Schriftenreihe Umweltingenieurwesen

Band 100

Dissertation

Dodiek Ika Candra

Development of a Virtual Power Plant based on a flexible Biogas Plant and a Photovoltaic-System

Professur

Abfall-
und Stoffstromwirtschaft

Agrar- und Umweltwissenschaftliche Fakultät

Universität Rostock

Traditio et Innovatio

Dissertation

HERAUSGEBER

Prof. Dr. mont. Michael Nelles
Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Professur Abfall- und Stoffstromwirtschaft
18051 Rostock

CIP-KURZTITELAUFNAHME

Dissertation Dodiek Ika Candra
Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Rostock, 2020

BEZUGSMÖGLICHKEITEN

Universität Rostock
Universitätsbibliothek, Schriftentausch,
18051 Rostock
Tel.: 0381/498-8639, Fax: 0381/498-8632
E-Mail: tausch.ub@uni-rostock.de

Universität Rostock
Agrar- und Umweltwissenschaftliche Fakultät
Professur Abfall- und Stoffstromwirtschaft
Justus-von-Liebig-Weg 6, 18059 Rostock
Tel.: 0381/498-3401, Fax: 0381/498-3402

ISBN 978-3-86009-518-8
https://doi.org/10.18453/rosdok_id00002814

Universität Rostock
Professur Abfall- und Stoffstromwirtschaft

Gedruckt in Deutschland auf Recyclingpapier.

Vorwort

Die Energieversorgung Deutschlands muss im Sinne einer nachhaltigen Entwicklung in den nächsten Jahrzehnten vollständig auf erneuerbare Energien (EE) umgestellt und die Versorgung der Industrie mit organischen Grundstoffen in diesem Jahrhundert von petro- auf biobasierte Stoffe ausgerichtet werden. Aufgrund der sehr guten Speicherbarkeit von Energie in der Biomasse muss sie in einem zukünftigen Energiesystem eine wesentliche Funktion beim Ausgleich der fluktuierenden Windenergie und Solarenergie übernehmen. Dies gilt insbesondere für den sehr flexibel einsetzbaren Energieträger Biogas, der entweder dezentral zur Strom- und Wärmebereitstellung oder zentral nach einer Aufbereitung auf Erdgasqualität und Durchleitung durch Erdgasnetze zur Strom-, Wärme- oder Kraftstoffbereitstellung genutzt werden kann. Inzwischen gibt es ca. 9.000 Biogasanlagen (BGA) in Deutschland.

Eine wesentliche Herausforderung in der Praxis der BGA ist die nachhaltige Einbindung in das Stromversorgungssystem in Deutschland, das mehr und mehr auf den beiden fluktuierenden Säulen Wind- und Solarstrom basiert. Vor diesem Hintergrund hat Herr Candra ein sehr praxisrelevantes Forschungsthema gewählt. Das übergeordnete Ziel des Promotionsvorhabens ist es, ein virtuelles Kraftwerk (VK), bestehend aus PV-Anlage, Biogasanlage und Batterie zu konzipieren und den wissenschaftlich fundierten Nachweis zu erbringen, dass sich damit eine sichere Stromversorgung in der Praxis darstellen lässt.

Das Vorhaben von Herrn Candra wurde im Rahmen des Promotionsprogramms „Stoffliche und energetische Verwertung von Abfällen und Biomasse" bearbeitet, das von der Professur Abfall- und Stoffstromwirtschaft koordiniert wird und in das u.a. die Technische Hochschule Aschaffenburg eingebunden ist. Die Arbeiten des kooperativen Promotionsverfahrens wurden von Mitte 2014 bis 2020 weitgehend an der TH Aschaffenburg berufsbegleitend durchgeführt, wo Herr Candra als wissenschaftlicher Mitarbeiter angestellt war. Auch aufgrund von anderen beruflichen Pflichten hat die Arbeit einen vergleichsweise langen Zeitraum in Anspruch genommen. Die Ergebnisse wurden in der vorliegenden Dissertation in Form einer Monografie ausgewertet und die Arbeit im Sommer 2020 an der Agrar- und Umweltwissenschaftlichen Fakultät eingereicht.

Die wissenschaftliche Bedeutung der vorliegenden Arbeit ergibt sich aus Sicht der Gutachter insbesondere aus folgenden Punkten:

- Herr Candra hat sich in den Jahren 2014 bis 2020 sehr intensiv mit dem wissenschaftlich schwierigen und sehr komplexen Thema der Integration erneuerbarer Energien in den Strommarkt bei Gewährleistung der Versorgungssicherheit auseinandergesetzt, was auch von hoher gesellschaftlicher Relevanz ist.

- Durch die entwickelten Methoden und Ergebnisse der vorliegenden Arbeit wird das Thema fachlich fundiert weiterentwickelt und ein wesentlicher wissenschaftlicher Beitrag zur Neuaufstellung der Stromversorgung durch erneuerbare Energien im Rahmen der Energiewende geleistet.

- Die Arbeit hat dabei die Bereitstellung gesicherter Leistung im Fokus, ein Thema, das mit dem Abschalten der großen Dampfkraftwerke in Deutschland in naher Zukunft verstärkt an Bedeutung gewinnen wird. Insgesamt hat Herr Candra auf Basis der aktuellen Methoden zur Anlagensteuerung und -optimierung (SGAM, KI-Optimierung) ein komplexes Modell eines virtuellen Kraftwerks entwickelt. Durch die Arbeit wird der Stand der Wissenschaft in der Fachdisziplin maßgeblich erweitert, insbesondere im Bereich des Einsatzes von KI zur Steuerung des virtuellen Kraftwerks und bei den Prognosen von PV-Leistung und der Last.

Abschließend wünschen wir Ihnen nun interessante fachliche Anregungen und viel Spaß beim Lesen der Dissertation von Herr Dr.-Ing. Dodiek Ika Candra.

Herzliche Grüße aus Aschaffenburg, Kassel und Rostock senden

Prof. Dr.-Ing. Kilian Hartmann
Technische Hochschule Aschaffenburg

Prof. Dr.-Ing. Kurt Rohrig
Universität Kassel und
Fraunhofer IEE

Prof. Dr. mont. Michael Nelles
Universität Rostock und
Deutsches Biomasseforschungszentrum gGmbH (DBFZ) Leipzig

Universität Rostock

Traditio et Innovatio

Department of Waste and Resource Management

Development of a Virtual Power Plant based on a flexible Biogas Plant and a Photovoltaic-System

Dissertation

Submitted in the fulfillment of the requirements

The Academic Board of Rostock University

Faculty of Agriculture and Environmental Sciences

For the Degree of Doctor of Engineering (Dr.-Ing.)

Dodiek Ika Candra

Born in Tulungagung 09.03.1984, Indonesia

Gutachter

Prof. Dr. Michael Nelles

Universität Rostock, AUF, Professur Abfall- und Stoffstromwirtschaft

Prof. Dr. Kilian Hartmann

Technische Hochschule Aschaffenburg, Professor für Energiewirtschaft und -managements

Prof. Dr.-Ing. Kurt Rohrig

Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik IEE

Stellvertretender Institutsleiter, Wissenschaftlicher Programmdirektor, Ombudsperson zur Sicherung der guten wissenschaftlichen Praxis

Universität Kassel

Datum der Einreichung : 23. Juni 2020

Datum der Promotionsverteidigung : 22. Oktober 2020

Dedication

- To the most precious gifts in my life — my family
- To the future of energy in our life — sustainable energy
- To the two things for human developments — science and education

I dedicate this work.

Acknowledgements

This thesis is one of the biggest presents that I have got in my life, thank God. Moreover, I would like to express my gratitude to the following people for supporting me with this study:

- **Prof. Dr. mont. Michael Nelles** for his supervisions, guidance, discussions, and scientific advices. It was a honor to be his Ph.D. student.
- **Prof. Dr. Kilian Hartmann** for his guidance, scientific advices, endless supports, funding possibilities and discussions during this study. It was an honor to be his Ph.D. student. Many thanks also his family who provided accommodation for me and my family at the beginning of this study and other valuable supports until now.
- **The Federal Ministry of Education and Research Germany** who provided funding for this study through Solar-Biogas-Batterie-Kombikraftwerk (SoBiBaKo) project.
- **Prof. Dr. Michael Kaloudis and his team** from Faculty of Engineering - Aschaffenburg University of Applied Sciences for his valuable supports in permit issuance, especially for residence permit, invitation letter and permissions to conduct this study in Aschaffenburg.
- **Prof. Dr. Hans-George Stark, Dr. Tilo Göckel and his team** from Aschaffenburg University of Applied Sciences, Center for Scientific Services - ZeWiS Obernburg for their supports during the flexible biogas implementation in Obernburg.
- **Mrs. Birgit Kühlborn and her team** from Personal Department - Aschaffenburg University of Applied Sciences, for her administrative assistance at Aschaffenburg University of Applied Sciences during the study.
- **Frank Nöthling, Frank Neumann, Christian Hofmann and Ralf Roßmann** from Renewable Energies and Energy Management Programme (E3) for their valuable time and discussions related to the battery storage system and VPP implementation at Aschaffenburg University of Applied Sciences.

- **Camillo Wilches** from bwe-energy systeme GmbH & co KG, who provided electricity pricing, support and advice for the implementation of flexible biogas during this study.
- **Waldemar Ganagin** from Hochschule für angewandte Wissenschaft und Kunst Hildesheim Holzminden Göttingen (HAWK Göttingen), who provided his assistance and expertise on flexible biogas 2 (ReBi2).
- **Dr.-Ing Manuel Bock** the Director of Computer Center - Aschaffenburg University of Applied Sciences for his personal resources allocation and permissions to develop VPP using the ICT infrastructure of Aschaffenburg University of Applied Sciences.
- **Max Englert, Kresimir Gronjak, Erwin Zilg, Tobias Fritsch, Benjamin Heike and Dominik Büttner** for their support in ICT preparation and VPP troubleshooting at Aschaffenburg University of Applied Sciences.
- **Mrs. Christine Herz** from Faculty of Agriculture and Environmental Sciences (AUF) - Universität Rostock for her assistances and helps for preparing all administrative requirements during this study.
- **Steven Hirt** for his valuable assisance in biogas installation and all non-technical supports for my family during this study.
- **Mr. Maximilian List and Oliver Bezzo** for their supports to the biogas installation, biogas feeding preparations and biogas tests.
- **Lyubomir Dimitrov and Tobias Koch** for his supports for biogas installation and to test MATLAB simulations.
- **Mr. Amid Nazeri** for his supports to prepare load data, price data and data for load forecast.
- **Mr. Phillip Vogel** for his support to test the connection between battery storage and its local controller.
- **Sergio Badon** for his supports to test the first draft of VPP’s GUI.
- **Dorothea Koch** for her supports on organizing the literatures of this study.
- **Mr. Stefan Meyer** and his colleagues from Finance Department of Aschaffenburg University of Applied Sciences for his support, especially during the process of purchasing and collecting tools, equipments and other various materials for the project.

- **Mrs. Beate Bauer** and **Mrs. DagmarTormählen-Roth** for their supports during work stays at Campus 2 of Aschaffenburg University of Applied Sciences.
- **Team from the AVG Aschaffenburg Germany** who provided load demand and solar data for this research project.
- **Team from the GBAB mBH Aschaffenburg Germany** who provided percolate to feed flexible biogas.
- **Dr. Gehrig Management and Technology Consulting GmbH, Fraunhofer IWES and University of Rostock Germany**, who supported the realization of this project.
- **All my friends** for their advices and supports to finish this study.

Last but not least, I would like to thank to my wife, my daughter, my parents and my grandmother for their endless love, patience, inspiration and encouragement given to me along this journey.

Aschaffenburg, June 2020

Dodiek Ika Candra

Executive Summary

A power production from a Photovoltaic plant (PV) is weather dependant, thus it is not a preferable option to cover loads. Moreover, battery storage as an energy buffer and complementary component is both limited by capacity and cost. There could still be residual loads from a combination of battery storage and PV.

Up until now, the concept of combining intermittent renewable energy sources (RES) and flexible generations (flexible biogas and battery) for power markets has yet to be developed. A proposed solution to manage the integration of intermittent energy sources and flexible energy sources is to organize them into an associated power plant through a virtual power plant (VPP).

The aim of this project is to develop an integrated power plant through VPP in order to respond to load demands by considering a corresponding power market product. There are four main methods applied during this study to develop such a system: integration algorithm (VPP development), VPP performance analyses, sensitivity analyses of developed integration in the electricity market and analysis of its boundaries.

The results show that the deployment of Multi-Agent based System (MAS) and Smart Grid Architecture Model (SGAM) concepts support the idea of the integration of intermittent RES (PV) and flexible power generators (biogas, battery) in a VPP. The combined power plant in this study provides a reliable, secure power supply, and is able to cover different load schemes with varying levels of electricity prices. The electricity generation costs from integrated power plants discovered in this research are competitive to market prices in several scenarios. In addition, the modular plug-and-play concept developed in this project is also adaptable to the grid infrastructure changes. Furthermore, the developed VPP quickly reacts to changing requirements (legal, economic, technical) without harming the stability of the system. Despite its multiple boundaries, the developed VPP was able to support the transformation of renewable sources, as it leads to a controllable and flexible energy system thus enhance more optimized market participation.

Kurzfassung

Die Strombereitstellung aus Photovoltaik-Anlagen (PV) ist wetterabhängig, daher kann sie alleine Lastanforderungen nicht zufriedenstellend absichern. Darüber hinaus sind Batteriespeichersysteme als Energiepuffer sowohl durch ihre Kapazität als auch durch die Kosten begrenzt. Auch die Kombination von PV und Batteriespeichersystemen kann spezifische Lastprofile nur in engen Grenzen absichern.

Bisher muss das Konzept der Kombination von intermittierenden erneuerbaren Energiequellen (EE) und flexiblen Stromerzeugern, z.B. flexible Biogasanlagen und Batteriespeichersysteme, für Strommärkte noch entwickelt werden. Eine mögliche Lösung besteht darin, sie in einer virtuellen Kraftwerk (VK) Plattform zu einem Kraftwerk zu integrieren.

Das Hauptziel dieser Studie ist die Entwicklung einer integrierten Stromerzeugung durch VK, um auf die Lastnachfrage zu reagieren bzw spezifische Strommarktprodukte zu liefern. Während dieser Forschung wurden vier Hauptmethoden angewandt: Integrationsalgorithmen und VK-Entwicklung, VK-Leistungsanalyse, Sensitivitäsanalyse der Integration in den Strommarkt und Bestimmung der Grenzen des VK.

Die Ergebnisse zeigen, dass Multi-Agent basiertes System (MAS) und Smart Grid Architekturmodell (SGAM) die Integration intermittierender erneuerbarer Energien (PV) und flexibler Kraftwerke (Biogas, Batterie) in ein VK ermöglichen. Das kombinierte Kraftwerk in dieser Studie bietet eine zuverlässige und sichere Stromversorgung und ist in der Lage, verschiedene Lastprofile mit unterschiedlichen Strompreisen zu bedienen. Die in dieser Studie ermittelten Stromgestehungskosten des VK entsprechen in manchen Szenarinen den aktuellen Marktpreisen. Darüber hinaus ist das in dieser Forschungsarbeit entwickelte modulare Plug-and-Play-Konzept auch an die Änderungen der Netzinfrastruktur anpassbar. Außerdem kann das entwickelte VK schnell auf sich ändernde Anforderungen (rechtlich, wirtschaftlich, technisch) reagieren, ohne die Stabilität des Systems zu beeinträchtigen. Trotz seiner Grenzen kann das entwickelte VK die Integration erneuerbarer Energien unterstützen, da es zu einem steuerbaren und flexiblen Energiesystem führt und so eine optimierte Marktbeteiligung fördert.

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List of Abbreviations

General terms

PV	Photovoltaic	EMS	Energy Management System
RES	Renewable Energy Sources	IS	Intelligent System
ICT	Information and Communication Technologies	BESS	Battery Energy Storage System
VPP	Virtual Power Plant	SOC	State of Charge
SCADA	Supervisory Control and Data Acquisition	GUI	Graphical User Interface
SoBiBaKo	Solar-Biogas-Batterie-Kombikraftwerk	SGAM	Smart Grid Architecture Model
BMBF	Bundesministerium für Bildung und Forschung	Ah	Ampere hour
MAS	Multi-Agent based System	V/A	Voltage/Ampere
GBAB	Gessellschaft für Bioabfallwirtschaft in Landkreis und Stadt Aschaffenburg GmbH	U/I	Symbol for Voltage/Current
kWh/MWh	kiloWatt hour/MegaWatt hour	P	Symbol for Power
ReBi	Regelbare Biogaserzeugung	OVP	Over Voltage Protection
AD	Anaerobic Digestion	OCP	Over Current Protection
PLC	Programmable Logic Controller	OPP	Over Power Protection
OPC UA	Open Platform Communications Unified Architecture	OTP	Over Temperature Protection
EEX	European Energy Exchange	OS	Operating System
EPEX	European Power Exchange	BIO	Flexible biogas
CM	Contribution Margin	PMS	Power Management System
DA	Day-Ahead	MABOA	Multi Agent Based Optimization Algorithm
WF	Week Futures	DSM	Demand Side Management

TWh	Terawatt hour	GA	Genetic Algorithm
CHP	Combined Heat and Power	DSO	Distribution System Operator
TVPP	Technical VPP	TSO	Transmission System Operator
CVPP	Commercial VPP	RE	Renewable Energy
DER	Distributed Energy Resources	AC	Alternating Current
MW	Megawatt	SCL	Structured Control Language
Fraunhofer IWES	Fraunhofer Institut für Windenergie und Energiesystemtechnik	DB	Database
EMSE	Energy Management System Eichhof	HW/SW	Hardware/Software
ReqMod-Harz	Regenerative Model Region Harz	BMS	Battery Management System
API	Application Programming Interface	a.m.	Ante meridiem: 12-hour before noon
DLL	Dynamic Link Library	p.m.	Post meridiem: 12-hour after noon
WCF	Windows Communication Foundation	VPN	Virtual Private Network
SQL	Structured Query Language	AB	Aschaffenburg
IES	Integrated Energy Sources	TCP-IP	Transmission Control Protocol-Internet Protocol
EEG	Erneubare Energien Gesetz	JSON	JavaScript Object Notification
D.I.C	Dodiek Ika Candra	HTML	Hypertext Mark-up Language
K.H	Kilian Hartmann	CEN	The European Committee for Electrotechnical Standardization for other technical areas
M.N	Michael Nelles	CENELEC	The European Committee for Electrotechnical Stand-

			ardization for electrical engineering *(French: Comité Européen de Normalisation)*
SoBiBaKo	Solar Biogas Batterie-Kombikraftwerk	ETSI	The European Telecommunications Standards Institute
IKT	Informations- und Kommunikationstechnologie	FBD	Functional Block Diagram
kV	kiloVolt	XML	Extensible Markup Language
KWK	Kraft-Wärme-Kopplung	XHTML	Extensible HyperText Markup Language
IEC	International Electrotechnical Commission	AJAX-WS	asynchronous JavaScript and XML—Web Service
VDE	Verband der Elektrotechnik, Elektronik und Informationstechnik	LAD	Ladder Diagram
DKE	Deutsche Kommission für Elektrotechnik, Elektronik und Informationstechnik	HTTP	Hypertext Transfer Protocol
OLR	Organic Loading Rate	TCOD	Total Chemical Oxygen Demand
ANN	Artificial Neural Networks		
Market terms			
MWMN	Monday Winter Middle-Night	MSPL	Monday Summer Peakload
MWEM	Monday Winter Early Morning	MSN	Monday Summer Night
MWLM	Monday Winter Late Morning	MSOP1	Monday Summer Off-Peak 1
MWEA	Monday Winter Early Afternoon	MSB	Monday Summer Business
MWRH	Monday Winter Rush-Hour	MSOP	Monday Summer Off-Peak
MWOP2	Monday Winter Off-Peak 2	MSM	Monday Summer Morning

MWBL	Monday Winter Baseload	MSHN	Monday Summer High Noon
MWPL	Monday Winter Peakload	MSA	Monday Summer Afternoon
MWN	Monday Winter Night	MSE	Monday Summer Evening
MWOP1	Monday Winter Off-Peak 1	MSSP	Monday Summer Sun Peak
MWB	Monday Winter Business	WF_SBL	Week Futures Summer Baseload
MWOP	Monday Winter Off-Peak	WF_SPL	Week Futures Summer Peakload
MWM	Monday Winter Morning	MWF_WBL	Monday Week Futures Winter Baseload
MWHN	Monday Winter High Noon	TWF_WBL	Tuesday Week Futures Winter Baseload
MWA	Monday Winter Afternoon	WWF_WBL	Wednesday Week Futures Winter Baseload
MWE	Monday Winter Evening	ThWF_WBL	Thursday Week Futures Winter Baseload
MWSP	Monday Winter Sun Peak	FWF_WBL	Friday Week Futures Winter Baseload
MSMN	Monday Summer Middle-Night	SWF_WBL	Saturday Week Futures Winter Baseload
MSEM	Monday Summer Early Morning	SuWF_WBL	Sunday Week Futures Winter Baseload
MSLM	Monday Summer Late Morning	MWF_WPL	Monday Week Futures Winter Peakload
MSEA	Monday Summer Early Afternoon	TWF_WPL	Tuesday Week Futures Winter Peakload
MSRH	Monday Summer Rush-Hour	WWF_WPL	Wednesday Week Futures Winter Peakload
MSOP2	Monday Summer Off-Peak 2	ThWF_WPL	Thursday Week Futures Winter Peakload
MSBL	Monday Summer Baseload	FWF_WPL	Friday Week Futures Winter Peakload
EA	Early Afternoon	PL	Peak Load
B	Business	BL	Base Load

HN	High-Noon	SSPL	Saturday Summer Peakload
SP	Sun Peak	SSN	Saturday Summer Night
MW	Monday Winter	SSOP1	Saturday Summer Off-Peak 1
SWMN	Saturday Winter Middle-Night	SSB	Saturday Summer Business
SWEM	Saturday Winter Early Morning	SSOP	Saturday Summer Off-Peak
SWLM	Saturday Winter Late Morning	SSM	Saturday Summer Morning
SWEA	Saturday Winter Early Afternoon	SSHN	Saturday Summer High Noon
SWRH	Saturday Winter Rush-Hour	SSA	Saturday Summer Afternoon
SWOP2	Saturday Winter Off-Peak 2	SSE	Saturday Summer Evening
SWBL	Saturday Winter Baseload	SSSP	Saturday Summer Sun Peak
SWPL	Saturday Winter Peakload	WF_WBL	Week Futures Winter Baseload
SWN	Saturday Winter Night	WF_WPL	Week Futures Winter Peakload
SWOP1	Saturday Winter Off-Peak 1	MWF_SBL	Monday Week Futures Summer Baseload
SWB	Saturday Winter Business	TWF_SBL	Tuesday Week Futures Summer Baseload
SWOP	Saturday Winter Off-Peak	WWF_SBL	Wednesday Week Futures Summer Baseload
SWM	Saturday Winter Morning	ThWF_SBL	Thursday Week Futures Summer Baseload
SWHN	Saturday Winter High Noon	FWF_SBL	Friday Week Futures Summer Baseload
SWA	Saturday Winter Afternoon	SWF_SBL	Saturday Week Futures Summer Baseload

SWE	Saturday Winter Evening	SuWF_SBL	Sunday Week Futures Summer Baseload
SWSP	Saturday Winter Sun Peak	MWF_SPL	Monday Week Futures Summer Peakload
SSMN	Saturday Summer Middle-Night	TWF_SPL	Tuesday Week Futures Summer Peakload
SSEM	Saturday Summer Early Morning	WWF_SPL	Wednesday Week Futures Summer Peakload
SSLM	Saturday Summer Late Morning	ThWF_SPL	Thursday Week Futures Summer Peakload
SSEA	Saturday Summer Early Afternoon	FWF_SPL	Friday Week Futures Summer Peakload
SSRH	Saturday Summer Rush-Hour	LM	Late Morning
SSOP2	Saturday Summer Off-Peak 2	M	Morning
SSBL	Saturday Summer Baseload	RH	Rush-Hour
DA	Day-Ahead market	SW	Saturday Winter
WF	Week Futures market	SS	Saturday Summer

1 Introduction

The need for power supply structure transformation which not only provides reliable power but is also adaptive to the dynamic change of energy structures becomes inavoidable due to the increasing share of Renewable Energy Sources (RES) in the grid. Furthermore, the future grid requirements have challenged the current power supplies to be upgradable and re-configurable. With regard to those phenomenon, the development of state-of-the-art Information and Communication Technology (ICT) and RES technologies should support this power supply development. The concept of VPP as one of advanced ICT developments brings traditional energy supply chains into the new era. This has been termed the “Internet of Energy” for future energy supply structures. It functions to smartly combine more power plants in the grid, which can be continuously developed and is not been seen as an “alternative solution” anymore.

