perspective, the transparency in the model is not as important as accuracy and complexity. Future work in this field, could be to consider a larger dataset along with other methods like support vector regression or autoregressive integrated moving averages models. Additionally, analysing model accuracy under different time granularities and geographic aggregations (e.g. floor, building, apartment type etc.) thus complementing the study done in [43] could also be considered.

3.5 Demand Response Bidding in Electricity Markets

With the higher penetration of DER in the electrical grid more flexibility in the consumption side is required. The available flexibility on the DER deployed in a residential building can become an attractive asset to be trade in the electricity markets. A VPP can bid demand response to an agrgegator that trades in the market. However, in the residential sector this flexibility may be subject to the behaviour of the residents.

In [45], the authors analyse the feasibility of having a flexible consumer in the Danish day-ahead market and regulating power market. The authors claim that consumers with electricity capacity of 20-70 kWh could enter the day-ahead market and with 70-230 kWh in the regulating power market. In [33], the authors develop and test a new market to attract small-scale DER in the regulating power market. Whether to adapt to the current market structure or to create a new market co-existing with the existing ones the role of a VPP in this new scenarios needs to be investigated. A generic market-based VPP for the Nordic power market has been proposed in [15]. In [46], the authors propose a bidding strategy for demand response and generating units to be provided by a VPP.

The flexibility potential that a VPP of a residential building can provided by demand response biddings to an aggregator has not yet been analysed. As a future plan this will be investigated.

4

Current Status and Future Plans

This chapter summarizes the contribution done in the first part of the PhD, describes the planned activities for completion of the project and concludes the document.

4.1 Current Work

The first part of the PhD has mainly been focused on designing and developing a VPP of a residential building to be used as a framework for future research. The main contributions are:

- The design of the ICT platform of the VPP and the initial prototyping of the designed platform including a realistic laboratory set-up for future tests.
- A novel methodology to assess demand response protocols along with demand response strategies.
- A design of a MPC-based control strategy for direct control of DER in a residential building.
- An initial study on prediction models for electricity consumption in residential buildings.

The contributions mentioned have been turned in one accepted publication and one submitted (see Appendix A for more details). During the first 1.5 years of the PhD all the required PhD courses have been completed (see Appendix B for more details). Furthermore, the dissemination activities done until now account to more than 350 hours and the pending hours before completion of the second year of the PhD have been planned to fulfil the 280 hours/year required from the Graduate School of Science and Technology (GSST) at AU.

4.2 Future Plans

The future plans for completion of the PhD project have been briefly mentioned in the previous chapter and are detailed here. The planned publications under the research areas mention hereafter are displayed in Appendix A.

4.2.1 VPP Deployment in Industrial Automation Electronics

The research done has led to a design of a VPP of a residential building and a laboratory set-up ready to be tested. It is the intention to extend the laboratory set-up shown in Figure 3.3 with the required add-ons to make a more relevant and realistic test bench. This could include considering two apartments (two BC9191) to illustrated the aggregation capabilities of the VPP. Different control algorithms will be analysed for scheduling appliances with demand response purposes and the possibility of adding a demand response protocol (e.g., SEP2) will be considered. It has been planned to work on this topic at the end of 2014 and the first months of 2015.

4.2.2 Controlling Algorithms for a Residential VPP

A direct control method based on a MPC has been proposed to regulate the local DER in a residential building and demand response provision. It is the intention to analyse the method proposed in a simulation environment together with electricity consumption prediction models. In this scenario, different controlling techniques considering different optimisation parameters could be analysed and a sensitivity analysis of the optimisation function could be done. The computational characteristics of the control strategy could also be analysed taking into account the device where the VPP could be deployed. The research on the control side of the VPP is scheduled for autumn 2015.

4.2.3 Prediction Models for Electricity Consumption

An initial analysis of prediction models for electricity consumption in residential buildings has been presented. The initial intention of the research in this area is to extend the analysis done by considering a larger dataset and considering different prediction models like support vector regression or autoregressive integrated moving averages models. Furthermore, an analysis of the spatial and temporal granularity effect on the accuracy of the model could be done thus extending the work done in [43]. Additionally, it would be desirable to validate the method proposed in scenarios where the operation of the VPP requires such methods (e.g., in the MPC operation). In order to have a larger dataset, the research on prediction models has been scheduled during spring 2015.

4.2.4 Demand Response Bidding in Electricity Markets

The market approach of a residential VPP has not yet been analysed. In contrast to bigger VPP, the envisioned VPP of a residential building is not meant to directly trade in the electricity market but instead it would exchange demand response bids with an aggregator that will trade in the market. The idea is to investigate on topics like the amount of flexibility that a VPP of a residential building could provide, taking into account the potential of this power flexibility in the electricity market but also which kind of bidding strategy should the VPP conduct with the aggregator. The initial intention is to carry out this research in the stay abroad, aiming to find a research institution with expertise in this research area. The stay abroad is scheduled for summer 2015.

4.2.5 Time planning

In the Gantt diagram displayed below the future plans sketch above are framed in time together with other relevant milestones and tasks like the stay abroad and thesis writing. The stay abroad is planned to last around 4 month starting on summer 2015.

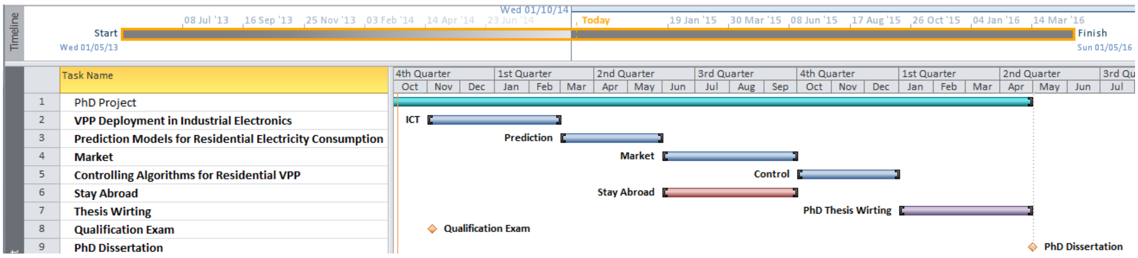


Figure 4.1: Gantt Diagram.

4.3 Final Remarks

This document has introduced the PhD project "Virtual Power Plant for Residential Demand Response" carried out at the Department of Engineering at AU. The document has summarised the progress of the PhD project during the first 1.5 years emphasising the contributions done. Additionally, the report has outlined the future research activities for the remaining 1.5 years. It is expected that the PhD project will be lead to completion on time.

Bibliography

[1] Internationa Energy Agency (IEA), "Key World Energy Statistics," Paris, Tech. Rep., 2014. [Online]. Available: http://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf

[2] J. Paulou, J. Lonsdale, M. Jamieson, I. Neuweg, P. Trucco, P. Maio, M. Blom, and G. Warringa, "Financing the energy renovation of buildings with Cohesion Policy funding," European Union, Tech. Rep. ENER/C3/2012-415, 2014.

[3] The Danish Government, "The National Reform Programme Denmark 2014," Ministry of Economic Affairs and the Interior, Copen, Tech. Rep. April, 2014. [Online]. Available: http://ec.europa.eu/europe2020/pdf/csr2014/nrp2014_denmark_en.pdf

[4] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart Grid — The New and Improved Power Grid: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 4, pp. 944–980, Jan. 2012. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6099519

[5] P. Siano, "Demand response and smart grids—A survey," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 461–478, Feb. 2014. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1364032113007211

[6] C. Goldman, M. Reid, and R. Levy, "Coordination of Energy Efficiency and Demand Response," Ernest Orlando Lawrence Berkeley National Laboratory, Tech. Rep. LBNL-3044E, 2010.