On the other hand, the current developments in biogas have has shown the technology as a potential flexible energy source in order to provide reliable energy, not only for conventional power system but also systems based on intermittent RES.

In this thesis, the study of the integration of flexible energy sources and intermittent RES through a Virtual Power Plant (VPP) is presented.

1.1 Motivation

The RE share of gross electricity consumption in Germany in 2015 reached about 31,5% and it is predicted to increase to 80% by 2050 (BDEW, 2017, p. 19). According to Ziesing (2016, p. 29), upuntil 2015, Germany had a capacity of 651,8 TWh in its gross electricity production, in which 162,5 TWh was based on renewables. The power generated from renewables in Germany in 2015 was dominated by Wind (79,206 GWh) followed by PV (38,726 GWh) and then Biogas (31,288 GWh) (BMWi, 2017, p. 8).

In addition to this, the number of installed RES from small scale investors in Germany is currently increasing. Until 2010, according to (Wassermann et al., 2015, p. 68), the percentage ownership of the installed capacities are private owners (51.5 % Wind (off-shore)), farmers (71.5% Biogas), Industries (41.5% Biomass) and Private owners (39.4 % PV).

One of the driving factors of this increment is the German strategy within the German Energy Act (EEG) that promotes RE developments and integration in the energy market. The positive development RES progresses however led to another issues in the power generation. There are at least three main issues on marketing and integrating RES to the electricity market, which are:

- The first issue is that installed RES-based power plants, especially small power generation, are not automatically able to participate in power markets due to minimum power constraints.
- The second issue is related to the reliability of generated power from intermittent RES. The generated energy from Wind and PV are weather dependant, thus posing additional challenges in grid reliability while increasing the share of RES.
- The third issue is related to the economic aspects of renewables in the grid. The RES-based power plants should be able to compete with fossil-based power plants in the liberalized power markets. The demand to generate reliable power from renewable-based power plants, which is technically and economically optimal in the future, will reach its maximum level when contribution of the the fossil-based power to the grid is minimized because of the energy transition target. With increasing installed capacity from renewable energy sources in German energy markets, energy prices from renewable energy sources are expected to decrease in the future. This thesis is therefore aimed at discovering the integration concept and the energy management concept in a VPP based on RES power plants, especially the combination of flexible generation (biogas and battery) and intermittent RES (a Photovoltaic (PV)-system) considering its market.

1.2 Statement of the problem or gaps

There is a current lack of integrated solutions which are able to minimize or solve these grid challenges (stability from intermittent RES, technical integration of RES in grids as well as markets and balancing mechanisms from a high share of RES) simultaneously from a combination of flexible biogas and intermittent RES. At the same time, energy storage as a balancing energy, such as batteries that can store excess energy from intermittent RES, has limited applicable storage capacity and rising deployment costs.

Whilst smart grids are aimed at minimizing risks and RES integrations, balancing energy that relies on flexible energy generation and storage are yet to be developed. An effective coordination and control in their integration with other energy sources is therefore indispensable. The combination of flexible energy generation, such as flexible biogas and VPP technologies, are supposed to be able to solve the problems of integrated RES in the grid and power market.

Moreover, smart grid integration methods (such as Multi-Agent based System (MAS) and Smart Grid Architecture Model (SGAM) concept), flexible biogas and VPP technologies are some of the current technologies that have been proposed as being able to handle these issues. The combination of these technologies is, however, still in the development stage. The integration of flexible biogas and intermittent RES are not yet able to answer grid challenges, which includes market integration.

1.3 Aim and significance of the study

As the challenges and gaps that have been described in Chapter Motivation and Statement of the problem or gaps show, further developments of integrated power plants that are able to control and balance power from high share intermittent RES are indispensable. To some extent, the simultaneous integration of intermittent RES, the use of flexible energy, and energy storage are required in order to support energy transition with a high share of RES.

<u>Aim</u>

The purpose of this study is to establish an integrated flexible energy generation (flexible biogas and battery) and intermittent RES (PV) through a VPP as a solution to grid challenges with a high share of RES.

Significance of the study

The outcomes of the study are intended to identify two main aspects:

- To identify, on a theoretical level, the technical requirements and methods of RES integration that enable functionalities of flexible energy generations (flexible biogas and battery) and intermittent RES (PV) to contribute to the development of power transformations with a high share of RES in the grid.
- On a practical level, to demonstrate the possibilities, technical boundaries, and abilities of flexible energy generations (flexible biogas and battery) and intermittent RES (PV) in order to support grid reliability, which is based on 100 % power from RES.

1.4 Hypotheses

Hypotheses of this research are developed and based on Theory (Chapter Theories), a Literature review (Chapter Literature Review) of current RES developments in order to respond to the challenges (Chapter Motivation) and gaps (Chapter Statement of the problem or gaps) of the study. It is also based on future projection of the potentials for other possible developments in smart grid topics. These hypotheses then need to be tested and further investigated to answer the research questions of the study (Chapter Research questions).

The hypotheses of this study are:

- State of the art (s-o-a) ICT and RES-based generation technologies can be combined to provide an effective coordination and control of integrated RES systems. VPP, as one of the s-o-a ICT concepts, enables techno-economically optimum power plant management, Distributed Energy Resource (DER) control and power market integrations.
- A VPP (from integrated flexible biogas, a PV system, and a battery system) using a MAS and SGAM concept is an applicable model to solve reliability, balancing and integration issues in a grid based on a high share of RES.
- Products of integrated flexible energy generations (flexible biogas and storage) and intermittent RES (PV) in a VPP are marketable in current market situations but are limited by their technical constraints and deployment costs.

- The integrated power plants in VPP enable RES-based power plants to provide reliable power in the grid with competitive costs in the liberalized German power market.

1.5 Research questions

The hypothesis and problem statement lead to the following main research question: How can flexible energy generation (biological flexible biogas and a battery storage) and intermittent RES (PV) be combined in a Virtual Power Plant (VPP) and to what extent is this combination able to answer load demands in the power markets?

The research questions is then formulated of the following specific problems:

- Which methods, components and developments are needed to combine flexible energy generation (biological flexible biogas and a battery storage) and intermittent RES (PV) in a VPP?
- How are the behaviors of integrated flexible energy generation (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP) able to cover load demands?
- What are the technical, economic optimum combinations of flexible energy generation (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP) to provide a reliable energy supply, an adaptable power to the future energy requirements and accessible power with a competitive price in the electricity market?
- What are technical limitations of integrated flexible energy generation (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP)?

1.6 Objectives

In order to achieve the aim of this study, the objective of this study are then classified into main and specific objectives. The main objective of this study is to develop a VPP using a MAS and SGAM concept to integrate flexible biogas, a battery storage and a PV system. This study also develops an approach to implement a combination of a flexible biogas and PV system including battery storage in a VPP, as well as to assess possible contributions and boundaries from this VPP to cover load demands in power markets.

It is expected that by researching these points, a concept and an application for integrated intermittent RES and flexible biogas to provide stable and reliable power, considering Germany's power market and high proportion of RES in the grid, can be provided to answer the challenges to the grid and market integration with a high share of RES.

The specific objectives of this thesis are:

(1) to develop and apply methods, components and developments to combine flexible biogas, battery storage, and a PV-system in a VPP.

(2) to analyze the performance of integrated flexible biogas, battery storage and a PV-system behaviors in a Virtual Power Plant (VPP) with regard to the management of load demands.

(3) to analyze techno-economic optimal configurations of VPP to manage load demands considering the current EPEX/EEX power markets conditions such as the Day-Ahead market and the Week Futures market

(4) to discover the system boundaries of developed VPP in this study.

1.7 Boundaries and scope

The boundaries and scope of this study are as follows:

- The research took place in Aschaffenburg, Germany through a "Solar-Biogas-Batterie-Kombikraftwerk (SoBiBaKo)" project. The project aimed to ensure energy supply stability, and to study the reliable operation of combined RES power plants for the development of future energy supply structures. Therefore, the characteristics of the power plants involved in this study were based on this specific location.
- Flexible biogas and a battery system represented flexible energy sources, whereas a PV system represented an intermittent RES.
- PV and load demands were synthetic data, which refered to PV power production and load demands data from a local grid operator.
- At the beginning of the research, a biogas power plant and a battery were not built yet. Therefore, the research also developed and built these two power plants. However, the biogas power plant was not yet connected to the CHP machine since it was a laboratory scale application.

- A local municipal waste management firm in Aschaffenburg, Germany provided the biogas substrate. The substrate was in the form of liquid percolate.
- The power plants (biogas, PV, and battery) in this study were installed in different locations in order to simulate the different conditions of distributed energy resources in the real application.
- The integration of these power plants mainly took place on ICT - configuration level since they were the only battery that had a direct connection to the grid.
- The theoretical concept and practical implementation to integrate flexible biogas, PV and Battery in a VPP were based on MAS and SGAM concepts.
- The main investigation in this study was limited to the strategy of each power plant in order to answer load demands in the grid by considering its characteristic.
- The VPP in this study also had energy management in order to find technical and economical optimal configurations of power plants. It was developed to find the power plants' profiles, costs and operational strategy in the VPP such as the feeding strategy (feeding timing and amount) of flexible biogas.
- Analysis on power market products was based on bid and market classifications from (Konstantin, 2013, pp. 51–56 and European Power Exchange, 2015).
- Lastly, the technical possibility of VPP was projected to the Germany's power market at different timeframe, load types, and time scale from Day-Ahead market to the future market.

1.8 Outline of the Thesis

This dissertation is organized as follows:

- The **first chapter** of this dissertation presents the background of this study followed by the importance of the study in motivation and scope. It further explains the problem of the study. Thisis then used as a basis for the objectives to solve the problems. At the end of the introduction, the outline of the thesis is presented.

- The **second chapter** describes the theory of electricity supply, DER components and power markets.
- The **third chapter** provides a literature review of energy transition in Germany, the technical potential of DER for a VPP, balancing energy through flexible energy resources, virtual power plants and integration concepts using MAS and SGAM model.
- The **fourth chapter** is aimed at outlining the materials and methods of a combined flexible biogas system, a PV system and battery storage used in the VPP that is developed in this study. The realizations of this chapter include the development of VPP structures. Different scenarios and sensitivity analysis in the VPP are applied by considering Germany's existing power market products in the European Energy Exchange (EEX)/ European Power Exchange (EPEX).
- In the **fifth chapter,** the results of the study are presented and are based on objectives and methods developed in the previous chapter.
- In the **sixth chapter**, the analysis of the study is presentedand focuses on the interactions and abilities of VPP components in VPP. It also discusses the economic andoptimal implementation of different VPP scenarios.
- In the **seventh chapter**, the conclusion of the study is provided. Furthermore, the chapter also provides future research recommendations.

2 Theories

This chapter provides a theory of the electricity supply chain process and smart grids concept as a basis for an understanding of the VPP development in this study. It also exposes RES-based DER technologies and power markets as components in the electricity supply chain process and smart grids.

2.1 Electricity supply chain and smart grid

2.1.1 Electricity supply chain

The electrical supply chain is related to the process of how the power supply is delivered to the consumer. The electricity supply chain consists of three main components in the grid system: power generation, transmission and distribution. Power generations supply or generate electricity to the grid through transmission lines after the generated power is conditioned, such as after the voltage is increased. Included in the power generations are generating power from conventional power plants, renewable energy and energy storage systems. This generated power requires transmission and distribution systems to deliver electricity to the end user. Transmission systems transmit generated energy from power generators over varied distances, normally for long distance users. This transmitted energy is then distributed by power distributions through distribution lines with stepped down voltage to the end user or consumer.

In order to ensure the successful process in the whole electricity supply chain, metering and controlling devices including system operators are required. The process in utilizing the metering, controlling and supervision of the electricity chain process is usually categorized in a system called Supervisory Control and Data Acquisition (SCADA). The implementation of the SCADA system in the electrical chain process includes the use of the Human Machine Interface (HMI) (Buchholz and Styczynski, Z.A., 2014).

Regarding future grid requirements, it is expected that the electricity supply chain will not traditionally use a top-down approach moving forward but a more interactive approach (Block, et al, 2010). The electricity supply chain should provide “freedom” and flexibility to all grid system participants in order to determine and actively interact with each other in the grid and power market system. Thus, new electricity supply chain concepts e.g. smart grid concepts are offered and developed.

2.1.2 Smart grid

Smart grids exist in various applications that predominately implement intelligent controls, operations and measurements in order to achieve a more reliable, efficient and secured power system. It also enhances self-healing and detection to provide a high reliabel grid system.

An electrical supply chain (grid system), using an intelligent Information Communication Technologies (ICT) that is able to bridge between the producer's system and the consumer's system, belongs to a smart grid. In addition, a collaboration between intelligent applications from both the supply chain system, market and consumers in the form of a smart grid technology is developed in order to manage and optimize energy exchange and ease the interaction between all the market stakeholders. Another example of a smart grid application is smart charging from the from the consumers'side. Compared to uncontrolled charging, the smart ICT system is able to help consumers in deciding the time to charge based on price and needs. It usually send charging signals at a specific time, e.g. when the price and needs are low (between 02:00 am and 10:00pm) (Figure 2.1) (Buchholz and Styczynski, Z.A., 2014).

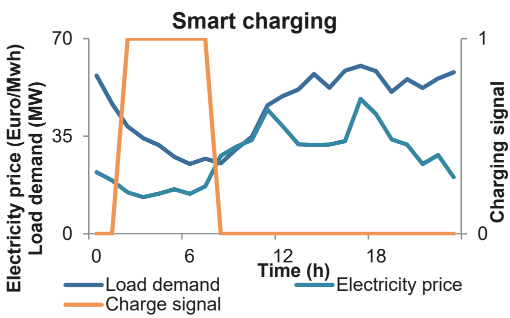


Figure 2.1. Smart grid sample application on a smart charging system.

Source:Adapted from (Buchholz and Styczynski, Z.A., 2014).

In Europe, the concern about the definition of smart grids and its related tasks has come from the European Union Commission Task Force for Smart Grids (EU Commission Task Force for Smart Grids, 2010, p. 9).

“A Smart Grid is an electricity network that can cost efficiently integrate the behavior and actions of all users connected to it – generators, consumers and those that do both – in order to ensure an economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety. A smart grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies in order to:

- Better facilitate the connection and operation of generators of all sizes and technologies.
- Allow consumers to play a part in optimizing the operation of the system.
- Provide consumers with greater information and options for how they use their supply.
- Significantly reduce the environmental impact of the whole electricity supply system.
- Maintain or even improve the existing high levels of system reliability, quality and security of supply.
- Maintain and improve the existing services efficiently."

In comparison to traditional electricity supply chains, smart grids have a different approach to how the electricity infrastructure, process and participants are built and how the interactions are developed (Figure 2.2). In an infrastructure system, smart grids implement more advanced digital technologies and infrastructure than in traditional systems which apply a real time and interactive process and operation of the grid system. Smart grids also provide flexibilities to its participants rather than passive, centralized and top down approaches as in traditional system. Each participant in a smart grid, whether it is from a small power producer or a big consumer, has flexibility and an active role in the grid system and power markets (Block, et.al, 2010).

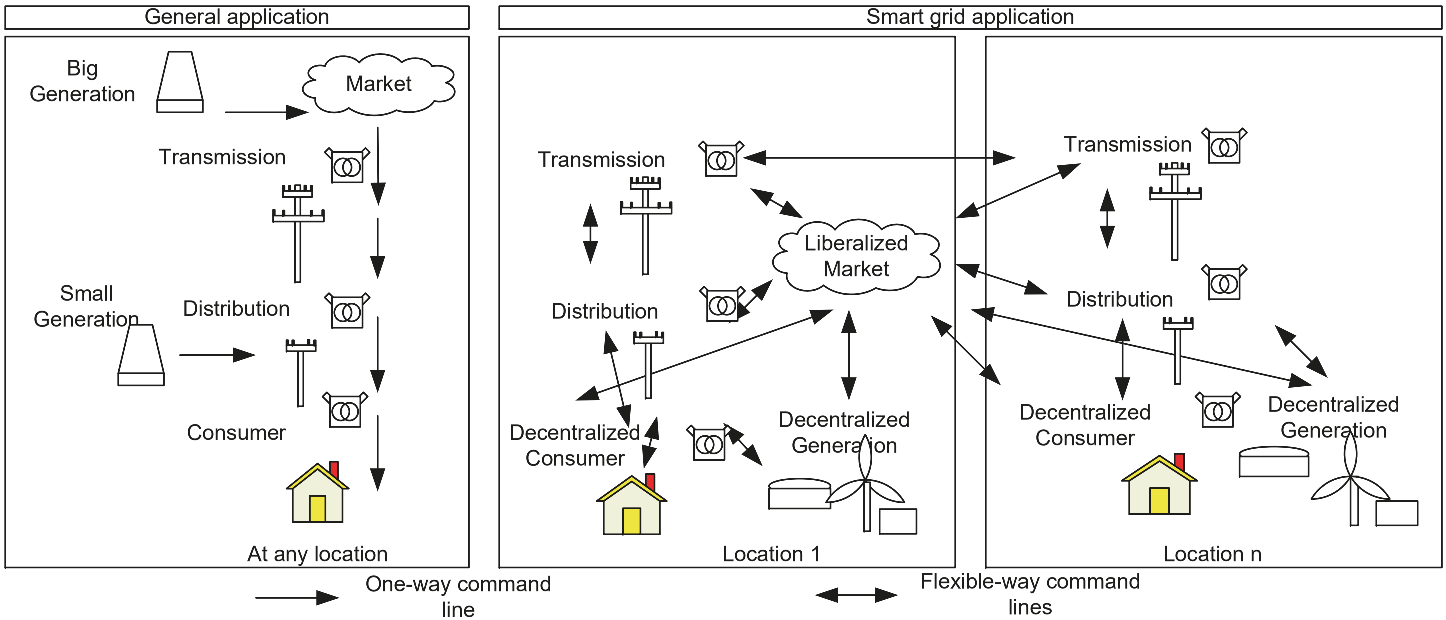


Figure 2.2. Smart grids system compared to traditional power system.

Source: Adapted from (Block, et.al, 2010).

Due to the implementation of a smart grid system, the geographical boundaries among grid participants or actors are not relevant anymore (Buchholz and Styczynski, Z.A., 2014). Through a VPP implementation, it is possible for consumers to choose and use power suppliers which are locally installed or may distribute to a wider area. If power generations are closely located to the load demands, then it could be defined as distributed energy or Distributed Energy Resources (DER). A DER system typically serves local and decentralized load demands. DER also includes the use of Renewable Energy Sources (RES), energy storage and distributed load demands.

2.1.3 Smart grid standards

A smart grid application is basically standardized based on general components, electronics, and telecommunication components, which are internationally under the scope of the International Organization for Standardization (ISO, for general application), International Electrotechnical Commission (IEC, for electronic engineering) and International Telecommunication Union (ITU, for telecommunications). In European countries, these standards are respectively adapted into into the European Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI). Whereas, in Germany, respectively are part-the standards are part of the of German Institute for Standardization (DIN) and the German Commission for Electrical Electronic and Information Technologies (DKE VDE DIN).

Table 2.1. Sample of Smart grid standards based on European and International standards in which VPP application is included.
Source: Adapted from (DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE, 2020; International Electrotechnical Commission, 2020a, 2020b).

Technical Committee (TC)	**Working Group (WG)**	**Related Standards**	**Application**
IEC TC 57	WG 17	IEC 61850-7-420	Communication systems for Distributed Energy Resources (DER)
IEC TC 118	WG 1	IEC TS 62939-2:2018	Smart grid user interface – Part 2: Architecture and requirements
IEC TC 57	WG 16	IEC 62325	Standards related to energy market communications
IEC TC 57	WG 13	IEC 61970	Energy management system application program interface (EMS-API)

2.1.4 Smart Grid Architecture Model (SGAM)

The SGAM is one of the most emphasized smart grid architecture frameworks in Europe. It represents three important aspects of a smart grid application which are as follows: physical electrical process, information management and interoperability aspect (Figure 2.3). In addition, the SGAM has a three-dimensional matrix model, which consists of domains, zones and interoperability layers of smart grid applications (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012, p. 30).

The physical electrical process in the SGAM represents the electricity supply chain which five domains (from 1 to 5). Those domains include customer premises, DER, distribution, transmission and bulk generation.

Information management consists of six levels of a power management system (from layer a to f). These layers include process, field, station, operation, enterprise and market respectively. According to (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012), layers a to d (process, field, station and operation) function to manage the real time application of the power system, whereas layers e and f (enterprise and market) handle the economic operational of the power system.

The interoperability layer of the SGAM has five components (layers A to E). These include the component layer, the communication layer, the information layer, the function layer and the business layer. Furthermore, these layers emphasize the interoperability of information exchange among technical, informational and organizational interoperability contexts of smart grids (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012).

In this context, the connection of physical devices and actors (in component layer (A)) as well as their protocol communications and mechanisms (in communication layer (B)) are applied. The implementation of this technical interoperability context of smart grids, provides smart grids the ability (through information layer (C) with model data) to provide information objects and exchanges so that function layer (D) as well as business layer (E) can work efficiently.

As an example of smart grid application, a VPP could also adopt the SGAM. As an example of the implementation of SGAM in a VPP is the VPP model built by (Etherden et al., 2016) using IEC 61850 and CIM standards. The SGAM was used to formulate and map VPP requirements as well as its component interactions. It was found that the application of SGAM was able to support the forming of VPP and its functionalities in the DER integrations.