[7] S. Shao, M. Pipattanasomporn, and S. Rahman, "Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles," *IEEE Transactions on Smart Grid*, vol. 2, no. 4, pp. 624–631, Dec. 2011. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6074980

[8] P. Bertoldi, B. Hirl, and N. Labanca, "Energy Efficiency Status Report 2012," Institute of Energy and Transport - JRC, Tech. Rep. EUR 25405 EN, 2012.

[9] M. Albano, L. Ferreira, T. Le Guilly, M. Ramiro, J. E. Faria, L. P. Duenas, R. Ferreira, E. Gaylard, D. J. Cubas, E. Roarke, D. Lux, S. Scalari, S. M. Sorensen, M. Gangolells, L. M. Pinho, and A. Skou, "The ENCOURAGE ICT architecture for heterogeneous smart grids," in *Eurocon 2013*. IEEE, Jul. 2013, pp. 1383–1390. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6625159

[10] A. Marqués, M. Serrano, S. Karnouskos, P. J. Marrón, R. Sauter, E. Bekiaris, E. Kesidou, and J. Höglund, "NOBEL– A Neighborhood Oriented Brokerage ELectricity and Monitoring System," in *Energy-Efficient Computing and Networking*, N. Hatziargyriou, A. Dimeas, T. Tomtsi, and A. Weidlich, Eds. Springer Berlin Heidelberg, 2011, vol. 54, pp. 187–196. [Online]. Available: http://link.springer.com/chapter/10.1007/978-3-642-19322-4_20

[11] B. Buchholz, D. Nestle, and A. Kiessling, "Individual customers' influence on the operation of virtual power plants," *2009 IEEE Power & Energy Society General Meeting*, pp. 1–6, Jul. 2009. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5275401

[12] A. Thavlov and H. W. Bindner, "An aggregation model for households connected in the low-voltage grid using a VPP interface," in *IEEE PES ISGT Europe 2013*. IEEE, Oct. 2013, pp. 1–5. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6695360

[13] H. Saboori, M. Mohammadi, and R. Taghe, "Virtual Power Plant (VPP), Definition, Concept, Components and Types," in *2011 Asia-Pacific Power and Energy Engineering Conference*. IEEE, Mar. 2011, pp. 1–4. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5749026

[14] D. Pudjianto, C. Ramsay, and G. Strbac, "Virtual power plant and system integration of distributed energy resources," *IET Renewable Power Generation*, vol. 1, no. 1, p. 10, 2007. [Online]. Available: http://digital-library.theiet.org/content/journals/10.1049/iet-rpg_20060023

[15] S. You, "Developing Virtual Power Plant for Optimized Distributed Energy Resources Operation and Integration," PhD Thesis, Technical University of Denmark, 2010.

[16] CEN-CENELEC-ETSI Smart Grid Coordination Group, "Smart Grid Reference Architecture Contents," Tech. Rep. November, 2012. [Online]. Available: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/xpert_group1_reference_architecture.pdf

[17] M. van Werven and M. Scheepers, "The changing role of distribution system operators in liberalised and decentralising electricity markets," in *2005 International Conference on Future Power Systems*. IEEE, 2005, pp. 6 pp.–6. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1600532

[18] H. Ochsendelf and O. Corradi, "Integration of fluctuating energy by electricity price control," Master Thesis, Technical University of Denmark, 2011.

[19] M. H. Albadi and E. F. El-Saadany, "Demand Response in Electricity Markets: An Overview," in *2007 IEEE Power Engineering Society General Meeting*. IEEE, Jun. 2007, pp. 1–5. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4275494

[20] Eurelectric, "Eurelectric views on Demand-Side Participation," Tech. Rep. D/2011/12.105/35, 2011. [Online]. Available: http://www.eurelectric.org/media/61240/dsp_report_0810-02_simple_page_final-2011-030-0638-01-e.pdf

[21] C. Timpe, "Smart Domestic Appliances Supporting the System Integration of Renewable Energy," Öko-Institut, Tech. Rep., 2009. [Online]. Available: www.smart-a.org

[22] L. Hancher, X. He, I. Azevedo, N. Keyaerts, L. Meeus, and J.-m. Glachant, "Shift , Not Drift : Towards Active Demand Response and Beyond," Tech. Rep., 2013.