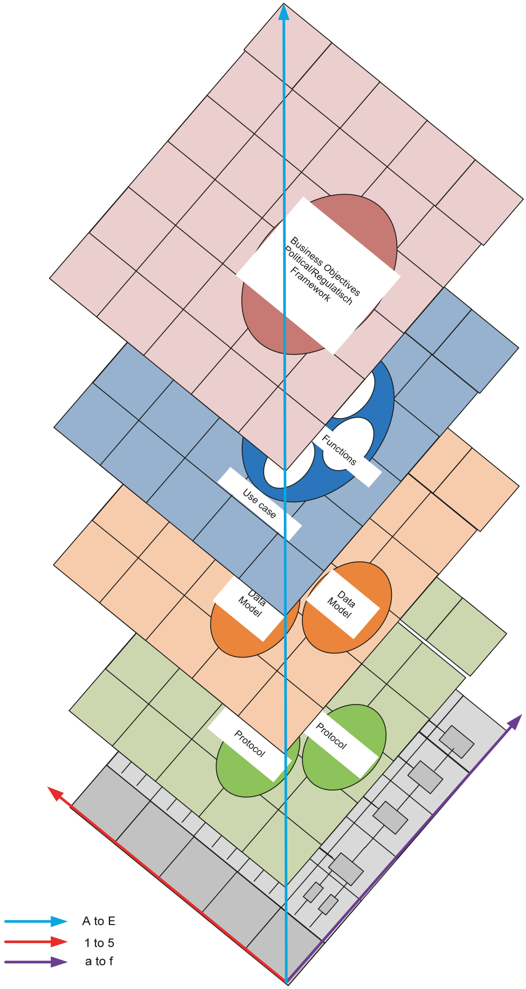


Figure 2.3. SGAM layers. The interoperability layers from A to E show the layers of component, communication, information, function and business respectively. In the domains, layers 1 to 5 show customer, DER, distribution, transmission and generation respectively. In the zones, layers a to f shows process, field, station, operation, enterprise and market respectively.
Source: Adapted from (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012, p. 30).

2.2 DER including energy storage

2.2.1 PV system

A PV system generates electricity through photovoltaic effect where sunlight is directly converted into electricity. The process taking place in a semiconductor material, so called solar cell, is absorbtion of photon energy into energized electrons. Technologies used to generate power from sunlight are made from silicon, thin-film and concentrating PV (IEC, 2012, p. 39). Electricity is generated when an external circuit is connected and the energized electrons flow as Direct Current (DC) electricity. Power production from cells or modules depends on a certain level of solar irradiation. Maximal power achieved in a PV module is characterized by a maximal point obtained from a Current (I)- Voltage (V) curve (Freris and Infield, 2008, p. 38). Intersections laying to the knee of the curves are the maximal points (Figure 2.4. S).

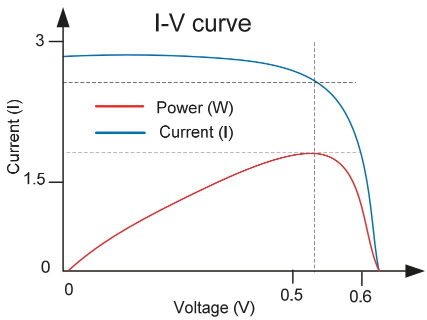


Figure 2.4. Sample of maximal power point in an I-V curve.
Source: Adapted from (Freris and Infield, 2008, p. 38).

In an on-grid application system, in order to achieve Alternating Current (AC), an inverter is used in a PV system (Figure 2.5.). Generated power from solar cells is converted to AC power and it is possible to directly feed into an electricity grid. In an off-grid application system, energy storage is used to store energy from PV and is then used as an energy buffer. In an off-grid application, PV power plant supplies local loads such as residential loads in rural areas which are not directly connected to grid.

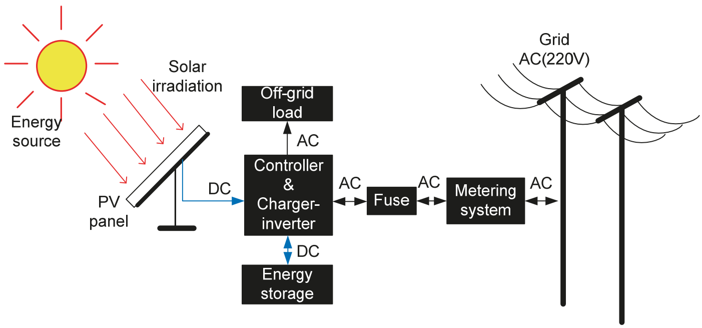


Figure 2.5. Typical configuration of an on-grid PV system.
Source: Adapted from (Partain and Fraas, 2010, p. 221).

Generated energy from PV is calculated in its peak energy E_{pv_peak}, corrected PV energy $E_{pv\_corrected}$, as well as in its annual energy E_{pv_annual}. Parameters used in this calculation are the total number of solar PV panels n with total panel PV area A_{pv} with each Watt-peak power per module W_{pv_peak}, solar panel efficiency η_{pv}, solar radiation G, annual average solar radiation G_{annual} and performance ratio or losses coefficient P. Correction factor cf determines the degree of the correction factor due to solar orientation and its inclination. Performance ratio is normally between 0,5 and 0,9 and represents all PV losses including inverter losses, cable losses, etc. According to (McFadyen, 2013), generated energy from PV is calculated by

$$E_{pv\_peak} = n\, A_{pv} \frac{W_{pv\_peak}}{1000} G\, \eta_{pv}$$

Equation 2.1

$$E_{pv\_corrected} = E_{pv\_peak}\mathrm{cf}$$

Equation 2.2

$$E_{pv\_annual} = n\, A_{pv} \frac{W_{pv\_peak}}{1000} \eta_{pv} G_{annual}\, P$$

Equation 2.3

2.2.2 Battery storage

A battery system (this refers to a rechargeable battery) in a PV plant is used as an energy storage and energy buffer. As an energy storage, a battery will store energy when there is excess power produced by a PV plant and will deliver power whenever it is needed. As an energy buffer, a battery maintains power availability from a PV plant to load and minimize instability power from intermittent RES into a stable and reliable power (Farret and Simões, 2006, pp. 262–299).

Types of energy storage

Many types of rechargeable battery have been used in a PV system, such as lead-acid batteries, nickel-cadmium batteries and lithium-ion batteries. (Farret and Simões, 2006, pp. 262–299) presented comparisons of different types of batteries including other energy storages such as ultra-capacitor and Compressed Air Energy Storage (CAES). These comparisons are useful to find an optimum battery type for a desired application e.g. off-grid residential power backup (Table 2.2.).

Table 2.2. Types of electric storage system.

Source: Adapted from (Ralon et al., 2017, pp. 40–44).

	Types	Rated Power (MW)	Discharge time (hr)	Characteristics
Large scale				
	Pumped hydro sto-rage	~500-~7000	~10-~100	Long discharge time, for large scale application
	Com-pressed air energy storage (CAES)	~1-~700	~2-~60~	Long discharge time, for large scale application , load leveling, spinning reserve, potential for DER
Medium scale bat-tery				
	Sodium Sulfur (Na-S)	~1-~100 ~3-~8	~6-~20 ~0,008-0,01	High cost, Safety concern, load lev-elling, spinning reserve
	Lead Acid (L/A)	~1-~100	~0.008-~10	Short lifetime, DER suitable,
DER sui-table				
	Lithium-Ion (Li-ion)	~0,005-~4	0,1-~20	DER suitable, po-tential for power quality support
	Nickel Me-tal Hybrid (Ni-MH), Nickel Cadmium (Ni/Cd)	~0,01-~40	~0,01-~10	DER suitable, ap-plicable for load leveling and spin-ning reserve
Others				
	Vanadium Redox (VR)	~0,07-~10	0,8-10	Potential for DER
	Double Layer Capacitor	~0,7-~60	~0,0003-~0,009	Applicable for power quality support

	Zinc bromine (Zn-Br)	~0,1-~0,7	~0,8-~4	Applicable for load leveling and spinning reserve
	Flywheels	~0,09-~10	~0,002-~0,9	Applicable power quality support

On a battery storage system application, parameters that need to be considered are including the state of charge SoC_{bat}, the depth of discharge DoD_{bat} and the battery efficiency η_{bat}. Battery efficiency represents the efficiency of battery in terms of its energy exchange in a battery or discharging/charging voltage efficiency $V_{bat\_discharge}$ / V_{bat_charge} and its Coulombic parameters $Q_{bat\_discharge}$/ Q_{bat_charge} . These paramaters are calculated using the following formulas:

$$SoC_{bat} = \frac{E_{bat\_available}}{C_{bat}V_{bat}} 100\%$$

Equation 2.4

$$DoD_{bat} = \frac{C_{bat}V_{bat} - E_{bat\_available}}{C_{bat}V_{bat}} 100\%$$

Equation 2.5

$$\eta_{bat} = \frac{E_{bat_{out}}}{E_{bat_{in}}} 100\%$$

Equation 2.6

$$\eta_{bat} = \frac{V_{bat_{discharge}}\, Q_{bat_{discharge}}}{V_{bat_{charge}}\, Q_{bat_{charge}}} 100\%$$

Equation 2.7

Whereas, $C_{bat}\,V_{bat}$ represents designed battery energy E_{bat} which is rated in terms of battery capacity C_{bat} (in Ampere Hour) and nominal voltage V_{bat} . Typical voltage for battery capacities are 20 AH, 100 AH, 200 AH and nominal voltages are 12 V, 24 V, 48 V or 96 V.

Methods to charge batteries

According to (Crompton, 2000), there are at least five basic methods to charge batteries (including pulse, random and float charge) and at least three different charging speeds; slow (at a rate of 0.1 of battery capacity), quick (at a rate of ~0.3 of battery capacity) and fast charge (at a rate one of battery capacity). Commercially, it is common that a battery charger applies Constant Voltage (CV), Constant Current (CC) and/or combined CV-CC (named as Constant Power or CP). In a typical battery charging application with constant current (Figure 2.6.), cell voltage will gradually increase until it reaches a steady level or its maximum cell voltage. Once maximum cell voltage is achieved, the current rate will gradually decrease until the charging process is stopped.

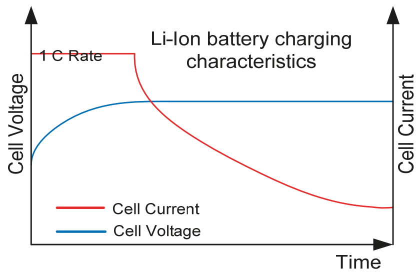


Figure 2.6. Charging characteristic.
Source: Adapted from (Crompton, 2000).

Apart from these charging characteristics, one issue that should be considered is the size of the battery charger. According to (Jancauskas and Kelly, 1996), there are still several missing perceptions regarding the design of a battery charger size. The inaccurate sizing of a battery charger (represented by charging Current) which is based on different load requirements of operating voltage, such as for the highest continuous and non-continuous load of battery, may lead to a power failure during power recovery. It has also been recommended to include the DC load calculation from system faults in the sizing of a battery charger.

In addition to this, the following parameters are relevant in defining battery performance (Farret and Simões, 2006, p. 265):

- capacity or availability to store energy (in Joule or Watt hour),
- specific energy or amount of energy stored per mass (in Watt hour/kilogram),
- energy density or amount of energy stored per volume (in Watt hour/m^3),
- specific power or amount of power per mass (in Watt/kilogram),
- efficiency (physically or electrically),
- recharge rate or rate time needed to store power,
- self-discharge or time needed to self discharge when unused,
- lifetime or service life of a battery,
- capital cost or initial cost from design to installation,
- operating cost.

2.2.3 Biogas power plant

<u>Biogas concept</u>

Biogas is mixture of gases composed from organic matter that are broken down through an Anaerobic Digestion (AD) process. The composition of biogas is methane (CH4), carbonic gas (CO_2) and traces (nitrogen N, Hydrogen H, and gas sulfidric H_2S). Based on (Al Seadi et al., 2008, pp. 21–23) there are 4 stages to produce biogas through an AD process (Figure 2.7.).

- Step 1, Hydrolysis, all materials (carbohydrates, fats, proteins) are broken down into fatty acids, glucose and amino acids using fermentative bacteria.
- Step 2, Acidogenesis, substances from step 1 are degraded into organic acids, CO_2, acetates and H_2 by the same bacteria in the hydrolysis step.
- Step3, Acetogenesis, previous substances from step 2 are degraded by acetogenic bacteria into CO_2, acetic acid and H_2.
- Step 4, Methanogenesis, methane and CO_2 are produced by methanogenic bacteria. In this process, methanogenic bacteria also work together with acetogenic bacteria to convert hydrogen and acids.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Equation 2.8

$$CH_3COO + H^+ \rightarrow CH_4 + CO_2$$

Equation 2.9

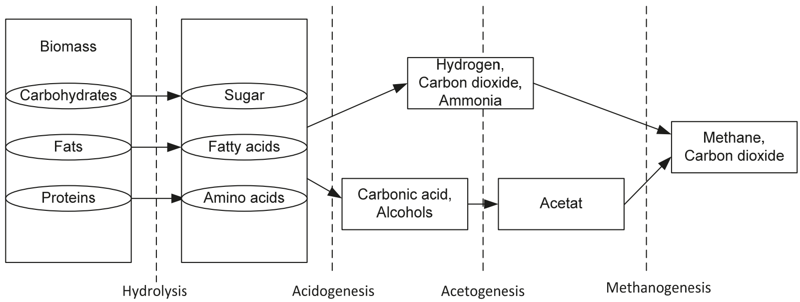


Figure 2.7. The Four steps of AD to produce biogas.

Source: Adapted from (Al Seadi et al., 2008, p. 21).

The Ideal temperature process for each step is varied. The Ideal process temperature to produce methane from methanogenesis bacteria is approximately 40°C (Al Seadi et al., 2008, p. 23). The process itself can be conducted as a batch, a continuous process, or a combination of both (Fachagentur Nachwachsende Rohstoffe et al., 2016, pp. 22–23). In a batch process, substrate is fed once at starting point of the process until no more biogas is produced from a specified substrate. There is no substrate exchange in this process. Whereas in a continuous process, substrate is fed continuously in order to discover biogas behaviors and its processes.

Biogas composition, gas and energy yield calculation

In order to calculate biogas composition, one method used is the Buswell formula (Deublein and Steinhauser, 2008, p. 89).

$$\mathrm{C_cH_hO_oN_nS_s} + \frac{1}{4}(4\mathrm{c} - \mathrm{h} - 2\mathrm{o} + 3\mathrm{n} + 2\mathrm{s})\mathrm{H_2O} \rightarrow \frac{1}{8}(4\mathrm{c} - \mathrm{h} + 2\mathrm{o} + 3\mathrm{n} + 2\mathrm{s})\mathrm{CO_2} + \frac{1}{8}(4\mathrm{c} + \mathrm{h} - 2\mathrm{o} - 3\mathrm{n} - 2\mathrm{s})\mathrm{CH4} + \mathrm{nNH_3} + \mathrm{sH_2S}$$

Equation 2.10

By typically using empirical data and by applying the Buswell formula, it is possible that a substrate consists of 50-75% CH_4, 25-45% CO_2 , 20-20.000 ppm H_2S, 0-1% Ammonia NH_3, 0-7% H_2O, <2% Nitrogen N_2, <2% O_2, and <1% Hydrogen H_2 (Fachagentur Nachwachsende Rohstoffe et al., 2016, p. 19).

An example gas and energy yield calculation from this Buswell formula is:

Assume that 100 kg, 85% wet content, of municipal waste has a composition of $\mathrm{C_{450}H_{2050}O_{950}N_{12}S_1}$ and using a method from (Banks, 2009) then the percentage $C_{percentage}$ and amount of biogas substrate C_{weight} can be calculated as follows:

$$C_{percentage} = \frac{450}{(450 + 2050 + 950 + 12 + 1)} = \frac{450}{3463} = 13\ [\%]$$

Equation 2.11

$$C_{weight} = \frac{15\ [\%]}{100\ [\%]} 100\ [\mathrm{kg}] \frac{13\ [\%]}{100\ [\%]} = 1{,}95\ [\mathrm{kg}]$$

Equation 2.12

This carbon content is then converted to biogas. In order to estimate the volume of each biogas composition using this formula, we need to know the amount of degraded biogas substrate or material. Assume 70% of this Carbon content is degraded to biogas with a composition of 60% CH_4 and 40% CO_2 then the amount of conveted $C_{degraded}$ to biogas is

$$C_{degraded} = \frac{70\ [\%]}{100\ [\%]} 1{,}95\ [\mathrm{kg}] = 0{,}14\ [\mathrm{kg}]$$

Equation 2.13

The amount of Methane $Methane_{weight}$

$$Methane_{weight} = Methane_{carbon_{weight}} \frac{\left(atomicweight_C + (4\ atomicweight_H)\right)}{atomicweight_C}$$

Equation 2.14

$$Methane_{weight} = \left(\frac{60\ [\%]}{100\ [\%]}\ 0{,}14\ [\mathrm{kg}]\right)\left(\frac{\left(12{,}011\ [\frac{\mathrm{g}}{\mathrm{mol}}] + \left(4\ \left(1{,}008\ [\frac{\mathrm{g}}{\mathrm{mol}}]\right)\right)\right)}{12{,}011\ [\frac{\mathrm{g}}{\mathrm{mol}}]}\right)$$

$$= \ 0{,}084\ [\mathrm{kg}] \frac{16{,}043\ [\frac{\mathrm{g}}{\mathrm{mol}}]}{12{,}011\ [\frac{\mathrm{g}}{\mathrm{mol}}]} = 0{,}112\ [\mathrm{kg}]$$

Equation 2.15

Therefore, if 1 mol gas at Standard Temperature and Pressure (STP, 273,15 K or 0 °C or 32 °F, 1 atm) conditions is 22,4 l, then for a volume of 0,112 kg of CH_4 $Methane_{vol}$ from 100 kg waste 85% wet content is

$$Methane_{vol} = \frac{112\ [\mathrm{g}]}{(12{,}011\ [\frac{\mathrm{g}}{\mathrm{mol}}] + (4\ (1{,}008\ [\frac{\mathrm{g}}{\mathrm{mol}}])))}\ 22{,}4\ [\frac{\mathrm{l}}{\mathrm{mol}}]$$

$$= \frac{112\ [\mathrm{g}]}{16{,}043\ [\frac{\mathrm{g}}{\mathrm{mol}}]} 22{,}4\ [\frac{\mathrm{l}}{\mathrm{mol}}]\ = 156{,}38\ [\mathrm{l}]$$

Equation 2.16

then 40% CO_2 from this waste substrate has the following CO_2 weight $CO2_{weight}$ and CO_2 volume $CO2_{volume}$

$$CO2_{weight} = \left(\frac{40\ [\%]}{100\ [\%]}\ 0,14\ [\text{kg}]\right)\left(\frac{\left(12,011\ [\frac{\text{g}}{\text{mol}}] + \left(2\ \left(15,999\ [\frac{\text{g}}{\text{mol}}]\right)\right)\right)}{12,011\ [\frac{\text{g}}{\text{mol}}]}\right)$$

$$= \ 0,056\ [\text{kg}]\,\frac{44,009\ [\frac{\text{g}}{\text{mol}}]}{12,011\ [\frac{\text{g}}{\text{mol}}]} = 0,205\ [\text{kg}]$$

Equation 2.17

$$CO2_{vol} = \frac{205\ [\text{g}]}{\left(12,011\ [\frac{\text{g}}{\text{mol}}] + \left(2\ \left(15,999\ [\frac{\text{g}}{\text{mol}}]\right)\right)\right)}\ 22,4\ [\frac{\text{l}}{\text{mol}}]$$

$$= \frac{205\ [\text{g}]}{44,009\ [\frac{\text{g}}{\text{mol}}]}\,22,4\ [\frac{\text{l}}{\text{mol}}] = \ 104,342[\text{l}]$$

Equation 2.18

Theoretically, biogas quantity and quality (in terms of Methane percentage) can be calculated using Busswell’s formula; however, some biogas parameters also influence biogas quantity and quality. According to (Fachagentur Nachwachsende Rohstoffe et al., 2016, pp. 12–19; Weiland, 2008, pp. 18–26), biogas quantity and quality are influenced by the process stability of chemical, biological and physical conditions of a digestion process (Table 2.3). Chemically and biologically, the following parameters profile are considered: wet content, redox potential, temperature, pH value, inhibitors, nutrients, oxygen level and FOS/TAC value. Physically, the following parameters are also considered: Organic Loading Rate (OLR), Hydraulic Retention Time (HRT), feeding rate and mixing process.

Table 2.3. Biogas process stability parameters requirements profile.

Source: Adapted from (Fachagentur Nachwachsende Rohstoffe et al., 2016, pp. 12–19; Weiland, 2008, pp. 18–26).

Type	Parameters	Requirement, respectively effect
Biological, chemical	Wet content	minimum 50%, digestion start when substrate has wet content
	Redox potential	Kept low (typically -0,1 V) for reduction and oxydation process and bacterial growth
	Temperature	Help bacteria to digest substrate, methanogenesis for mesophilic bacteria 32-42 °C and for thermophilic 50-58 °C
	pH value	Ensures digestion process: hydrolysis 4,5-6,3, for methanogenesis 6,8-8
	Nutrients	Related to the ratio of substrate composition C:N:P or C:N ratio, can increase or decrease pH value therefore inhibit the digestion process
	Oxygen level	Required for 1st& 2nd digestion process, but it must be kept low for 3rd and 4th digestion process
	inhibitor	Kept low; If N ratio is high, pH and NH_3 would be high therefore can inhibit digestion process
	FOS/TAC value	Volatile fatty acid over buffer capacity.
Physical	OLR	OLR influences (mostly negative correlation) volatile substrate VS degradation and biogas yield. OLR represents amount of VS per- (m^3 day) $[\frac{kg}{m3\ day}]$
	HRT	Diverse HRT value based on substrate types and must be at less as or as same as digestion process. It represents the average time of solid and liquids in the digestion process.
	Feeding rate	Feeding rate is related to OLR. When feeding rate is too high, methane forming would be interrupted.
	Mixing process	Optimum mixed substrate and digestion process helps the bacteria to digest the substrate optimally

Biogas power plant

A typical co-digestion configuration of a biogas power plant (Figure 2.8.) in order to generate electricity consists of (1) a control room, (2) a feeding storage, (3) a feeding system, (4) a co-substrate storage from biowaste, (5) a digester, (6 and 8) biogas storages, (7) a second digester (a digestate storage), (9) a Combined Heat and Power (CHP) system, (10) a transformer and (11) a grid connection. All biogas plants components are connected to each other based on their purposes: SCADA lines, heating lines, power lines, and feeding lines. SCADA lines manage the SCADA information processes in the biogas power plants which include measurement lines for biogas parameters (pH value, gas quantity, etc), control and command lines to machines (stirring, pumps, CHP, etc) from a control room. Heating lines connect the heating system of a biogas power plant. Feeding lines connect feeding storage including co-substrate storage to the feeding system and digester. Power lines connect biogas (Methane) to a CHP system and its generated power to a grid system.

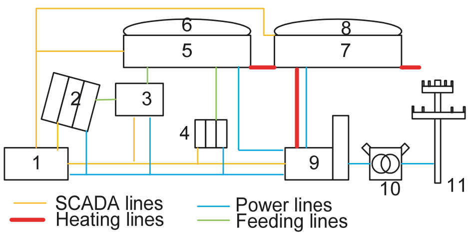


Figure 2.8. Typical co-digestation biogas system configuration.

Source: Adapted from (Al Seadi et al., 2008, p. 62).

Controllers and monitoring systems in biogas power plants (Figure 2.8.) are required to monitor and control biogas processes and its performance including biogas process stability. As a minimum requirement, some of these biogas parameters including type of substrate, temperature, pH value, gas quality and quantity need to be controlled and monitored.

Generated electrical energy from biogas $E_{biogas_{el}}$ and generated thermal energy from biogas $E_{biogas_{th}}$ from CHP machines is calculated by considering biogas quantity Q_{biogas}, biogas calorific value CV_{biogas}, electrical CHP efficiency $\eta_{CHP_{el}}$ and thermal CHP efficiency $\eta_{CHP_{th}}$.

$$E_{biogas\_el} = Q_{biogas} CV_{biogas} \eta_{CHP\_el}$$

Equation 2.19

$$E_{biogas_{th}} = Q_{biogas} CV_{biogas} \eta_{CHP_{th}}$$

Equation 2.20

Generated electrical energy in a biogas power plant can also be conducted by considering its methane content $Q_{methane}$ and methane calorific value $CV_{methane}$.

$$E_{methane_{el}} = Q_{methane} CV_{methane} \eta_{CHP_{el}}$$

Equation 2.21

As an example to calculate E_{biogas_el} , E_{biogas_th} and $E_{methane\_el}$ as follows:

For amount of biogas Q_{biogas}1 m^3 (assumed 1 m^3 has CV_{biogas} 22 Mega Joules), $Q_{methane}$1 m^3 (assume 1 m^3 CH_4 has $CV_{methane}$36 Mega Joules), η_{CHP_el}40%, η_{CHP_th}50% and CHP losses 10 % (by considering 1 W = 1 Js^{-1})

$$E_{biogas\_el} = \frac{40[\%]}{100[\%]} \frac{22\ [\mathrm{MJ}]}{\left(\frac{1\ [\mathrm{J}]}{1[\mathrm{Ws}]} \frac{3600\ [\mathrm{s}]}{1\ [\mathrm{h}]} \frac{1000\ [\mathrm{W}]}{1\ [\mathrm{kW}]}\right)}$$

$$E_{biogas\_el} = 0{,}4 \frac{22\ [\mathrm{MJ}]}{\left(\frac{3{,}6\ [\mathrm{MJ}]}{[\mathrm{kWh}]}\right)}$$

$$E_{biogas\_el} = 2{,}4\ [\mathrm{kWh_{el}}]$$

Equation 2.22

$$E_{biogas\_th} = \frac{50[\%]}{100[\%]} \frac{22\ [MJ]}{\left(\frac{1\ [J]}{1[Ws]} \frac{3600\ [s]}{1\ [h]} \frac{1000\ [W]}{1\ [kW]}\right)}$$

$$E_{biogas\_th} = 0{,}5 \frac{22\ [MJ]}{\left(\frac{3{,}6\ [MJ]}{[kWh]}\right)}$$

$$E_{biogas\_th} = 3{,}06\ \mathrm{kWh_{th}}$$

Equation 2.23

$$E_{methane\_el} = \frac{40[\%]}{100[\%]} \frac{36\ [MJ]}{\left(\frac{1\ [J]}{1[Ws]} \frac{3600\ [s]}{1\ [h]} \frac{1000\ [W]}{1\ [kW]}\right)}$$

$$E_{methane\_el} = 0{,}4 \frac{36\ [MJ]}{\left(\frac{3{,}6\ [MJ]}{[kWh]}\right)}$$

$$E_{methane\_el} = 4\ [\mathrm{kWh_{el}}]$$

Equation 2.24

If CH_4 volume is 156,38 l then:

$$E_{methane\_el} = 4\ [\frac{\mathrm{kWh_{el}}}{\mathrm{m^3}}]\ 0{,}15638\ [\mathrm{m^3}] = 0{,}626\ [\mathrm{kWh_{el}}]$$

Equation 2.25

2.3 Power markets

2.3.1 Overview of power market structures in Germany

According to (Konstantin, 2013, European Power Exchange, 2015, epexspot, 2020), there are different trading mechanisms to deliver electricity power in the German market, including through power exchange and through OTC market. Through the power exchange mechanism, it is possible to deliver power products to the European Power Exchange (EPEX) and the European Energy Exchange (EEX) market. The EPEX market is related to the SPOT market which consists

of Intraday and Day-Ahead markets. In addition, the EEX market is related to future markets which consists of futures and options market.
Through Over The Counter (OTC), it is possible to deliver every kind of power product besides of EPEX and EEX and is not limited by intraday, Day-Ahead, Futures or options power products .

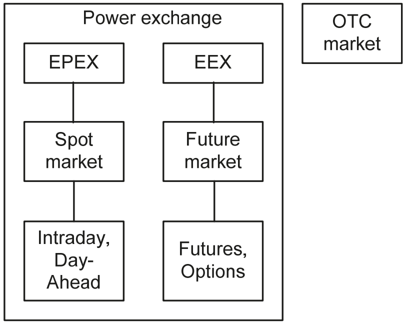


Figure 2.9. Power markets in Germany.

Source: Adapted from (Konstantin, 2013, European Power Exchange, 2015, ep-exspot, 2020).

In addition, according to (European Commission, 2017, p. 13), the German electricity market is the largest electricity market in Europe. Until September 2017, Germany had more than 60 % of the total monthly traded electricity volume of 1,322 TWh (including exchange and OTC). This volume is followed by the Nordic markets, the UK and France over the last months. In Germany, until Q3 in 2017 in Germany there were more than 1,200 TWh OTC markets and about 400 TWh exchange markets (incl. SPOT market) on most European markets. Germany also took a significant role in cross border trade electricity activity within Central Western Europe (Germany, Netherlands, France, Luxemburg, Belgium, Austria, Switzerland). For several years, only Central Western Europe had exported their electricity to the Nordic, the Baltic and other European countries.

2.3.2 EEX and EPEX power products

According to (Konstantin, 2013 and European Power Exchange, 2015) EEX and EPEX power products (Table 2.4) are classified into time-based contracts or block contracts. Time-based contracts refer to SPOT Market products which are delivered based on their occurrence in the markets e.g. Middle-Night (01:00 a.m. to 04:00 a.m.). Whereas, block contracts are used for SPOT Market products which are delivered with constant power over a period. There are different power delivery mechanisms in the SPOT Market (auction handle type (Day-Ahead) and/or continuous handle type (as Intraday)) and Termin Market. In the SPOT Market, especially the DA market, the market participants deliver their ability to sell/buy (including volume in MWh and price in €/MWh) market products up to 12:00 a.m. on the previous day. After that, demand and supply match making processes can be conducted. Whereas, in the future market, the handling of market products takes place within a specific area and a specific time. The contractors (classed as handlers or market participants) receive the contracts once their buying/selling proposals are approved. If the SPOT market price at any due date is higher/lower than the contracted price, the price difference should be considered (received or paid back to/by the contractors).

Table 2.4. Bid classifications.
Source: Adapted from (Konstantin, 2013 and European Power Exchange, 2015).

No.	Bid name	Time (from - to)	Contract type	Market type
1	Middle-Night Block	01:00–04:00	Time-based	SPOT
2	Early Morning Block	05:00–08:00	Time-based	SPOT
3	Late morning Block	09:00–12:00	Time-based	SPOT
4	Early Afternoon Block	13:00–16:00	Time-based	SPOT
5	Rush Hour Block	17:00–20:00	Time-based	SPOT
6	Off-Peak 2 Block	21:00–24:00	Time-based	SPOT
7	Baseload Block	01:00–24:00	Block	SPOT
8	Peakload Block	08:00–20:00	Block	SPOT
9	Night Block	01:00–06:00	Time-based	SPOT
10	Off-Peak 1 Block	01:00–08:00	Time-based	SPOT
11	Business Block	09:00–16:00	Time-based	SPOT
12	Off-Peak Block	01:00–08:00	Time-based	SPOT

		& 21:00–24:00		
13	Morning Block	07:00–10:00	Time-based	SPOT
14	High Noon Block	11:00–14:00	Time-based	SPOT
15	Afternoon Block	15:00–18:00	Time-based	SPOT
16	Evening Block	19:00–24:00	Time-based	SPOT
17	Sun Peak Block	11:00–16:00	Time-based	SPOT
18	Weekly Peak-load Block	08:00–20:00 (Monday–Friday)	Block	SPOT or Futures/Termin
19	Weekly Base-load Block	01:00–24:00 (Monday–Sunday)	Block	SPOT or Futures
20	Base-Futures	01:00–24:00 Daily, weekly, monthly, quarterly, yearly	Block or time-based	Futures
21	Peak-Futures	08:00–20:00 Daily, weekly, monthly, quarterly, yearly	Block or time-based	Futures
22	Off-Peak Futures	Monthly, quarterly, yearly	Block or time-based	Futures
23	Weekend Futures	Monthly, quarterly, yearly	Block or time-based	Futures
24	Intraday-Floor Futures	Daily, weekly, monthly, quarterly, yearly	Block or time-based	Futures
25	Intraday-Capacity Futures	Daily, weekly, monthly, quarterly, yearly	Block or time-based	Futures

3 Literature Review

This chapter analyses the DER challenges in the energy transition in Germany which is mainly triggered by RES-based DER, followed by presenting potential solutions from integrated RES-based DER. The potential solutions include the possibility of balancing energy through flexible energy resources and VPP as a RES-based DER integration solution. Moreover, the technical potential to integrate RES-based DER and its integration concept in a VPP are also analysed.

3.1 DER challenges and flexible generations

High DER penetration on a grid system

Despite the development of the RES in Germany being seen as a positive step forward, there are at least three technical challenges that influence RES development progressing. These challenges concern the technical frameworks of RES, the natural behavior of RES, as well as due the surplus power from high share RES.

The first challenge is related to the reliability of generated power from intermittent RES. The generated energy from Wind and Solar PV are weather dependent, thus posing additional challenges to the increasing share of RES in Germany. The fluctuating energy causes a challenge for RES to provide reliable power to the market according to load requirements. The risks of network stability from a high share of RES in the grid will also rise due to this behavior.

The second challenge is that not all installed RES-based power plants are able to enter and directly feed their generated power to the grid and power market. Currently, the RES based power plants feed their electrical power independent from load demands. This is due to the technical limitations and regulatory frameworks. Technical limitations are related to the ability of power plants to be integrated in the grid using the assistance of additional technical devices, such as a smart metering system. In regulatory frameworks, there are technical frameworks which every power plants should obey e.g. the Renewable Energy Act (EEG). Moreover, for those who do not have experience in participating in energy markets, how to choose which markets to enter and the technical requirements to apply market integration remain unclear.

The third challenge is the balancing mechanism due to the high share of the RES. With a high portion of RES in the grid, the excess power is a problem to be solved. The increasing excess power from a high share of RES in the grid influences a price drop in the liberalized market (Pollitt and Anaya, 2016), therefore raising the pressure to find a new method of power market in the grid (Kopp et al., 2012). Some solutions, which are attempting to address this issue, are a power export-import mechanism with neighboring areas, the utilization of energy storage and balancing power plants and the utilization of smart grid technologies like a VPP.

A high penetration of DER in the grid may cause technical and economical issues, therefore advance functions in smart grids are required e.g. the utilization of balancing energy strategies and a Virtual Power Plant (VPP).

Biogas in Germany and its potential for balancing power

Until 2016, in Germany, biogas contributed around 16,9 % of the total RES-based electricity generation portfolio in Germany (The Federal Ministry for Economic Affairs and Energy, 2017, p. 9). With this relatively high share in contribution, biogas has a potential role in providing a balancing of power plants from intermittent RES as well as for load demand.

Balancing power from biogas is done by balancing power from intermittent RES and/or balancing load demands. In balancing power from the RES-based power plants, biogas is able to provide positive/negative values balancing from Wind or PV power plants (Güntert, 2013; Hahn et al., 2014; Thrän, 2015; Thrän and Krautz, 2014). (Energiewende, 2013, pp. 11–12) believed that techno-economically adapted biomass-based power plants in the future will be able to provide a flexible role in power balancing.

In balancing load demands, biogas is able to support the grid as a back-up power supply. According to Laleman et al (2012), biogas should be able to support the grid as a back-up power supply, to respond to demands, to support in load-shedding, and to minimize power generation costs.

Biogas together with Wind is suitable for balancing energy for partial load operation specially for secondary balancing market (Kohler et al., 2010, p. 21). Using applied ICT technology such as a VPP, this power balancing from biogas allows the minute reserve power, including the possibility to provide positive/ negative energy balance (Keitlinghaus, 2011).

(Braun et al., 2014; Hochloff and Braun, 2014; Lauer et al., 2017) revealed that compared to conventional power generations, applying flexible biogas provides greater economic benefits as well as increase the RES integration level in the grid.

To summarize, the relevant biogas roles related to intermittent supply and electricity markets are:

- Improving integration of intermittent RES in future energy system.
  Biogas as a flexible power provider is able to balance grid frequency, residual load, weather dependent- and seasonal load demand (Dotzauer et al., 2015; Gils, 2015) based on technological approaches mentioned by (Szarka et al., 2013).
- Providing flexibility, such as demand-oriented power supply.
  According to (Szarka et al., 2013) there are some technical options and possibilities for biogas to provide flexible power to be sold in the future, SPOT and in the control energy market. These options are related to the entire biogas process, from substrate to the grid injection management.
- Profit optimization and the GHG emission reduction

  Economic assessments, profit optimization, and the GHG assessments integrating flexible biogas to other RES, as well as providing flexibility from biogas in power generation, has been studied so far. Operating CHP units in a fully flexible mode is more economically feasible than semi flexible or constant (Lauer et al., 2017). However, the revenue among them is not significantly diverse. In the long-run, with simulated electricity prices in SPOT and control power market, (Loßner et al., 2017) found that the use of flexible generations, including battery storage power control in the VPP, could increase the current trading revenues up to 30 % in 2030.

Flexible generation from biogas

Current developments of biogas technology have enabled the biogas plant to produce flexible biogas. Flexible energy generation is determined by the ability of power generation to change its output based on certain controls. Flexible biogas power plants mean greater flexibility of biogas to produce electrical energy based on load demand.

The concept of demand-driven biogas for demand-driven electricity has been reviewed (Hahn et al., 2014). Some of concepts provided are using storage (including grid injection), feeding management, CHP management and flexible energy generation from biogas plants.

In the biological process, many researchers have investigated demand driven biogas potential by influencing Anaerobic Digestion (AD) processes to produce flexible gas production. Regarding this concept, (Sonnleitner and Eckel, 2014) specifically the influence of microbial activities in producing flexible biogas production. In addition to this (Ganagin et al., 2014) also proposed new configuration concepts for producing flexible biogas. Two stages of biogas configuration were built which consist of a Continuous Stirred Tank Reactor (CSTR) and a fixed-bed reactor. A CSTR is equipped with biogas storage to produce constant biogas production. A fixed bed reactor is used for generating flexible biogas production.

In order to make use of the biogas ability as a demand driven power plant, the specified power management is required so that flexible biogas solely or combined with other RES-based power plants is able to provide power based on power markets as well as to cover the residual load from intermittent of the RES.

PV system in Germany and its potential to answer load demands

In Germany, potential power provided by PV systems until 2016 was 20,20 % (one-fifth) of 188,2 billion kWh of the total electricity supply from Renewable Energy (RE) (The Federal Ministry for Economic Affairs and Energy, 2017, p. 9). Apart from quantitative calculations, qualitatively, PV has potential to support services in the grid. Some of the grid support services from PV include peak load and ancillary service supports. (Keitlinghaus, 2011, p. 4) mentioned that a PV system has the ability to answer peak and medium load based on high power production at noon. A PV system also has good capabilities to deliver ancillary services such as power/voltage control, congestion management, reduction of power losses, and improvement of power quality (Corera, José and Maire, 2009, p. 14).

However, PV system’s power production relies on weather conditions, particularly solar irradiation. Therefore, there is a challenge for supporting electricity reliability. The challenge remains how to deliver reliable generated power from PV systems to the grids. Despite PV power production changing slowly and is more predictable compared to wind power plants, forecasted PV cannot guarantee the reliability of PV power. In the relative specified area e.g. installed roof PV, it is still difficult to provide a stable frequency (Freris and Infield, 2008, p. 86).

Residual load from PV

In order to balance fluctuating electricity production from a PV system, two methods are applicable in utilizing energy storage and adapting the availability of power from PV. Utilizing energy storage helps grid to increase energy reliability from intermittent RES, such as from PV by smoothing and balancing power (Garcia et al., 2013; Heide et al., 2011).

Adapting the availability of power from PV is applicable through PV forecasting system and simultaneuos control of a PV system in a VPP. In this method, (Al-Zu'bi, 2011) proved that heat and electricity load demand in a region could be answered by combining a PV system and a biogas power plant. Residual load from a PV system is tackled by a biogas power plant within certain energy management, such as substrate feeding management. Additionally, (Agsten et al., 2012) proposed a VPP as a solution to cope with fluctuating supply from PV and to provide reliable power to the grid.

3.2 VPP for integrating and marketing power plants

3.2.1 VPP definition

Up to now, there is no exact definition and determination about VPP. Many researchers such as (Corera, José and Maire, 2009; Saboori et al., 2011; Zwaenepoel, 2016) distinguish VPP into 2 categories: Technical VPP and Commercial VPP (Table 3.1). A TVPP is mainly focused on the technical services of a VPP in the grid, integrates DER physically and is not directly focused on the electricity market developments such as price developments. A TVPP takes a role in helping system operators (TSO and DSO) to manage energy in its specific location. On the other hand, a CVPP is directly related to the physical integration of DER in a VPP, but rather to trade the energy from DER in the electricity markets. A CVPP is able to influence the price in the electricity markets, as CVPP can directly take a decision to provide services based on, for example, price signals from electricity markets.

Table 3.1. Scope and boundaries VPP.

Source: Adapted from (Corera, José & Maire, 2009; Saboori et al., 2011; Zwaenepoel, 2016).

	VPP	
	Technical VPP	**Commercial VPP**
Components	Generations and Consumers incl. storages	Generations and Consumers incl. storages
Aim	• To physically integrate DER into the grid • To aggregate DER into a single unit of power plant • To manage incl. control of technical services of DER to system operator	• To trade energy or marketing DER values (profit oriented) in energy markets • To aggregate and to enable active participation in small generators and producers in the energy markets (to min. 0,1 MW for 15 minutes) • To possibly possibility influence the market signals
Constraints or limitations	TVPP functions are geographically limited	• Depends on operational area of energy trading • Mainly focus on financial aspect of energy trading of CVPP participants • Not necessary to handle physical (technical) energy imbalance
Principle of operation	Optimizing technical services of TVPP participants in the grid	Optimizing benefits (profits) of energy portfolio in energy markets
Operational requirements	• TVPP profiles prediction • Control management of TVPP participants • Real-time measurements of energy	• CVPP profiles prediction i.e. 15-minutes profile • CVPP profiles submission to the system operator • real-time measurements of energy

3.2.2 VPP components

In many applications (Corera, José and Maire, 2009; El Bakari et al., 2009; El Bakari and Kling, 2011, 2010; Lombardi et al., 2009; Lukovic et al., 2010; Saboori et al., 2011; Vandoorn et al., 2011), VPP components should, at a minimum, consist of energy generation, ICT and energy storage.

An ICT-infrastructure of a VPP depends on the complexity of a VPP and the purpose of a VPP. Within an ICT I, there is a located controller and forecasting system as well as optimization for VPP application. In general, the functions of ICT components in a VPP are:

- network communication,
- collecting network data/metering,
- monitoring - optimization process and controlling power plant (Lorenz, 2012; Svetina and Nemček, 2011).

(El Bakari and Kling, 2010) presented the ICT of a VPP by implementing intelligent devices and smart meters, wireless, cable connections, central control computers and software. The software used in a VPP is varied and has no preference standard. In some applications such as in (Hochloff and Schreiber, 2012, p. 8), MATLAB was used to simulate a VPP with CPLEX software for its optimization algorithm.

(Decker and Lyngby, 2008; DONG Energy, 2013; Hansen et al., 2013) presented the ICT of a VPP by implementing a database software, data providers, web hosts and developing software such as Microsoft Visual Studio. By implementing Windows OS-based software specifically Microsoft Communication and Windows Workflow Foundation they were able to reduce the complexity of the ICT implementation in the VPP.

3.2.3 VPP control types

According to (Decker and Lyngby, 2008; Setiawan, 2007; Vandoorn et al., 2011; You, 2010) the control types of a VPP can be categorized in three criteria; centralized, distributed and fully distributed controlled VPP (Figure 3.1.).

- Distributed control type: a VPP has the ability to control local controllers as well as the DERs (loads, power generators, or energy storages). In distributed control, huge amounts of data are exchanged between local controllers and central control. (Dimeas and Hatziargyriou, 2007) assumed that a centralized VPP is sometimes not easy to be implemented due to non-technical issue such as owner willingness to share production data. However, (Mabanga et al., 2011) argued that VPP users have advantages from this configuration especially regarding fast implementation and system reliability.

- Fully distributed control type: a VPP has the ability to control local controller but has no direct access to DER. In addition, in this type of VPP, central control only works for simple task such as monitoring and providing updated status to the local controllers. In this controller, central control is able to receive and adapt increasing number of local controller in the network.
- Centralized control type: a VPP minimizes its dependency from the local controller by establishing direct access to control the DER. In this control type, DER operator functions are sometimes by-passed by the VPP operator.

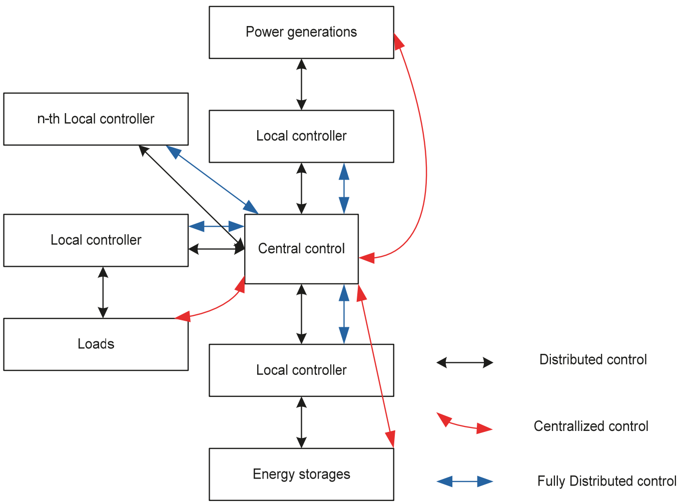


Figure 3.1. VPP control types.

Source: Adapted from (Decker & Lyngby, 2008; Setiawan, 2007; Vandoorn et al., 2011; You, 2010).

In addition to those three control types, (Setiawan, 2007; Thavlov and Bindner, 2015; You, 2010) proposed direct-based and price signal-based mechanism to control VPP. With direct control, it is possible for a VPP to minimize error in a shorter time interval. A direct control in a VPP can be achieved by weighting optimization (Thavlov and Bindner, 2015). Whereas, price signal-based control enables VPP to respond to any required power based on prices developments in the power markets.

3.2.4 VPP benefits for future energy generation

The benefits of using a VPP system is assigned into technical and non-technical aspects for different VPP's stakeholders (Table 3.2). Regarding the technical aspects, a VPP helps stakeholders to ensure the reliability of power services to the grid e.g. the reliable power. While, with non-technical aspects, VPP presents the ability of different stakeholders to realize their target such as economic optimization in the power markets and RES system developments.

Table 3.2: Benefits of a VPP system for different stakeholder.
Source: Adapted from (Corera, José and Maire, 2009; Decker and Lyngby, 2008; El Bakari et al., 2009; Hansen et al., 2013; Lombardi et al., 2009; Nezamabadi and Gharehpetian, 2011; Olejnczak, 2011; Saboori et al., 2011; Siemens AG, 2013; Vandoorn et al., 2011).