[23] CEN-CENELEC-ETSI Smart Grid Coordination Group, "SG-CG / M490 / Methodology & New Applications Annex B Concepts , Elements and Tools for the Smart Grid Methodology," Tech. Rep., 2013. [Online]. Available: http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/xpert_group3_methodology.pdf

[24] Smart Energy Demand Coalition, "A Demand Response Action Plan For Europe - Regulatory requirements and market models," Brussels, Tech. Rep., 2013. [Online]. Available: http://sedc-coalition.eu/wp-content/uploads/2013/07/sedc-dr-action-plan-final-.pdf

[25] S. Humeau, T. K. Wijaya, M. Vasirani, and K. Aberer, "Electricity load forecasting for residential customers: Exploiting aggregation and correlation between households," in *2013 Sustainable Internet and ICT for Sustainability (SustainIT)*. IEEE, Oct. 2013, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6685208

[26] S. Lukovic, I. Kaitovic, M. Mura, and U. Bondi, "Virtual Power Plant As a Bridge between Distributed Energy Resources and Smart Grid," in *2010 43rd Hawaii International Conference on System Sciences*. IEEE, 2010, pp. 1–8. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5428349

[27] S. Sucic, A. Martinic, and D. Francesconi, "Utilizing SOA-ready devices for virtual power plant control in semantic-enabled Smart Grid Analyzing IEC 61850 and OPC UA integration methodology," in *2011 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. IEEE, Oct. 2011, pp. 43–48. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6102362

[28] B. Jansen, C. Binding, O. Sundstrom, and D. Gantenbein, "Architecture and Communication of an Electric Vehicle Virtual Power Plant," in *2010 First IEEE International Conference on Smart Grid Communications*. IEEE, Oct. 2010, pp. 149–154. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5622033

[29] Kamstrup, "Kamstrup 382 communication interface specification," Tech. Rep. [Online]. Available: www.kamstrup.com

[30] Bekhoff, "TwinCAT ADS," Tech. Rep. [Online]. Available: http://www.beckhoff.com/

[31] OpenADR Alliance, "OpenADR 2.0b Profile Specification," Tech. Rep. 20120912-1, 2013.

[32] ZigBee Alliance, "Smart Energy Profile 2 Application Protocol Standard," Tech. Rep. 13-0200-00, 2013.

[33] Ea Energy Analyses, "Activating electricity demand as regulating power," Tech. Rep., 2013.

[34] Z. Yu and A. Dexter, "Hierarchical fuzzy control of low-energy building systems," *Solar Energy*, vol. 84, no. 4, pp. 538–548, Apr. 2010. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0038092X09000644

[35] V. M. Zavala, J. Wang, S. Leyffer, E. M. Constantinescu, M. Anitescu, and G. Conzelmann, "Proactive Energy Management for Next-Generation Building Systems," in *Fourth National Conference of IBPSA-USA*, New York, Oct. 2010.

[36] F. Oldewurtel, A. Parisio, C. N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, and K. Wirth, "Energy efficient building climate control using Stochastic Model Predictive Control and weather predictions," in *American Control Conference (ACC), 2010*, 2010, pp. 5100–5105.

[37] D. Kolokotsa, A. Pouliezos, G. Stavrakakis, and C. Lazos, "Predictive control techniques for energy and indoor environmental quality management in buildings," *Building and Environment*, vol. 44, no. 9, pp. 1850–1863, Sep. 2009. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0360132308002990

[38] J. K. Ward, J. Wall, S. West, and R. D. Dear, "Beyond Comfort – Managing the Impact of HVAC Control on the Outside World," in *Air Conditioning and the Low Carbon Cooling Challenge*, no. July, London, 2008, pp. 27–29. [Online]. Available: http://nceub.commoncense.info/uploads/W2008_53Ward.pdf

[39] F. Tahersima, P. P. Madsen, and P. Andersen, "An intuitive definition of demand flexibility in direct load control," in *2013 IEEE International Conference on Control Applications (CCA)*. IEEE, Aug. 2013, pp. 521–526. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6662802

[40] T. Hong, "Energy Forecasting : Past , Present , and Future," *The International Journal of Applied Forecasting*, vol. Winter 2014, pp. 43–49, 2014.