Stakeholders	**Benefits**
DER operator/owner	Technical and economic benefits from participating the market
Distributed System Operator (DSO)/Transmission System Operator (TSO)	Ensures grid reliability
Policy makers	Supports the RE developments and power system transformations
Suppliers and aggregators	Creates a new business model in power systems and ensures aggregation reliability

For VPP or DER owners: a VPP enables DER owners to actively participate in electricity markets and receive benefits from it (Nikonowicz and Milewski, 2012). Operators also have flexibility to deliver markets products based on the most techno-economic benefits. For instance, due to the flexibility of biogas power plants and competitive prices, the operators have the possibility to deliver one or more products to the electricity markets. Thus, DERs in the VPP have the possibility of increasing benefits from marketing their generated power (Petersen et al., 2013). Compared to the independent and non-market-oriented, DER in the VPP gains more revenues (Loßner et al., 2017).

For energy managers, suppliers or aggregators i.e. DSO/TSO: VPP provides easiness to meet supply and demands (Houwing et al., 2009). VPP enables DSO to provide system state estimator between load and generation. (Koraki and Strunz, 2018) proposed a VPP as service control to overcome distributed network constraints for diverse resources.

In the TSO, the VPP supports voltage control, tertiary reserve management and market participators (Corera, José and Maire, 2009). The VPP is also a solution for variable loads in networks and for problems such as balancing power, congestion management, voltage profile regulation and oscillation clearance (Kirrmann, n.d.; Saemisch, 2012; Siemens AG, 2013; Vandoorn et al., 2011).

For policy makers: The application of a VPP enables current power transition to meet future grid requirements e.g. network expansion. A VPP supports network expansion capability, especially as increasing RE penetration into grids drives a transformation from centralized generation to distributed generation power (El Bakari et al., 2009; El Bakari and Kling, 2010; IEC, 2012; Lorenz, 2012).

For electricity markets: A VPP provides many trading options for DERs in various electricity market frames such as Day-Ahead and Intraday market (Plancke et al., 2015; Sowa et al., 2014). The trading options offered by a VPP depend on a VPP's parameters such as target, market orientation, and DER specifications (Pandžić et al., 2013). These trading options provide a good environment for consumers to have guaranteed energy security.

In different market frames, a VPP takes a significant role. In short term electricity markets, a VPP supports costs reduction (Arslan and Karasan, 2013; Houwing et al., 2009). In a reserve power market, a VPP helps to minimise the risk of losing power . In a mid-term and long-term electricity market, a VPP provides an increased security of supply with scheduling and planning

3.2.5 The VPP standards

The International Electrotechnical Commission (IEC) working group of Decentralized Electrical Energy Systems from International Electrotechnical Commission

(IEC) are currently working on the VPP standards; the IEC 63189-1 ED1 concerns a VPP's architecture and functional requirements and the IEC TS 63189-2ED1 concerns VPP use cases (IEC, 2020a, 2020b). In Germany, the Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE) and the Deutsche Kommission Elektrotechnik Elektronik Informationstechnik (DKE) are adopting these standards.

3.2.6 VPP implementations in the grid

Implementation of a VPP system in the grid is aimed at minimising intermittency generation from RES power plants. It is often said that the VPP consists of a combined power plant from intermittent energy generations and flexible energy generations including storage.

Some implementations of the RES-based DER in a VPP include the use of combined Wind and PV to increase DER penetration levels in the grid (Rodrigues and Estanqueiro, 2011) and to help pump storage system (Li et al., 2010). VPP based on biogas to provide grid services helps to balance wind power (Houwing et al., 2009) and participation in the power reserve. On the other hand, (Schloegl, 2010) integrated biogas, PV, wind, and local loads with energy storage from Regenerative Model Region Harz (RegModHarz) in a VPP to provide reliable power by utilizing flexibility of biogas and storage. In other applications, combined power plants in a VPP from (Hansen et al., 2013; Knorr et al., 2014) were able to provide an ancillary service to a grid.

3.2.7 Power management in a VPP

Power management in combined power plants

The management energy in a VPP is unique and depends on services that would be provided by a VPP. (El Bakari et al., 2009) reviewed the literature of future control management in a VPP including micro grids, smart grids, active networks and autonomous networks. For all these controls, one type configuration was based on hierarchical/layered controls as (Vandoorn et al., 2011)) and other researchers presented. In layered controls, network problems can be solved before being escalated to the higher layer, but application can be complicated.

Power management concepts in a VPP are applied in a computer- and a control-based management system called Supervisory Control and Data Acquisition

(SCADA). By implementing SCADA in a VPP, a VPP user is able to control and monitor the behavior of VPP.

(Kramer et al., 2010; Mabanga et al., 2011) analysed the management of energy in a VPP by giving prior notification and instantaneous reserve power (10 min to a Day-Ahead) to customers. Because of its connection to controllers of each power plant, as well as load demands, system frequency in a VPP could be controlled automatically (Zhang, 2011). This concept has effectively provided an available system reserve capacity for loads.

(Nezamabadi und Gharehpetian 2011) developed an Energy Management System (EMS) for VPP optimization in three scenarios. In the first scenario, each DER followed its own dedicated loads. Using this scenario, they found that there was a dependency on storage to save excess energy, but still a shortage in peak hours. In the second scenario, a VPP determines that DERs which have the minimum cost would answer load demands. In this scenario, VPP was limited by the use of available and cheapest energy provided by the DERs, thus leading to an increase in unmet loads. In the third scenario, a VPP combined a dedicated load and the minimum cost on its operation. In this scenario, a VPP found the most preferable system in order to answer load demands so that drawbacks from 1st and 2nd scenario could be overcomed.

Other management methods analysed by (Svetina and Nemček, 2011) were based on demand and distributed generators in order to answer load demands. Reducing peak loads and the peak management of a power plant are also optional strategies. However, to balance fluctuating energy generation in a VPP, storage systems or sufficient flexible capacity has to be included. (Al-Zu’bi, 2011; Bühler, 2012).

(Al-Zu’bi, 2011) managed the power of hybrid power plants in a VPP through the following points:

- Implementing power flow management by specializing the task of each power plant. Load was mainly covered by a PV system, a biogas plant handling residual load form a PV system, and a storage system was also used in order to:
    - store power when load was less than generated power from a PV system and a biogas plant.

  - deliver power when load was greater than generated power from a PV system and a biogas plant.

- Simulation of all power plant components; biogas processes, a PV system, load and generated power.
- Optimization of a biogas plant by substrate management to ensure biogas availability
- Some scenarios regarding the number of power generators such as more PV or more biogas plant.
- All management strategies were handled by MATLAB

Similar to (Al-Zu'bi, 2011), (Lombardi et al., 2009) used the same scenarios in order to manage energy but deployed different types of power plants and electrolyzers instead of batteries. However, these implementations were not yet explicitly applied in a VPP platform did not consider load demands in power markets. The method that integrates different power plants in the case was still missing.

In addition to this, the management of energy in a VPP needs a model of VPP components and a set of rules. These are required to improve a VPP's performance since in a practical implementation, not all the behaviors of a VPP's components are known and are uncertain factor. (Kramer et al., 2010) introduced VPP components modeling simulation using a Learning Classifier System (LCS) method that was aimed at managing storage and reserve power plants. The LCS method worked in manipulating a set of rules with load-supply prediction and genetic operation in a VPP. As the result, the fluctuation in energy supply was compensated by the readily available supply for total energy demand. Demand side management was also implemented in this method by considering price and urgency of load. Moreover, (El Bakari and Kling, 2010) found that, a VPP,by conducting energy flow management in a modified distribution network and by applying synchronous measurement, monitoring and control though intelligent devices, was able to provide a more flexible energy flow to the grid, thus ancillary systems and power quality services could also be provided.

Optimization methods

A comprehensive review of optimization methods in a VPP was previously undertaken by (Nosratabadi et al., 2017). Optimization methods in a VPP or combined power plant vary and depend on the complexity of a VPP or combined power plant system itself. There is no rule in choosing which method should be best applied. However, it is preferable to choose a well-known and well-proved optimization method for a VPP or combined power plant. Some of the popular optimization methods for power management in combined power plants include Mixed-Integer Linear Programming (MILP) and Mixed-Integer Nonlinear Programming (MINLP).

The MILP method finds an optimum solution from a linear objective function of integer-based variables and constraints. A MILP maximizes a function $f(x)$ for all x values which is constrained by:

$$A(x) \leq b$$

Equation 3.1

$$x \geq 0$$

Equation 3.2

where: A is a matrix and b is a vector.

A sample of the MILP method in a power generation is provided by (Kuzle et al., 2011) to find optimum cost for integrated power plants.

The MINLP method, on the other hand, is aimed at finding an optimum solution from a non-linear function $f(x)$ for all x values, which is subjected to (Equation 3.1) and (Equation 3.2). In some applications, a MINLP is combined with other optimization algorithm to increase the accuracy of the optimization solution. As an exampleof this method, (Mashhour and Moghaddas-Tafreshi, 2011) combined MINLP and Genetic Algorithm (GA) to find the optimum VPP's bidding strategy.

Aside from these two methods, there are other methods to manage a VPP which are based on economic analysis. For example, (Lucian et al., 2012; Toma et al., 2012) proposed technical influences in the power plants and a longer-term analysis. (Toma et al., 2012) argued that cost benefit analysis in the marketing of generated power from power plants through a VPP platform were able to gain economic benefits, specially in the long term. In addition, adjusting load percentage would also help VPP to cover load demands (Lucian et al., 2012).

3.2.8 Forecasting in VPP

Forecasting Model for power management

Forecast is used for power management in a VPP in order to generate input parameters, such as loads scheduling or developing scenarios. Forecast in a VPP is essential in order to minimize uncertaint factors, for example from less predicted PV power production and miscalculated power from a VPP’s energy management system. Some known forecasting models are, time series modeling, regression modeling, moving average modeling, exponential modeling, regression modeling, and Artificial Neural Network modeling.

Empirically, some studies were undertaken related to the forecasting model for power management. For example, (Al-Zu’bi, 2011; Born, 2001) (Al-Zu'bi 22 February /2012). (Al-Zu’bi, 2011) found that a scenario of power management could be completed through a simulation and forecast model to develop scenarios for answering load demand based on a PV plant and a biogas plant.

In addition, (Born, 2001) used the forecast of load, a PV system, and a wind system to help match making between load and supply. Supply and demand profiles were generated based on this modeling. At the end, these sample implementations could answer future load demand by including forecast methods in power management.

Furthermore, methods for forecasting load and supply is varied, but most researchers refer to the use of the Artificial Neural Network (ANN) due to its high accuracy (Alfares and Nazeeruddin, 2002). ANN is defined as an array of processors called neurons, which are highly connected to each other (Figure 3.2.). There are many applications of ANN in real world. ANN is useful to predict weather forecast, market, or learning a trend curve.

ANN is determined as its original name "neuron" and works by imitating neuronal structure working principle (Figure 3.2.). ANN is organized into different layers (input, hidden and output layer) which are working as nodes with specific activation functions to each other through interconnected links. The input layer is a layer which receives information from outside of the network. The hidden layer is a layer which connecting input and output layer to do weighting process in the network. The output layer represents the response of the ANN process to the information input. The number of layers is reconfigurable.

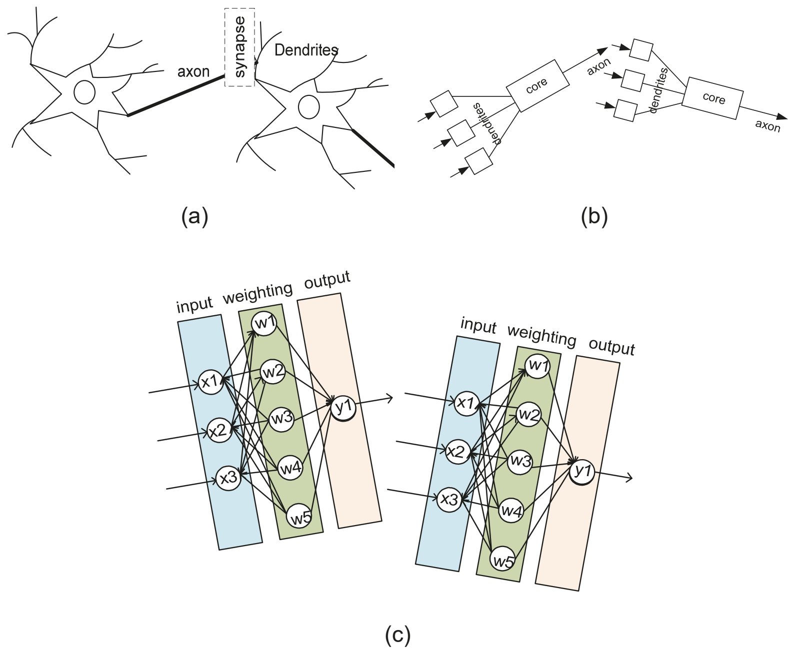


Figure 3.2. Basic idea of an example ANN: (a) neuron synapses, (b) imitated neuron synapses, (c) simplified imitated neuron, ANN structure with 2 neurons.
Source: Adapted from (Haykin, 2009, pp. 8–11).

Imagine in a single ANN structure, there are 3 inputs (x_1, x_2, x_3) , 5 weights $(w_1, w_2, w_3, w_4, \mathrm{w}_5)$, with bias b , 1 output (y_1), and activation function as bridge to real world (the $f(\quad)$ function), then an ANN therefore have the following mathematical expression:

$$\mathrm{y}_1 = f(x_1\mathrm{w}_1 + x_2\mathrm{w}_2 + x_3\mathrm{w}_3 + x_4\mathrm{w}_4 + x_5\mathrm{w}_5 + \mathrm{b})$$

Equation 3.3

Some of the possible activation functions (methods) of an ANN are semi linear with threshold value 0, sigmoid (logistic values from 0 to 1), bipolar sigmoid (logistic values from -1 to 1) or hyperbolic tangent (hyperbolic tangent values from -1 to 1) (Haykin, 2009, pp. 13–15) (Figure 3.3).

Semi linear function

$$y = f(x) \begin{cases} 0, for\ x \ \leq 0 \\ x, for\ x > 0 \end{cases}$$

Equation 3.4

derivative for semi linear function is

$$y' = f'(x) \begin{cases} 0, for\ x \ \leq 0 \\ 1, for\ x > 0 \end{cases}$$

Equation 3.5

Sigmoid function

$$y = f(x) = \frac{1}{1 + e^{-x}}$$

Equation 3.6

derivative for sigmoid function is

$$y' = f'(x) = f(x)(1 - (f(x))$$

Equation 3.7

bipolar sigmoid

$$y = f(x) = \frac{2}{1 + e^{-x}} - 1$$

Equation 3.8

derivative for bipolar sigmoid is

$$y' = f'(x) = \frac{(1 + f(x))(1 - f(x))}{2}$$

Equation 3.9

Hyperbolic tangent function

$$y = f(x) = tanh(x) = \frac{e^{x} - e^{-x}}{e^{x} + e^{-x}}$$

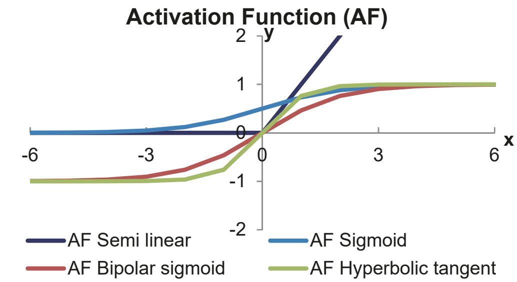
Equation 3.10

derivative for hyperbolic tangent is

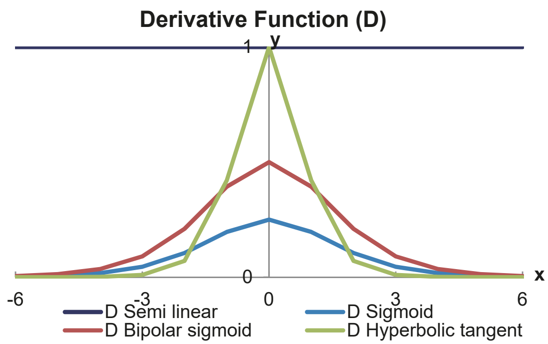
$$y' = f'(x) = 1 - f(x)^2$$

Equation 3.11

figure of these activation functions and derivative from these activation functions are



(a)



(b)

Figure 3.3. Figure of (a) activation function and (b) their derivatives of ANN used in this study.

Source: Own Depiction.

(Papalexopoulos et al., 1994) used an ANN in order to develop a load model for an energy management system for the Pacific Gas & Electric Company. Special events such as holidays were considered. Historical loads, weather related loads and seasonal related loads as inputs for ANN were also considered. He found that the ANN model was robust and accurate in predicting load under a wide variety of power system operating conditions.

Furthermore, some researchers have been reviewed and implemented ANN for different subjects as well, such as (Hippert et al., 2001) who conducted short term load forecasting, (Monteiro et al., 2013) for PV power forecast, and (Kianmehr et al., 2014) which studied forcasting of biogas production.

Short-, medium-, and long-term forecasting

In addition to the forecasting for power management forecasting system in general VPP is classified into three categories based on their time frames: short-term (up to days), medium-term (from days up to months), and long-term (from months up to years) (Table 3.3).

Table 3.3: Forecasting system.

Source: Adapted from (Hong, 2010, p. 9; Phuangpornpitak and Prommee, 2016, p. 22).

Forecasting	Time frame	Usage	Influencing factors
Short-term: -Near-real time (15 minutes range, every few hours) - Day-Ahead (15 minutes, daily)	Near real time, minutes - up to days	Network planning, real time supply-demand match making process for real time / SPOT/ Day-Ahead market	Weather, time of day (holidays, workdays), historical data,
Medium-term: - Week Ahead (15 minutes range, weekly and/or daily) - Month Ahead (15 minutes or daily range, weekly)	Days - up to months	Network planning	Time of day (holidays, workdays), historical data, Growth rate
Long-term: -Year Ahead (daily or monthly range, monthly or yearly) - Multi Year Ahead (monthly or yearly range, monthly or yearly)	Months - up to years	Investment / capacity planning	Historical data, Growth rate,

3.3 Integration concept using Multi Agent-Based concept

<u>MAS concept</u>

Several concepts aimed at synergizing different components in a VPP by applying a Mullti-Agent based System (MAS) Model is conducted in this study. There is no exact definition for the MAS concept. Therefore, up to now, the application of the MAS in the power generation sphere is yet to be developed.

In the MAS concept, a VPP is defined as a collection of entities in the power generation system, which refer to DERs and ICT components. Each entity has its own function and characteristic. This entity is then classified as an agent. In the MAS, agents shall communicate and interact with each other in order to serve common goals (Figure 3.4.). Without a collaboration, agents could not serve goals optimally. Thus, according to (Cheng, 2011), agents require a communication "bridge" to collaborate with each others. A complete review of how the agent can communicate and interact with each other has been previously discussed by (Al-Jumaily and Al-Jaafreh, 2006).

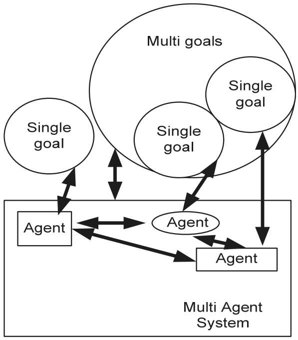


Figure 3.4. Interractions and a collection of agents to serve goal(s) in a MAS system.

Source: Adapted from (Hossain and Mahmud, 2014; Strasser et al., 2015).

One of the solutions to determine the agents' characteristics is by modeling the agents. Depending on the complexity of the MAS approach, modeling agents varies from abstractions level to the detailed mathematical model and program. However, the determinations of agent characteristics are quite challenging (Held, 2010). The identification of the power plant’s parameters and behaviors depends on the knowledge of the power plants.

The implementations of MAS and its benefits

In order to apply the MAS approach in more concrete ways, some researchers have applied the MAS approach to different power generation levels according to their functions (Dimeas and Hatziargyriou, 2007; Yan et al., 2015). At the field location level, there are dispatcher agents and controller agents. The interactions between these agents are handled at the management level. Whereas, in the enterprise level, agents’s interactions with the electricity markets are handled.

Nevertheless, the MAS is still considered one of the well-known approaches for alternative power generation systems. This is due to it being adaptive and autonomous and its suitability for a decentralized system (Hossain and Mahmud, 2014; Yan et al., 2015). According to (Hossain and Mahmud, 2014) the MAS is adaptive to any changes including its ability to do self-healing in the power generation system failures. The MAS approach is not a top-down approach but more flexible (van Dam et al., 2008).

With regard to integrated power plants and power generation controls, the implementation of the MAS is able to support a reduction in the complexity of power regulations, evidenced by (Kremers, 2013). According to (Kok et al., 2008), the MAS approach or agent approach was able to complete automatic regulation in balancing power plants. It could manage to save up to 40% of Wind power imbalances. Furthermore, the agent approach was able to optimize the reduction of CO2-emissions (Skarvelis-Kazakos et al., 2013) and to optimize integration of flexible producers, such as electric vehicles and intermittent power plants or wind to the electricity markets (Vasirani et al., 2013).

3.4 Integration concept using Smart Grid Architectures Model (SGAM) concept

With the SGAM, a VPP with a combined DERs is described from abstractions to implementations level by adopting a VPP role model from the European Network of Transmission System Operators for Electricity (ENTSOE) (European Network of Transmission System Operators for Electricity, 2015) (Figure 3.5.). A VPP in a smart grid concept can be described according to the SGAM proposed by "Comité Européen de Normalisation Électrotechnique" or European Committee or Electrotechnical Standardization (CENELEC) as the European standard for a smart grid model.

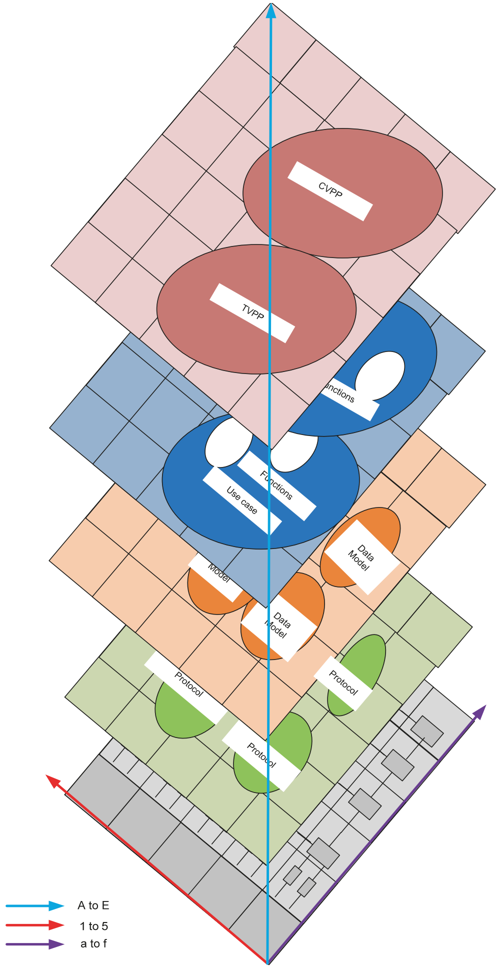


Figure 3.5. Overview of two types of VPP (TVPP and CVPP) in SGAM architecture. In the interoperability layers from A to E show component, communication, information, function and business layer respectively. In the domains layers 1 to 5 show customer, DER, distribution, transmission and generation layer respectively. In layers a to f show process, field, station, operation, enterprise and market layer respectively.

Source: Adapted from (CEN-CENELEC-ETSI Smart Grid Coordination Group, 2012; Etherden et al., 2016).

Regarding agent architecture models, VPP applications have yet to be developed. One benefit of the architecture model is that smart grids i.e. VPP would have the ability to manage power plants flexibly as well as to be automonously and would be able to undertake self-healing.

3.5 Technical Potentials to integrate RES-based DER

In this study, the potentials of RES current developments are limited to biogas, PV, wind and battery (Table 3.4). Potentials that are classified as non-ICT-related are the amount of installed capacity, forecasting technology and the developments of biogas and intermittent RES technologies. Whereas, in ICT-related potentials are the development of ICT-based converters and controllers technologies.

Table 3.4. State-of-the-art of biogas and intermittent RES to support implementation of a VPP.

Source: Adapted from (Bundesverband der Energie- und Wasserwirtschaft e.V., 2017; de Alencar et al., 2017; Feuerhahn et al., 2014; Ganagin et al., 2014; Hahn et al., 2014; Kabalci, 2016; Lawder et al., 2014; Pelland et al., 2013; Xu, 2013; Xue et al., 2011).

Technical potentials to combine flexible energy from biogas and intermittent RES in a VPP				
Type	**Biogas**	**PV**	**Wind**	**Battery**
Non-ICT related	Flexible biogas generation (Ganagin et al., 2014; Hahn et al., 2014). Biomass potential power supply in Germany (per-2016): 45,6 TWh or 7 % brutto (Bundesverband der Energie- und Wasserwirtschaft e.V., 2017).	Solar radiation and PV power forecast technologies (Pelland et al., 2013). PV potential power supply in Germany (per-2016): 38,2 TWh or 5.9% brutto (Bundesverband der Energie- und Wasserwirtschaft e.V., 2017).	Wind forecast (de Alencar et al., 2017). Active/reactive power control from generator technologies: Induction, Double Fed Induction, Synchronous with converter. Potential energy in Germany (per-2016): 65 TWh (offshore, 3,2%) and 12,4 (onshore,10%) brutto (Bundesverband der Energie- und Wasserwirtschaft e.V., 2017).	Forecasting and modeling for battery degradation management (Xu, 2013).
ICT-related	CHP controller (Feuerhahn et al., 2014), Smart meters incl. communication Gateway (Kabalci, 2016).	PV Smart inverter (Xue et al., 2011), Smart meters incl. communication Gateway (Kabalci, 2016).	Converter (Xue et al., 2011), Smart meters incl. communication Gateway (Kabalci, 2016).	Battery Energy Management System (Lawder et al., 2014), Smart meters incl. communication Gateway (Kabalci, 2016).

4 Materials and Methods

This chapter explains materials and methods used for the VPP developments in this study. It consists of load profiles, market power, DER (BESS, biogas, PV) model and implementation of a VPP.

4.1 Materials

This sub-chapter describes materials utilized in VPP developments. It considers determined data (load demand, the EEX/EPEX market prices, power markets, PV), simulation data and tools.

4.1.1 Load profiles

The trend of monthly load profiles of Aschaffenburg ity used in this study take into account their properties: maximum value, minimum value, quartile 1 (Q1), quartile 2 (Q2) and quartile 3 (Q3) (Figure 4.1). The total value of load demands fluctuated during the year. It's peak level was 110 MW in January and reached the lowest level of 9 MW in May. In addition, the monthly average of load demands had the higher value in Autumn than in Spring. Figure 4.1 describes that unlike the maximum value, the value of Q1, Q2 and Q3, and the minimum values of load demands in each month was relatively flat. The majority of months had similar minimum load values: January, February, April and June had minimum load demands of approx. 11 MW, while in July, August and October load demands were also similar at approx. 13 MW.

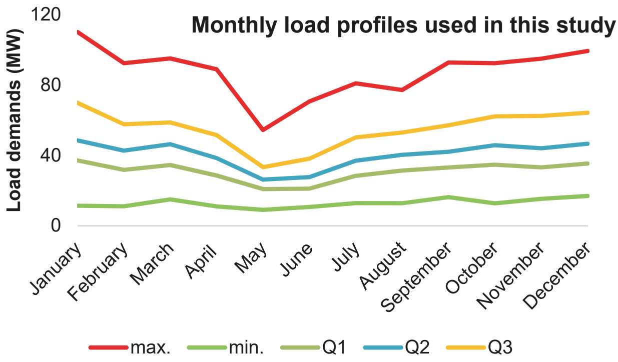


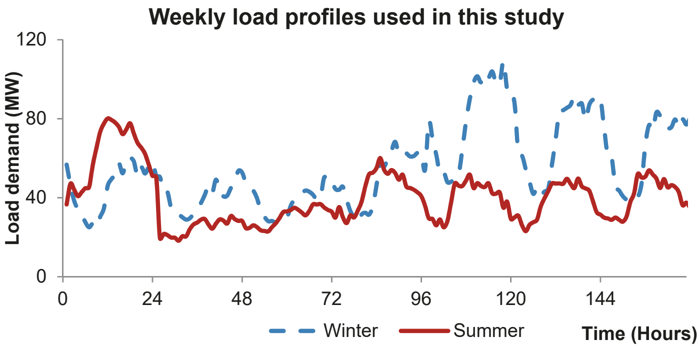
Figure 4.1. Monthly load profiles used in this study.

Source: *Adapted from* (Ullrich, 2015).

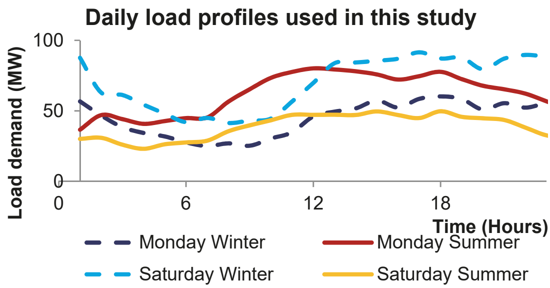
In order to conduct further analysis in the VPP, data of a week load profile from January and July were selected to represent Week Futures market bids. Additionally, for Day-Ahead (DA) market analyses purpose, Monday and Saturday were selected to represent the starting behavior of load demands during Weekday and Weekend.

In the weekly load profiles (Figure 4.2. (a)) there was not a significant difference between load profiles in summer and in winter, especially from Tuesday till Thursday. The reason is that on those days, load profiles were mainly dominated by local large consumers, especially from the business sector, with relative constant demands.

Weekly load profiles in summer were, for the majority of the time, lower than in winter. On Monday in summer time, it fluctuated between 20 MW and 80 MW. On this day, local electricity demands were usually dominated by local enterprises, which, most of them being factory plants or enterprises, required higher power than on other days to start the business. In contrast, the required electricity production would have been different in winter since local electricity consumers, especially households, increased their demands. The value of electricity requirements in winter reached its peak at 4 at the weekend. This behavior is clearly seen if daily load profiles are analyzed (Figure 4.2. (b)).



(a)



(b)

Figure 4.2. Load profiles used in this study: (a) Weekly load profiles, (b) Daily load profiles.

Source: adapted from (Candra et al., 2018).

4.1.2 Power markets of VPP

In order to adapt power market requirements in terms of power product categories such as base load or peak load, determined load profiles from (chapter 4.1.1) are calculated by adopting methods conducted by (Candra et al., 2018; Zoerner, 2013). Load profiles would then be classified as a bid. Each bid in a power market has required power and duration properties.

Imagine a bid for a load in Rush-Hour (Figure 4.3.) has required power and power duration between 17:00 and 20:00 hour.

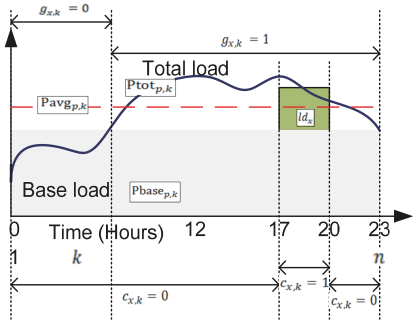


Figure 4.3. Sample of Rush-Hour (RH) bid calculation for DA market in this study, where: m is WF winter or WF summer and p is market category. *Source: Adapted from (Candra et al., 2018; Zoerner, 2013).*

Then, the volume from this bid $BVOL_x$ in a DA market scenario x (see Appendix 10,

Table 10.7) for time duration $k = 1$ to maximum time frame n of respective bid is then can be calculated by

$$BVOL_x = \sum_{k=1}^{n} c_{x,k} \left(\frac{\sum_{k=1}^{n} (g_{x,k} Pres_{p,k})}{s_x} \right)$$

Equation 4.1

The respective bid is calculated from equally distributed $BVOL_x$ which is based on the number of signal $g_{x,k}$ for the area where $c_{x,k}$ equal to 1.

$$ld_x = \left(\frac{BVOL_x}{\sum_{k=1}^{n} g_{x,k}} \right)$$

Equation 4.2

where:

- $BVOL_x$ calculation is used to calculate total bid volume of market x which is not base load.
- ld_x is bid (load) at market x.
- $k = 1$ to maximum time frame n.

- n is not always equal to 24 (hourly interval with 24 points for a day). It depends on the intervals of load demands such as hourly, 15-minutely or others and type of markets (daily or weekly). Therefore n is calculated by number of intervals per hour t_int $[\frac{\text{intervals}}{\text{hours}}]$ multiplied by number of points per interval per day $\_point$ $[\frac{}{\text{intervals days}}]$, 24 $[\text{hours}]$ and number of days t_day $[\text{days}]$.

$$n = t\_int \quad t\_point \quad t\_day$$

Equation 4.3

- A $c_{x,k}$ represents a constant of bid x at time k.

$$c_{x,k} = \begin{cases} 1, \text{for k is equal to time where load occurs} \\ 0, \text{for others k values} \end{cases}$$

Equation 4.4

- A $g_{x,k}$ is an artificial signal to indicate that there is residual load market product x at time k. A $g_{x,k}$ is calculated by

$$g_{x,k} = \begin{cases} 1, \text{if } Pres_{p,k} > 0 \\ 0, \text{if } Pres_{p,k} \leq 0 \end{cases}$$

Equation 4.5

- A $Pres_{p,k}$ is residual load from total load $Ptot_{p,k}$ after subtracted by base load $Pbase_{p,k}$ of market category p (see Appendix 10,Table 10.8) at time k. The equation of $Pres_{p,k}$ is

$$Pres_{p,k} = Ptot_{p,k} - Pbase_{p,k}$$

Equation 4.6

- $Pbase_{p,k}$ is derived from this equation

$$Pbase_{p,k} = Pavg_{p,k} - Paravg_{p,k}$$

Equation 4.7

- A $Pavg_{p,k}$ is the average value of total load of market category p. This value is calculated one time for all k.
- A $Paravg_{p,k}$ is the average deviation of market category p. This value is calculated one time for all k.

- A s_x represents number of remaining $g_{x,k}$ signals over a calculated time frame from $k = 1$ to n . Thus, the s_x formula would be

$$s_x = \sum_{k=1}^{n} g_{x,k}$$

Equation 4.8

In addition to $BVOL_x$ calculation for DA market, in WF w market base load is calculated using (eq base), whereas peak load $Ppeakw_w$ is calculated using 2 times of average deviation value to reduce processing time in the VPP server.

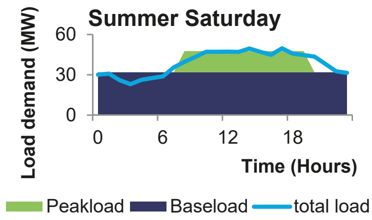
$$Ppeakw_w = 2Paravg_{m,k}$$

Equation 4.9

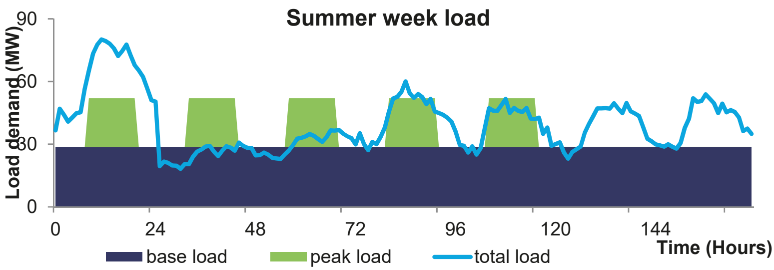
where

- A $Paravg_{m,k}$ is the average deviation of market category m (WF winter or WF summer). This value is calculated one time for all k.

At the end there will be total 68 market products in DA market and four market products in WF markets. The sample of bid product for WF market and DA market are presented in (Figure 4.4. (a) and (b)).



(**a**)



(**b**)

Figure 4.4. Sample of adapted load profiles to market products (a) in summer on Saturday in DA market; (b) in summer weekly in WF market.

Source: Adapted from (Candra et al., 2018).

4.1.3 EEX/EPEX market prices

Market prices used in this study were derived from the EEX data (European Power Exchange, 2015). An excerpt of market prices from the Week Futures (WF) market from detailed market prices in (Appendix 10,Table 10.6) is provided by (Figure 4.5). In addition, based on Figure 4.5., value peak prices in summer were mostly lower than in winter except on Tuesday. This occurs because ratio between demand for peak load over available power generations are higher than in winter.

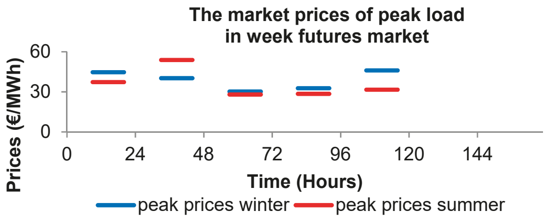


Figure 4.5. An excerpt of market prices for peak load in WF market in this study. *Source: Adapted from (Candra et al., 2018; European Power Exchange, 2015).*

4.1.4 PV potential characteristic

PV potential characteristic in this study (Figure 4.6.) was derived from a week's data in winter (26th January to 1st February 2015) and a week in summer (6th-12th July 2015). In summer, on weekdays, solar radiation was at least 4 times higher than in winter. But, on weekends in summer, especially on Sundays, there was a huge reduction in solar power availability. Compared to summer, solar radiation in winter was relatively similar during the chosen week in this study.

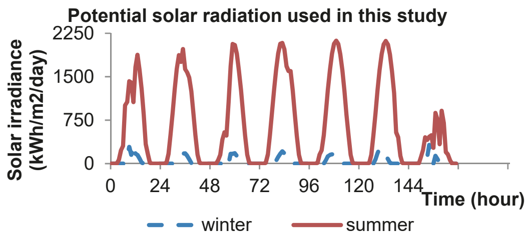


Figure 4.6. Potential solar radiation in this study.
Source: Adapted from (Candra et al., 2018).

4.1.5 Required software and tools

Most of the software tools (Table 4.1) to develop VPP are based on MATLAB, as MATLAB is able to handle complex interface challenges from different components in a VPP. The optimization agent which is built in a MATLAB-Simulink is converted using MATLAB compiler and PLC coder in order to be implemented in a local controller. Open source and community-based software were also used in this research project. In addition, a TIA Portal V13 was used because the VPP in this project implements PLC S7-1200 from Siemens as its local controllers. The following are the applied software tools to develop a VPP:

Table 4.1. Software tools in the VPP developments.
Source: Own Depiction.

Purpose	**Chosen tools**	**Alternatives**
Optimization	Matlab-Simulink	Optaplaner, Fico, Anylogic, HOMER, Matpower, R, Scilab
Prediction and forecast	Matlab, Python (Python Software Foundation, 2001)	Zaitun software (Zaitun Software, 2008), R, Scilab
User interface programming	Microsoft Visual Studio community specially Apache Cordova (The Apache Software Foundation, 2013), Python Kivy (Python Software Foundation, 2001)	Eclipse
Local controller programming	TIA Portal V13	(depends on PLC types)
Architecture	Adoption of SGAM Toolbox (Josef Ressel Center for User-Centric Privacy, Security and Control, 2020), GNS3 (SolarWinds Worldwide, LLC, 2016)	Eclipse, Enterprise Architect

4.2 Methods

This chapter describes implemented approaches or methods to combine intermittent RES (PV power plant) and flexible energy generations (flexible biogas and BESS) in a VPP. These methods are built according to objectives.

4.2.1 VPP design developments

Development of a VPP design is based on the adoption of the previous study from (Candra et al., 2017a) by implementing both the Multi-Agent based Systems (MAS) and VPP technical frameworks based on the Smart Grid Architecture Model (SGAM).

Implementing the MAS concept

In the VPP in this study, all related components (hardware and intelligent parts) are modeled as the MAS (Figure 4.7.).

These modules represent the VPP components as multi-agents (collection of agents) based on their functionalities: user interface, optimization, servers and power plants. Regarding the collection of agents, the MAS servers has agents that consist of an ICT module, an application server, a web server and a database.

The MAS based on real time and the simulated MAS are developed in this study. The real-time application MAS concept is connected to the grid and power market, whereas the simulated MAS is the real-time application of the MAS concept using MATLAB-Simulink environment, sometimes referred to as a MATLAB-based MAS. The VPP in this study consists of:

- a MAS BESS (Battery Energy Storage System), MAS VPP servers and a MAS GUI (Graphical User Interface) deployed in real time MAS.
- a MAS PV and a MAS grid deployed in a MATLAB-based MAS.
- a MAS BESS (Battery Energy Storage System), a MAS biogas (there was no CHP machine connected to a MAS Biogas) and a MAS optimization deployed in the combination of real-time MAS and MATLAB-base MAS.

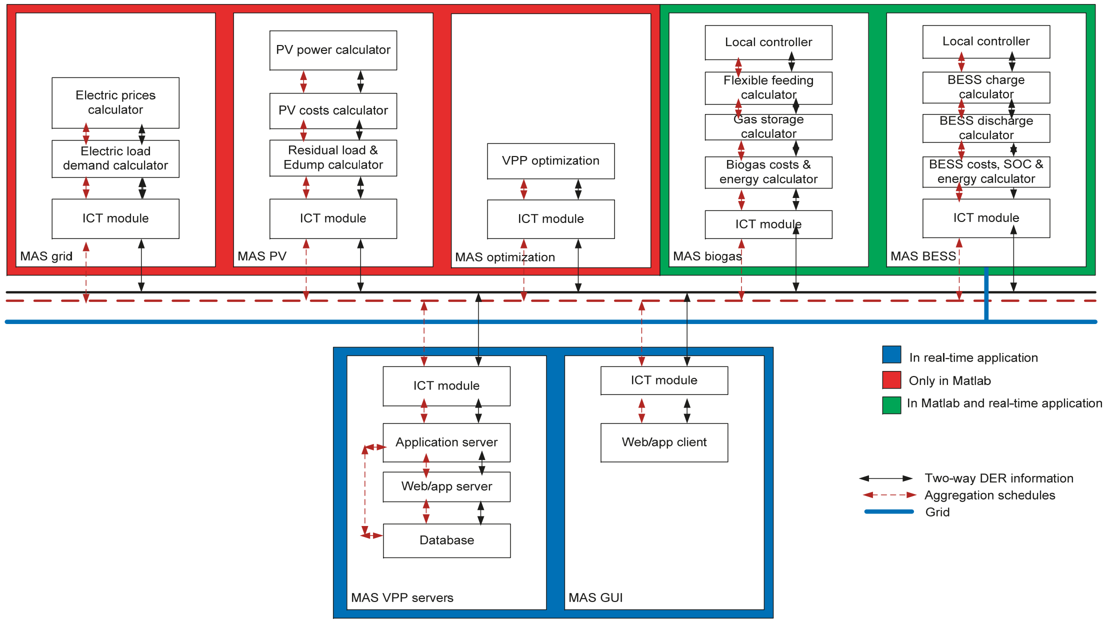


Figure 4.7. MAS design in this study.

Source: Own Depiction.

Developing integration mechanism of the MAS in the VPP

The integration of power plants takes place in two steps; hardware integration and intelligent integration. In the hardware integration, the integration of RES takes place by adapting RES power plant hardware requirements such as intelligent controller to the VPP. If power plants are not yet ready to be integrated (per-hardware connection), the intelligent controller must be added. Intelligent controllers work to manage information exchange between a VPP and RES power plants. Intelligent controllers in this study are based on the PLC S7-1200 from Siemens with a specific VPP program to connect and control RES within VPP application (Figure 4.8.).

Figure 4.8. Local controller as a required device in the VPP’s hardware integration (based on PLC S7-1200 from Siemens).

Source: Own Depiction.

Once the hardware integration process is completed, the next step is to establish the intelligent integration. In this integration, a VPP creates a model of integrated RES power plants, their configurations, and their functional tests. In case of a membership cancellation or re-assignment, a VPP as per-hardware as well as per-software will disable or suspend the RES power plants functionalities as well as any links to a VPP (Figure 4.9.).

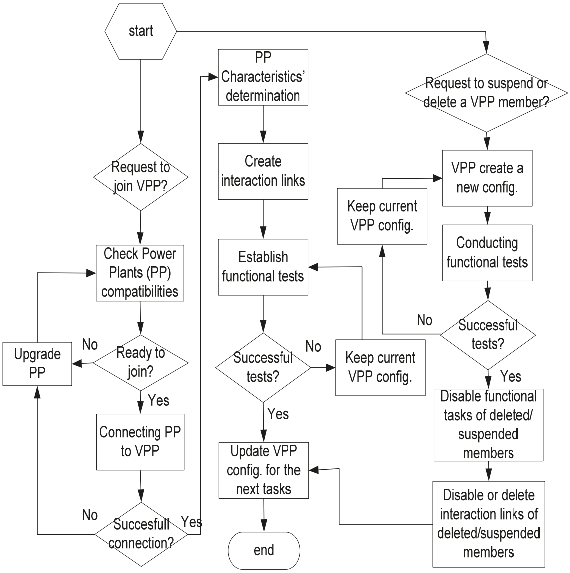


Figure 4.9. Integration mechanism of RES power plants to a VPP in this study. *Source: Own Depiction.*

<u>Developing the MAS communications model</u>

The MAS in this VPP communicates using an identifier principle mechanism. The identifier works on a sequential as well as an asynchronous mode. In the sequential mode, the identifier works based on the central commands from the VPP. The sequential mode sends commands and receives response mechanisms from DER components through the VPP servers. On the other hand, asynchronous mode is applied when VPP servers are able to receive responses from all the MASes (that consist of VPP components). An example of this mechanism is the response of VPP components regarding their ability to aggregate power. Each of the VPP components are allowed to send their response to VPP servers without waiting for other VPP component responses.

Followings are a sample of identifiers built during the MAS communications in order to monitor and control VPP (Figure 4.10.):

- Identifier 1: the VPP operators through the MAS GUI ask the VPP servers about the VPP current information.
- Identifier 2: the MAS VPP servers request DER information from the other MAS (grid, optimization, IES). Request is sent asynchronously to all each MAS.
- Identifier 3: The MAS VPP servers receive asynchronous response about DER from the MAS grid, the MAS optimization, the MAS PV, the MAS BESS and the MAS biogas.
- Identifier 4: The results from Identifier 3 are forwarded as a response of identifier 1 to the MAS GUI.
- Identifier 5: Administrator through the MAS GUI requests the VPP servers to control the VPP.
- Identifier 6: The MAS VPP servers ask the MAS optimization to generate aggregation schedules for an IES (Integrated Energy Sources).
- Identifier 7: The MAS optimization collects all information from the MAS grid and the IES.
- Identifier 8: The MAS optimization receives the requested data from the Identifier 7.
- Identifier 9: The MAS optimization generates aggregation schedules based on results from Identifier 8. If aggregation schedules are ready, the MAS optimization, asks the IES to follow the aggregation schedules.
- Identifier 10: The IES executes aggregation schedules, after that send acknowledgements to the MAS optimization.
- Identifier 11: If load demands cannot be answered by the IES generated power, then the MAS optimization will go back to process the Identifiers from 7 to 10. Otherwise, the MAS optimization provide an acknowledgement signal to the MAS VPP servers to inform that the task has been executed.
- Identifier 12: the MAS VPP servers send a response to the MAS GUI that a specific process has been completed.