[41] Association of Edison Illuminating Companies, "Demand Response Measurement & Verification," Tech. Rep. March, 2009. [Online]. Available: https://www.smartgrid.gov/sites/default/files/pdfs/demand_response.pdf

[42] R. E. Edwards, J. New, and L. E. Parker, "Predicting future hourly residential electrical consumption: A machine learning case study," *Energy and Buildings*, vol. 49, pp. 591–603, Jun. 2012. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378778812001582

[43] R. K. Jain, K. M. Smith, P. J. Culligan, and J. E. Taylor, "Forecasting energy consumption of multi-family residential buildings using support vector regression: Investigating the impact of temporal and spatial monitoring granularity on performance accuracy," *Applied Energy*, vol. 123, pp. 168–178, Jun. 2014. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0306261914002013

[44] J. Grant, M. Eltoukhy, and S. Asfour, "Short-Term Electrical Peak Demand Forecasting in a Large Government Building Using Artificial Neural Networks," *Energies*, vol. 7, no. 4, pp. 1935–1953, Mar. 2014. [Online]. Available: http://www.mdpi.com/1996-1073/7/4/1935/

[45] B. Biegel, L. H. Hansen, J. Stoustrup, P. Andersen, and S. Harbo, "Value of flexible consumption in the electricity markets," *Energy*, vol. 66, pp. 354–362, Mar. 2014. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0360544213011110

[46] A. Mnatsakanyan and S. Kennedy, "Optimal demand response bidding and pricing mechanism: Application for a virtual power plant," in *2013 1st IEEE Conference on Technologies for Sustainability (SusTech)*. IEEE, Aug. 2013, pp. 167–174. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6617315

A

Publications

This appendix outlines the completed and planned contributions of the PhD project in terms of scientific publications and project deliverables. For each planned publications the expected time of submission and the target publisher (e.g., conference or journal) are shown.

Accepted

- S. Rotger-Griful, and R. H. Jacobsen, ”Control of Smart Grid Residential Buildings with Demand Response,” in *Computational Intelligence Applications in Modeling and Control,* ser. Studies in Computational Intelligence, editors A. T. Azar, and S. Vaidyanathan, Springer 2014, vol. 575 *[Final proofing 09-09-2014]*

Submitted

- S. A. Mikkelsen, E. Ebeid, S. Rotger-Griful, and R. H. Jacobsen, ”A Methodology to Evaluate Demand Response Communication Protocols for the Smart Grid”, in *Design, Automation and Test in Europe (DATE)*, 2015 *[Submitted 19-09-2014]*

Planned

- ”Scheduling Residential Loads with Virtual Power Plant for Demand Response Deployed in Industrial Automation Equipment”, IEEE International Conference on Industrial Informatics (*INDIN 2015*), summer 2015
- ”Prediction Models of Electricity Consumption in Residential Buildings for Demand Response”, conference publication, autumn 2015
- ”Potential of Building’s VPP to Provide Demand Response Aggregation to Electricity Markets”, conference publication, winter 2015
- ”Model Predictive Control of a Virtual Power Plant of a Residential Building”, conference publication, spring 2016
- ”Virtual Power Plant of a Residential Building for Demand Response Provision: An Holistic Approach”, journal publication, spring 2016

VPP4SGR Project Deliverables

- ”D2.2 - System Requirements”, December 2013, 22 pages, *[Main editor]*
- ”D2.3 - IT Platform Specification”, October 2014, 22 pages, *[Main editor]*
- ”D2.4 - Field Trial Specification”, September 2014, 25 pages, *[Main editor]*

B

Courses

This section contains a list of all the courses taken during the first 1.5 years of the PhD project. The sum of all the credits leads to 31 ECTS, thus fulfilling the requirements from the GSST from AU. The courses has been chosen to complement the formation of the PhD study from a holistic perspective. A brief description is provided for each of the courses.