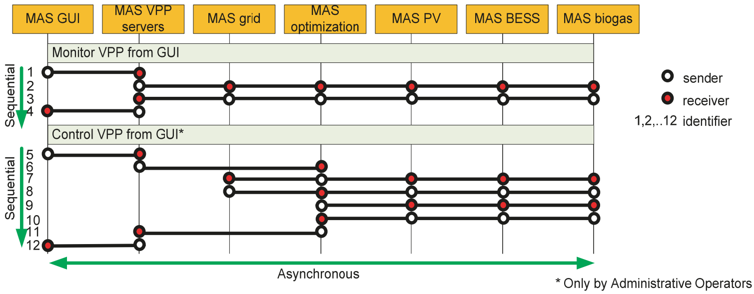


Figure 4.10. MAS communication to control and monitor VPP from a GUI.
Source: Adapted from (Candra et al., 2017b).

Implementing the SGAM concept

In comparison to the MAS concept, the SGAM concept has more detailed information about a VPP design. With this concept, a VPP design is classified into several layers: Business layer, Function layer, Information layer, Communication layer, Component layer and Security layer.

The SGAM Business Layer

At the Business layer level, a VPP is classified into several Business Case Analyses (BCA) and Business Goals (BG) (Figure 4.11.). Business Goals represent goals of the Business Cases of Business Actors. Business Goals in this study were to meet grid requirements such as reliable power, optimizing DER, monitoring DER and aggregating/ dis-aggregating DER.

Business Case Analyses represent Business Cases among VPP components. Included in this BCA are the grid requirements delivery from system operators to VPP operators, calls for balancing power from VPP operators to DER operators, VPP membership management, forecasting systems for VPP and data acquisition (control signal, DER schedule, measured value, status DER) from the DER.

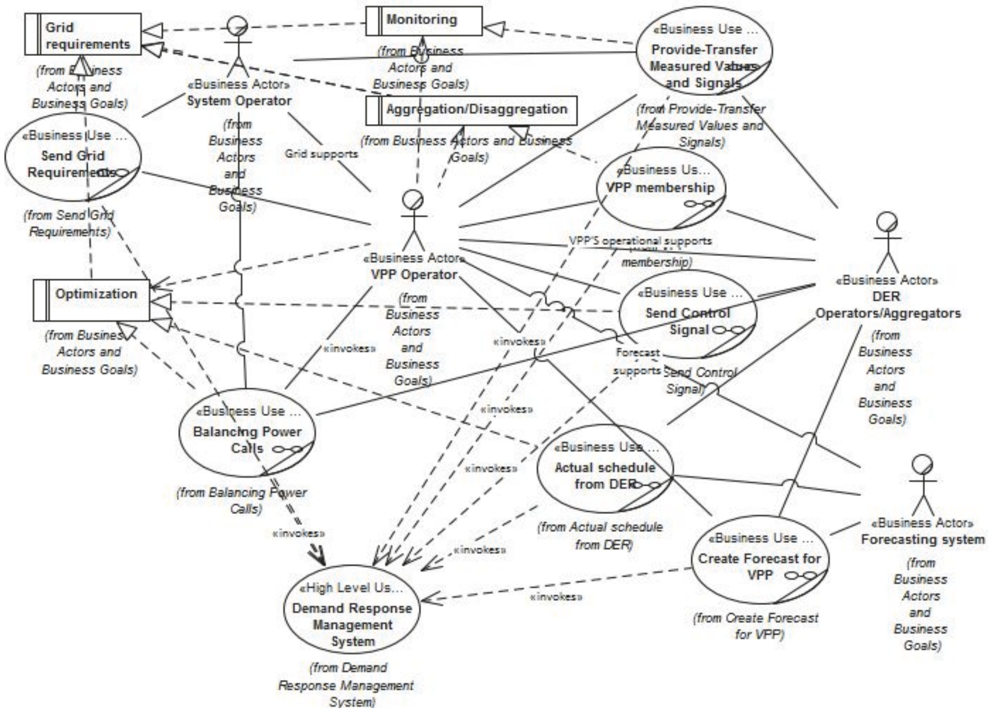


Figure 4.11. Business Layer of VPP on this study.
Source: Own Depiction.

The SGAM Function Layer

On the Function Layer (Figure 4.12.), VPP is classified as a High-Level User Case (HLUC) as a Demand Response Management System (DRMS). In this DRMS, VPP provides control of the DER, generates operation plans and acquires data from VPP actors.

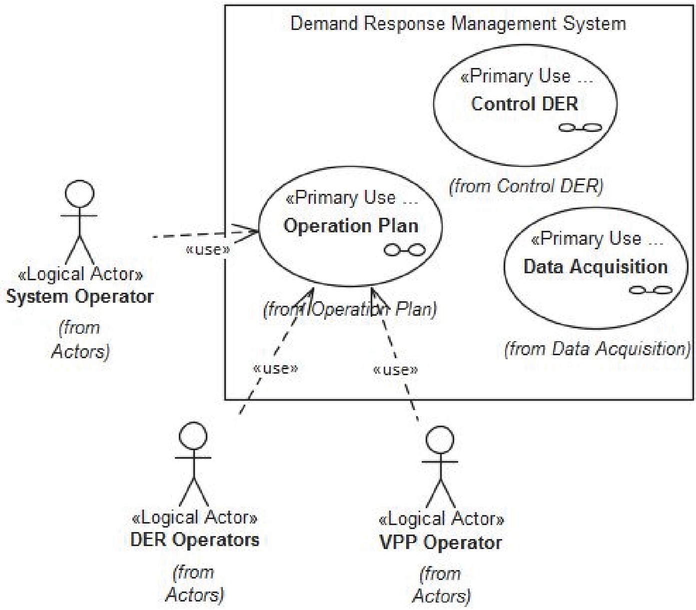


Figure 4.12. Function Layer of VPP on this study.
Source: Own Depiction.

In an activity graph (Figure 4.13.), DRMS HLUC is executed in two cycles: continuous cycle and user-defined cycle (such as 1s or 15 minutes cycles). In the continuous operation, DRMS HLUC executes data acquisition and controls DER, whereas in the user-defined cycle, VPP generates operational plans based on energy demands and energy availabilitiy.

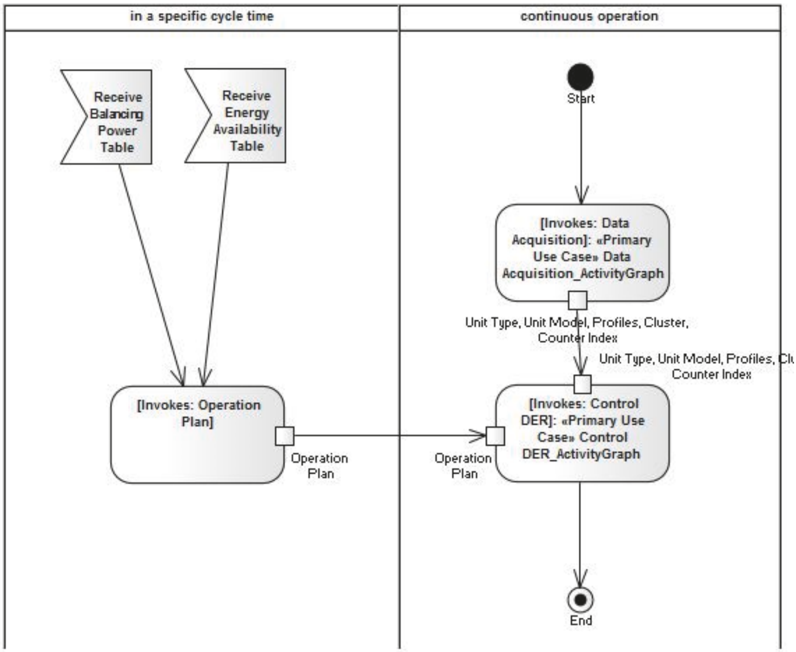


Figure 4.13. DRMS activity graph on this study.

Source: Own Depiction.

<u>The SGAM Information Layer</u>

At the Information Layer (Figure 4.14.), a VPP is applied into 4 parts: Information Objects, Business Context View, Standard & Information Object Mapping and Canonical Data Model. Information Objects determine information data exchanges between VPP servers and VPP client with the associate data models e.g. operation plans of a VPP which is triggered by a VPP operator for all VPP actors.

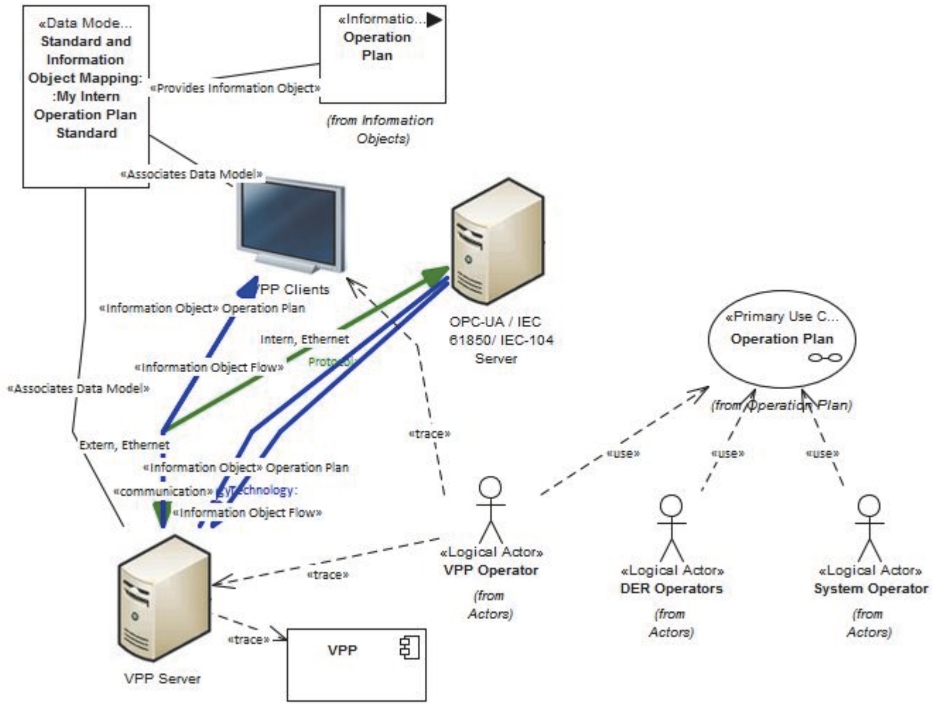


Figure 4.14. Information Objects of Information Layer of VPP on this study.

Source: Own Depiction.

In the Business Context View (Figure 4.15.), VPP servers are located in the DER-Operation of SGAM matrix layer. Remote Terminal Units (in this study, PLCs) are connected to DER controllers. VPP clients are located in the Operation-Customer Premise for VPP users.

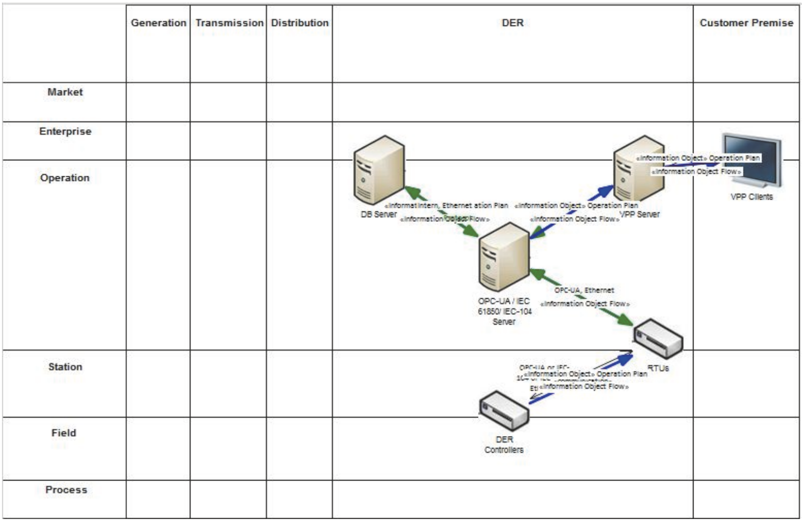


Figure 4.15. Business Context View of Information Layer of VPP on this study.
Source: Own Depiction.

The Standard & Information Object Mapping part describes a mapping of the Information Objects and the VPP standards data model from operation plan, OPC-UA, IEC-104 or IEC 61850 model (Figure 4.16.).

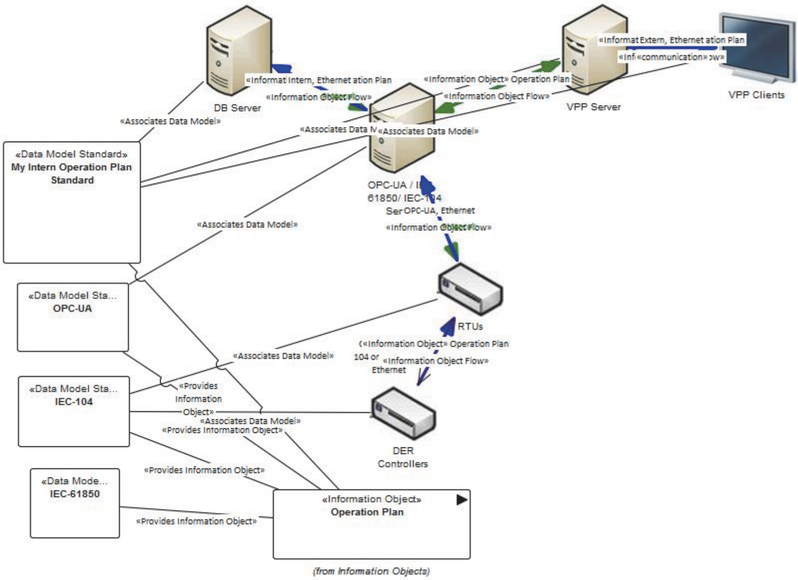


Figure 4.16. Standard & Information Object Mapping of the Function Layer of a VPP in this study.

Source: Own Depiction.

The Canonical data model represents data models of a VPP in the SGAM matrix Layer (Figure 4.17.). In the Station-DER matrix layer, a VPP uses its standard data models (OPC-UA, IEC-104 or IEC 61850). In the Operation-DER matrix layer, a VPP uses an operational planning data model.

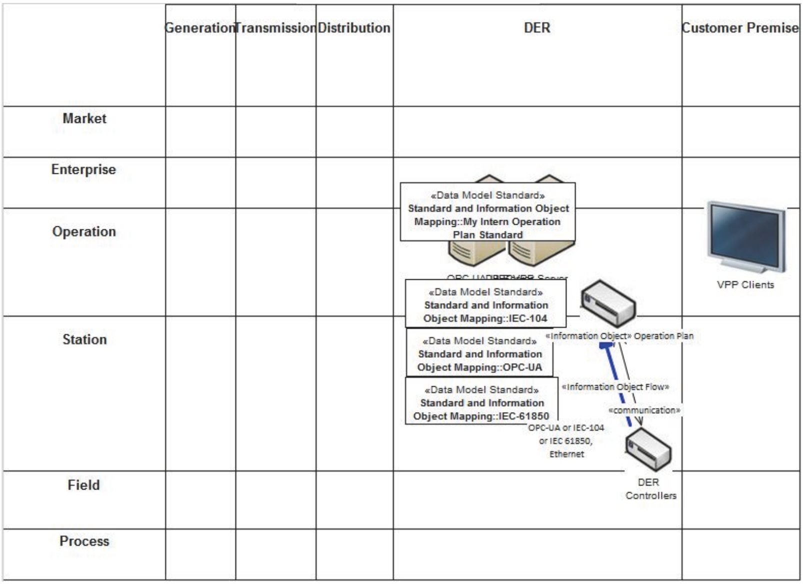


Figure 4.17. Canonical data model of the Function Layer of the VPP in this study.

Source: Own Depiction.

<u>The SGAM Communication Layer</u>

The Communication Layer in this VPP study describes communication protocol models that are used among VPP ICT-components (RTUs, Servers, Clients, DER controllers) (Figure 4.18.).

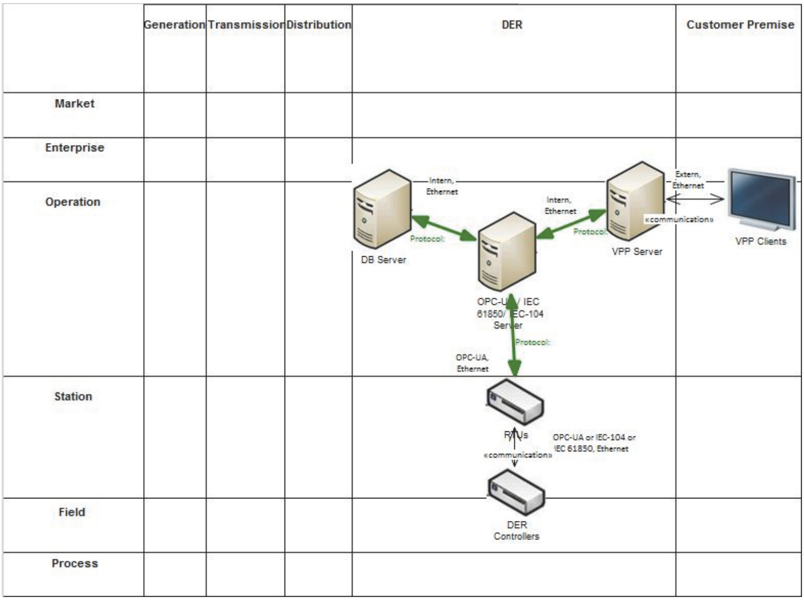


Figure 4.18. Communication Layer of the VPP in this study.

Source: Own Depiction.

<u>The SGAM Component Layer</u>

A Component Layer describes hardware components of a VPP and their relationship including protocol and information exchanges in a VPP (Figure 4.19.). At the lowest level (Process Layer of DER, represented by red lines), a Biogas and a BESS are connected to Low Voltage (LV) Networks which step up to High Voltage (HV) Networks in the Transmission level. A Biogas and a BESS are connected (blue line) to DER controllers (PLCs) by a specific technology communication such as server-client technology settings from DER.

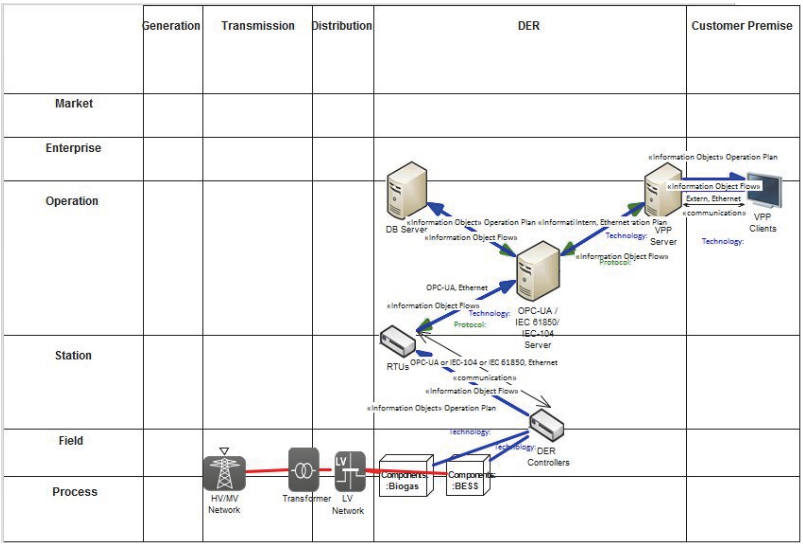


Figure 4.19. Component Layer of VPP on this study.

Source: Own Depiction.

These components are handled by different VPP actors. VPP operator handles VPP servers-clients and RTUs components (Figure 4.20.). DER operators handle DER controllers which are connected to a BESS or a biogas. System operator handles power exchange between DER (a BESS and a biogas) and power system networks.

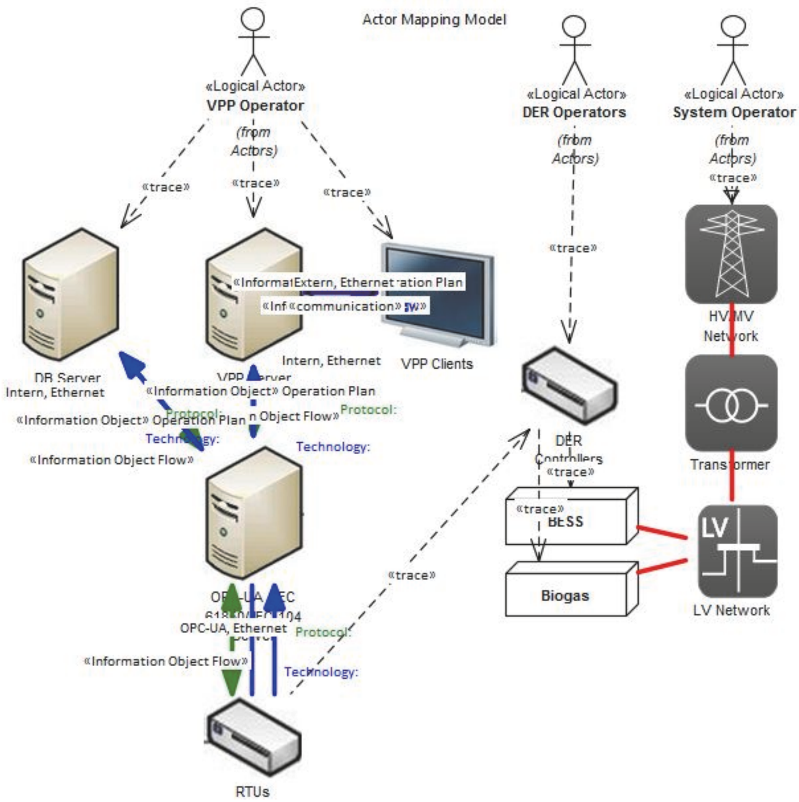


Figure 4.20. Component Layer of VPP (Actor Mapping Model) on this study.

Source: Own Depiction.

<u>The SGAM Security Requirements</u>

Security requirements of a VPP are categorized into requirements based on possible risks: from servers-clients interactions (attacks from external sources) and Hardware/Software of VPP servers-VPP clients security (Figure 4.21.). In order to handle these risks, VPP applies a redundancy system in order to provide a hardware security and a VPN connection for software security.