Academic English for non-Danish PhD Students 09.2013-10.2013

Aarhus University, PhD Course, 3 ECTS

Transferable skills PhD course on tools and knowledge, in form of vocabulary and grammatical structure, to critique, identify and write scientific articles.

Network Security Essentials 10.2013-01.2014

Aarhus University, Master Course, 5 ECTS

Reading master course on basics of network security, providing an holistic viewpoint, from cryptography techniques to key distribution methods. Based on the book: W. Stalling, "Network Security Essentials - Applications and Standards", Pearson.

Data Management 02.2014-04.2014

Aarhus University, Master Course, 5 ECTS

Master course on database management systems. The course entailed an introduction to different communication protocols and data formats, database design, database development and database querying (SQL).

Specifications of IT Systems 02.2014-04.2014

Aarhus University, Master Course, 5 ECTS

Master course on specification of systems. The course provide insights in requirements elicitation, requirements specification, templates for specification, formal specification and techniques on reviewing and inspecting specifications.

Introduction to R 04.2014-05.2014

Aarhus University, PhD Course, 1 ECTS

Transferable skills PhD course on introduction to the statistics software *R*.

Science Teaching: Introduction to Science Teaching 05.2014-07.2014
Aarhus University, PhD Course, 3 ECTS

Transferable skills PhD course on science teaching. The course provided a toolbox of techniques for teaching activities and know-how on designing a dissemination activity (learning goals, assessment methods and activities).

Electricity Market Analytics 06.2014-07.2014
Aalborg University, PhD Course, 4 ECTS

PhD course on fundamentals on electricity market and optimisation techniques for these markets. The course provided a detailed description of electricity markets and the clearing mechanisms behind them. Additionally, the course introduces a set of optimisation techniques (stochastic programming and robust optimisation) for decision making of different actors in these markets.

Computational Data Analysis 08.2014-09.2014
Technical University of Denmark, PhD Course, 5 ECTS

PhD course on several methods for data analysis. The course provide a toolbox of methods and models for regression and classification to analyse different datasets with vary of purposes. Based on the book: T. Hastie, R. Tibshirani, and J. Friedman, ”The Elements of Statistical Learning - Data Mining, Inference, and Prediction”, Springer.

C

Acronyms

ADS Automation Device Specification.
AU Aarhus University.
BRP Balance Responsible Party.
CEN-ELEC European Committee for Electrotechnical Standardization.
CV Coefficient of Variance.
DER Distributed Energy Resources.
DSM Demand-Side Management.
DSO Distribution System Operator.
EMS Energy Management System.
EU European Union.
EV Electric Vehicle.
GDL Grundfos Dormitory Lab.
GSST Graduate School of Science and Technology.
HVAC Heating, Ventilating and Air Conditioning.
ICT Information and Communication Technology.
KMP Kamstrup Meter Protocol.
MAPE Mean Absolute Percentage Error.
MPC Model Predictive Control.
MSE Mean Square Error.
NIST National Institute of Standards and Technology.
OPC Object Linking and Embedding for Process Control.
PLC Programmable Logic Controller.
SEP2 Smart Energy Profile 2.0.
TSO Transmission System Operator.
US United States.
VPP Virtual Power Plant.
VPP4SGR Virtual Power Plants for Smart Grid Ready Buildings and Customers.

Sergi Rotger-Griful, Virtual Power Plant for Residential Demand Response, 2014

Department of Engineering
Aarhus University
Inge Lehmanns Gade 10
8000 Aarhus
Denmark

Tel.: +45 8715 0000