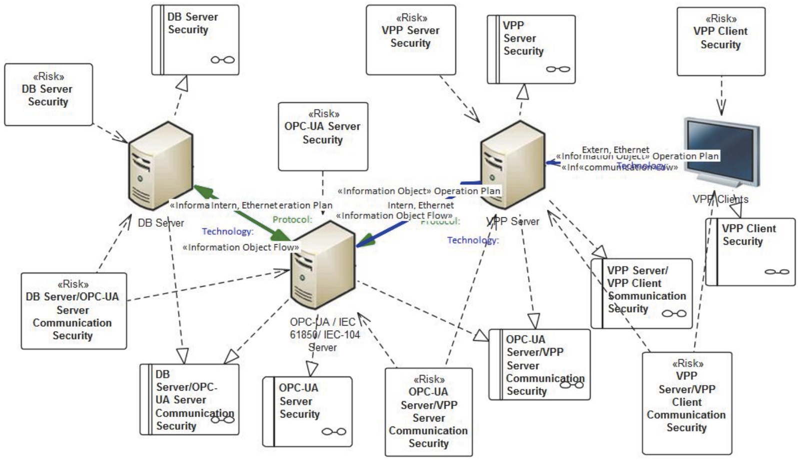


Figure 4.21. Security Requirements of the VPP in this study.

Source: Own Depiction.

4.2.2 Developing the networking and ICT architecture of the VPP

Developing ICT models of a VPP consists of developing a networking system and an ICT architecture model. Developing a networking system is related to the ICT networking system, whereas developing an ICT model is related to the model of an ICT infrastructure of a VPP. These models are parts of the SGAM Information layer, the communication layer and the SGAM component layer.

Developing a networking system

The networking system of the VPP in this study was built firstly using GNS3, then implemented in real University networks. GNS3 *(SolarWinds Worldwide, LLC, 2016)* is aimed at simulating routing of IP addresses, test of connected PCs and other networking systems on this VPP (Figure 4.22.).

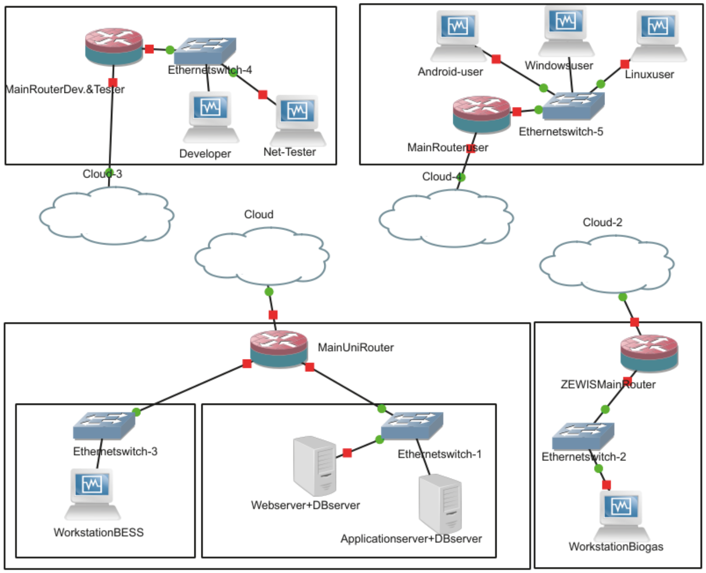


Figure 4.22. Networking system of the VPP in this study using GNS3.
Source: Own Depiction.

For copyright and security purposes of the Aschaffenburg University of Applied Sciences, the IP addresses and networks configurations are not published in this manuscript.

Developing an ICT architecture model

Implementing the current development of ICT to solve the integration challenges of a VPP from a combined flexible biogas and a PV system, including a battery system in the grid and power markets, focuses on the development of back-end and front-end technology of a VPP. With regard to these back-end and front-end technologies, it is important to determine the most important VPP requirements, such as ability to provide reliable power so that the complexity of a VPP development can be reduced.

The ICT architecture of the VPP (as described in the SGAM architecture parts) is based on the adoption of the ICT architecture of the VPP from (Candra et al., 2017a) that consist of a utilization of a Virtual Private Network (VPN) and a firewall systems for ICT security. Firewall and VPN connections are fundamental for a secure ICT system (Figure 4.23.). Furthermore, Open Platform Communications (OPC) and Transmission Control Protocol-Internet Protocol (TCP/IP) connections are the two mains protocols applied to this model. The RES power plants (Biogas and Battery) and VPP servers are described in three different locations (3 areas).

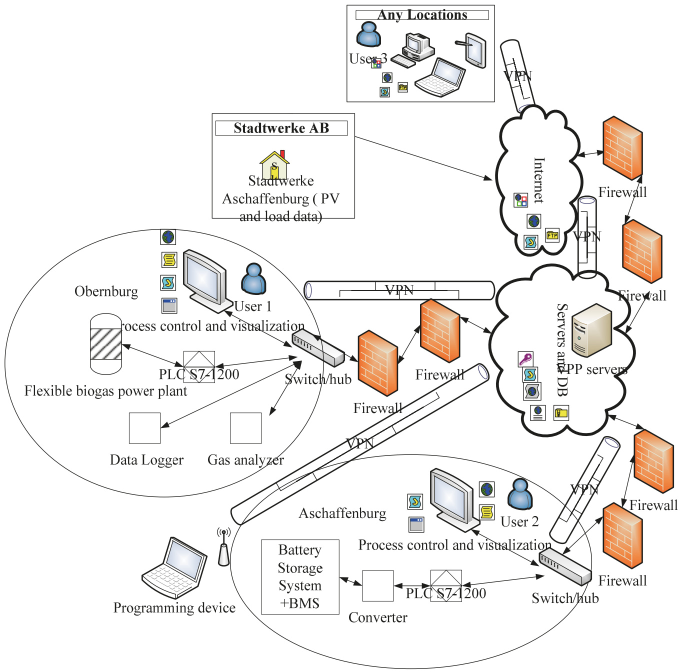


Figure 4.23. ICT architecture in this VPP.

Source: Adapted from (Candra et al., 2017).

4.2.3 Developing Distributed Energy Resources and their models

Developing DER and their models includes hardware/ software developments of Battery Energy Storage (BESS), Biogas power plants, PV model systems and load demands.

Developing PV model

This model calculates PV power production based on solar irradiation, coefficient factors and multiplication factors. Coefficient factors are simplified as a constant of the total efficiency value of PV power plants, whereas multiplication factors are used to represent the magnitude of PV power. The model of PV power plants in this VPP is simplified by this formula

$$Ppv(t) = G(t)cm$$

Equation 4.10

In operation, the VPP is also considering the availability of energy in batteries. As a consequence, the VPP will distribute some of the generated PV power to charge the battery. To calculate the energy to charge the battery, an excess PV energy model was built. This model calculates the difference between the value of the load demand and the value of the generated power from the PV. If there is a positive difference, then the PV has energy to charge the battery. If there is a negative difference, then the PV has no energy to charge the battery. This difference also means that to answer load demand, the VPP needs energy from biogas.

In this VPP model, the excess energy from the PV will be charged directly to the battery independent of the price of selling electricity to the grid and the cost to charge the battery.

Developing flexible biogas power plants

Developing flexible biogas power plants includes development of biogas models and a laboratory scale biogas power plant. The biogas model development consists of two sub-mathematical models: an energy biogas model and a biogas feeding model (Figure 4.24.).

The energy biogas model calculates usable biogas $Ebiou$, energy that must be delivered from biogas $Ebiomust$, control signals to start flexible feeding cnt, energy from biogas storage $Ebiosto$ and power alarms in biogas $bioal$.

$$Ebiou, Ebiomust, cnt, Ebiosto, bioal = f(Efa, effCHP, Emaxsto, Esto)$$

Equation 4.11

Energy from biogas at time (t) is calculated based previous energy from biogas $Ebio(t-1)$, previous energy must be delivered by biogas $Ebiomust(t-1)$, initial energy from biogas storage IC, generated biogas energy from biogas processes without additional feeding $Ebiog(t)$ and biogas energy from flexible feeding $Ebiof(t)$.

$$Ebio(t) = \left(Ebio(t-1) - Ebiomust(t-1)\right) + \left(IC + Ebiog(t) + Ebiof(t)\right)$$

Equation 4.12

The biogas feeding energy model manages flexible feeding operations (time frame and amount) of flexible biogas power plants. Control signal $cnt(t)$ for time (t) will be actived previously before time $(t-1)$ when total biogas energy $Ebio(t)$ is less than the energy that must be delivered by biogas $Ebiomust(t)$. Alarm on biogas $bioal(t)$ is actived when energy from biogas storage $Ebiosto(t)$ is empty.

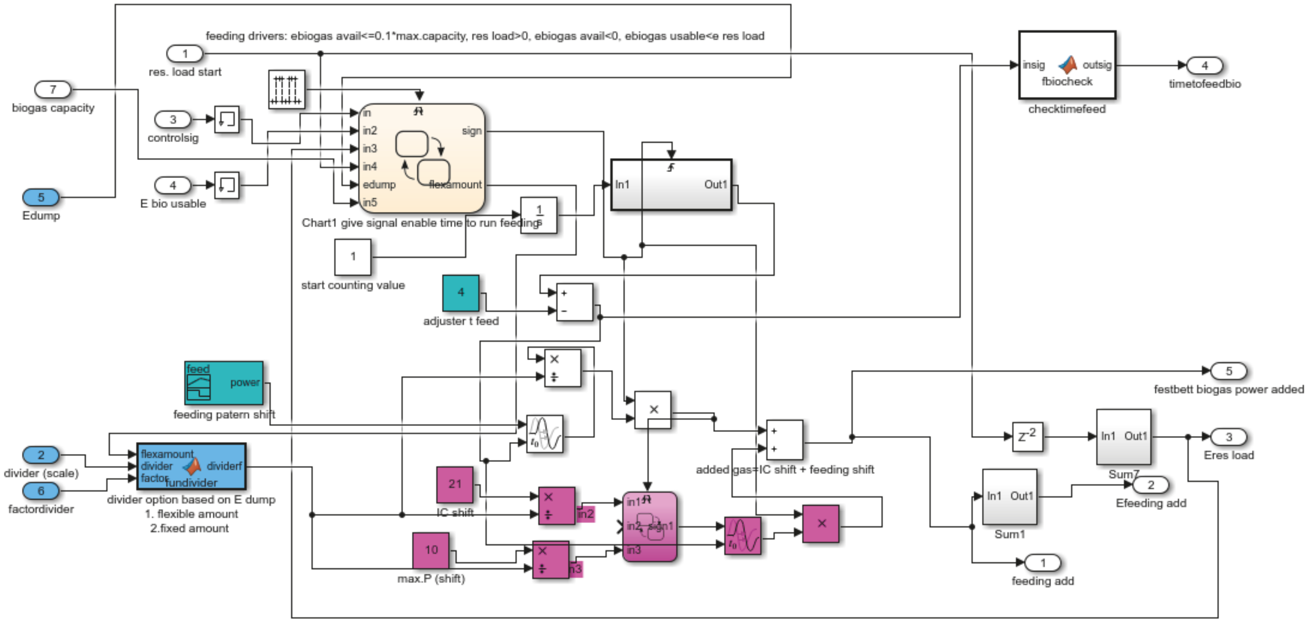
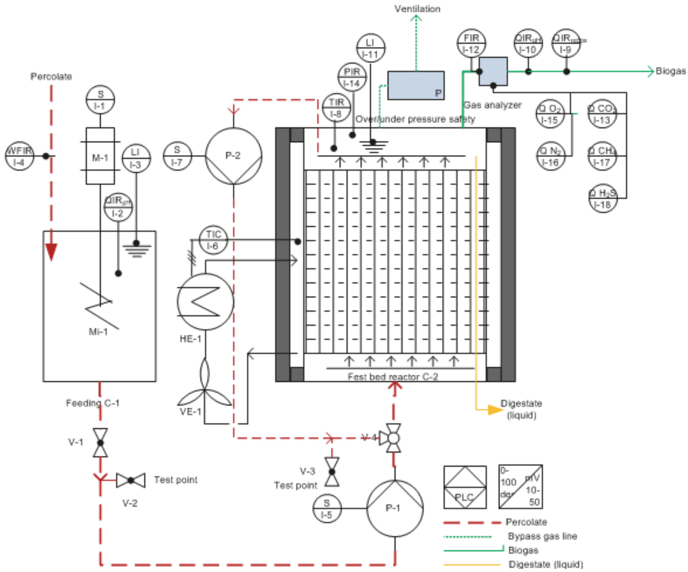


Figure 4.24. Biogas feeding energy model.

Source: Own Depiction.

These models (energy biogas model and biogas feeding energy models) are then applied in a laboratory scale biogas power plant adapted from a controllable biogas energy model from (Ganagin et al., 2011). The lab. scale biogas has 2 digesters: a feeding reactor (140 l) and fest-bed reactor (300 l) (Figure 4.25.) (for full specification, see Appendix 10.3). A fixed bed reactor will be fed by liquid percolate from products from composting management in Aschaffenburg, Germany.



(a)

(b)

Figure 4.25. Flexible biogas infrastructure for this study: (a) Design of a lab. scale flexible biogas power plant based on fest bed reactor, (b) Developed flexible biogas.
Source: Adapted from (Candra et al., 2017b).

<u>Developing a Battery Energy Storage System (BESS)</u>

Developments of a BESS consists of BESS model simulation and its hardware implementation. Schematically, a BESS model manages the calculation of a SOC battery, available energy in the battery, energy exchange in the battery and the battery cycle (Figure 4.26.).

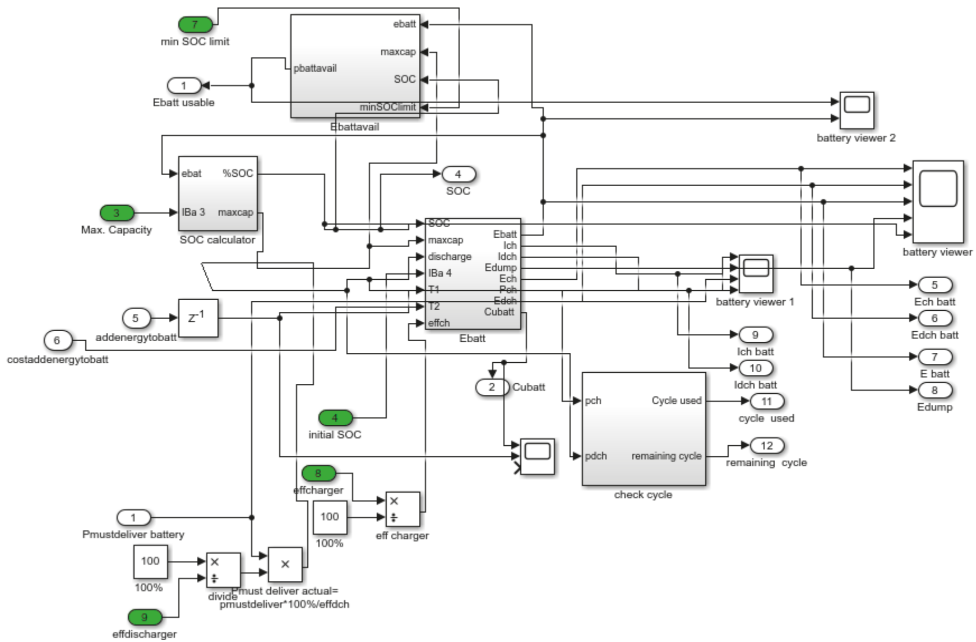


Figure 4.26. A BESS model on MATLAB-Simulink.

Source: Own Depiction.

On the SOC calculator, available energy on the battery will be compared to maximum battery energy.

$$SOC(t) = \frac{Ebat(t)}{Ebatmax} 100\%$$

Equation 4.13

For the energy battery model, considering initial the SOC $Esoc_0$, the following parameters are calculated: energy battery, charging/discharging current, dumping energy, charging/discharging energy and cost per unit unit battery.

$$Ebat(t) = Esoc_0 + \sum_{n=1}^{t} (Ebatch_n - Ebatdch_n)$$

Equation 4.14

Charging BESS should be done if only at SOC < 100 % and excess PV energy $Eexcesspv(t)$ is more than or equal to the remaining BESS energy $Ebatrem(t)$,

$$Eexcesspv(t) \geq Ebatrem(t)$$

Equation 4.15

$$Ebatrem(t) = \frac{(100 - SOC(t))}{100} Ebatmax$$

Equation 4.16

Charging current $Ich(t)$is then calculated from $batrem(t)$, the constant BESS voltage Vbat and charger efficiency $\eta_{ch.}$

$$Ich(t) = \frac{Ebatrem(t)}{\mathrm{Vbat}} \eta_{ch}$$

Equation 4.17

Thus, dumping energy at BESS $Edumpbat(t)$ would be calculated from the energy to charge BESS $Ebatch(t)$ and the excess PV energy $Eexcesspv(t)$.

$$Edumpbat(t) = Eexcesspv(t) - Ebatch(t)$$

Equation 4.18

In case where the BESS is not full (SOC < 100%) and excess PV energy is less than the remaining BESS energy, the charging current would be

$$Ich(t) = Eexcesspv(t)\eta_{ch}$$

Equation 4.19

Discharging current t $Idch(t)$ is based on the energy that must be delivered by the BESS information from optimization mode $Ebatmust(t)$, efficiency discharger $\eta dch(t)$ at constant voltage $Vbat$.

$$Idch(t) = \frac{Ebatmust(t)}{\mathrm{Vbat}}\eta_{dch}$$

Equation 4.20

In order to maintain battery capacity in the SOC range between 10% and 90 %, the usable available BESS energy $Ebatus(t)$ has to be calculated from current the BESS energy $Ebat(t)$ after having being reduced by its set minimum BESS energy $Ebatmin$.

$$Ebatus(t) = Ebat(t) - Ebatmin$$

Equation 4.21

Usable available energy from BESS is then used as available BESS energy information that would be delivered to the optimization model.

The set minimum BESS energy is calculated from minimum set BESS SOC limit $minSOClimit$ relative to maximum BESS energy $Ebatmax$.

$$Ebatmin = \frac{minSOClimit}{100}Ebatmax$$

Equation 4.22

As an optional feature for this model, a cycle calculation model is built by considering the number of charge and discharge cycles on the battery. The remaining cycle $Crem(t)$is calculated by the total full cycles $Cfull$ and cycles already used $Cused(t)$.

$$Crem(t) = Cfull - Cused(t)$$

Equation 4.23

$$Cused(t) = \sum_{n=1}^{t}(Cch_n + Cdch_n)$$

Equation 4.24

In this case, one cycle charge is equal to one time BESS charged, and one cycle discharge is equal to one time BESS discharged.

Additionally, in its real hardware implementation, the charging function is undertaken by a charger and the discharging function is undertaken by an inverter as a discharger (Figure 4.27.). The VPP server sends the schedule (time, amount) for the BESS system to charge/discharge its energy based in the VPP planning requirement. A PLC takes control of BESS components.

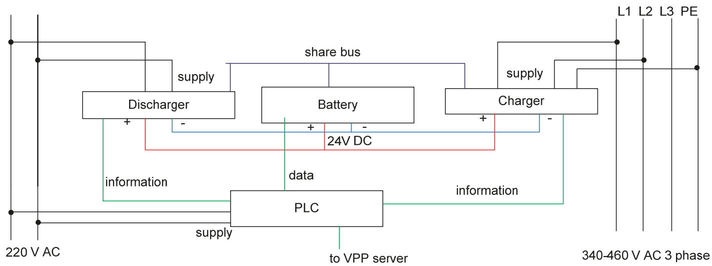


Figure 4.27. Schematic design of the BESS component in this study.

Source: Own Depiction.

The battery infrastructure for this study is similar to the battery infrastructure used by (Candra et al., 2017b). It consists of a battery, a charger, a discharger and a local controller (Figure 4.28.) with a lab-scale specifications.

Figure 4.28. A BESS under testing in this study.

Source: Adapted from (Candra et al., 2017).

4.2.4 Developing load demands' and PV's forecasting system

The forecasting system in a VPP has two main functions which are to predict the actual data and forecast the possible future of actual data. In the prediction part, the forecasting system in a VPP will try to learn the actual behavior of the data and try to regenerate the predicted data. The generated predicted data is then used by the forecasting part to forecast the possible future behavior of the actual data.

The forecasting system in this study was limited to the forecasting of load demands and the possible generated power from PV by conducting historical data analysis. The load demands forecast was developed using an Artificial Neural Network (ANN) analysis and concepts from (Papalexopoulos et al., 1994; Park et al., 1991; Santos et al., 2006) since ANN is one of the best model so far (Alfares and Nazeeruddin, 2002). The results forecast were calculated and based on historical data or data mining collection.

A PV power forecast considers proposed methods from (Monteiro et al., 2013; Swanepoel, 2010).Vector of uncertainty for a probability forecast is built to determine the point of probability PV power production in kW.

The trend of the curve is analyzed using ANN, thus mathematical functions will be developed at the end. Three criteria considered in the forecasting systems are error value, Mean Absolute Error (*MAE*) and Mean Square Error (*MSE*). *MAE* indicates forecast accuracy which shows the average of all absolute errors between forecasted and actual value. *MSE*, on the other hand, is not based on mean or average values, but rather on minimizing an underestimate in forecasting due to the impact of infrequent and relatively large errors. *MSE* is conducted by squaring the error before considering their mean values. It provides weighting for relatively large and infrequent errors. Combining *MAE* and *MSE* analyses is helpful in determining the error variation of the forecasting system. If *MSE* is greater than *MAE*, the error variance is relatively large. If *MSE* is equal to *MAE*, the error variance is negligible. Imagine n_e is number of error, p is data point, x_p is actual value at data point$p$, $\mathrm{y_p}$ is prediction at data point p, *MAE* and *MSA* arethen calculated by

$$MAE = \frac{1}{n_e}\sum_{p=1}^{n_e}\left|y_{\mathrm{p}} - \mathrm{x}_{\mathrm{p}}\right|$$

Equation 4.25

$$MSE = \sqrt{\frac{1}{n_e}\sum_{p=1}^{n_e}\left(y_{\mathrm{p}} - \mathrm{x}_{\mathrm{p}}\right)^2}$$

Equation 4.26

Sensitivity analyses of the forecasting system

Sensitivity analyses of the forecasting system are developed for a total of 95 observed pieces of data with each 10000 iterations based on a combination of these parameters: object (PV or demands), activation FNN function (semi linear, sigmoid, bipolar sigmoid, hyperbolic tangent), input layer (1, 20, 47) and hidden layer (1, 20, 47). Each of the ANN activation methods for PV or load demand forecasting system has 9 ANN configurations (Table 4.2). At the end there are (3 x 3) x 2 x 4 combinations (see Appendix 10.6, Table 10.3).

Table 4.2. Forecasting configurations for PV and demand for 4 ANN activation methods (semi linear, sigmoid, bipolar sigmoid, hyperbolic tangent).

Source: Own Depiction.

No.	Input layer(s)	Hidden layer(s)	Output layer(s)	Iteration
1	1	1	1	10000
2	1	20	1	10000
3	1	47	1	10000
4	20	1	1	10000
5	20	20	1	10000
6	20	47	1	10000
7	47	1	1	10000
8	47	20	1	10000
9	47	47	1	10000

4.2.5 Developing a VPP's optimization model

An optimization model is the core processor unit of a VPP. This model detects energy shortage and calculates the optimum energy, optimum cost, and optimum configuration of the combined power plants. The optimization model in this study is based on the Optimal Power Flow (OPF) model which itself is based on energy-cost based optimization.

DER based-on RES has stochastic dynamic characteristics, for example PV dynamically produces stochastic power based on solar irradiation. An adaptation of OPF analysis, such as in IEEE bus network in RES-based DER, relies on this characteristic to optimize energy produced as well as the cost expended (Figure 4.29.). OPF based on an optimal energy-cost optimization model is aimed at optimizing the techno-economical dispatching energy strategy.

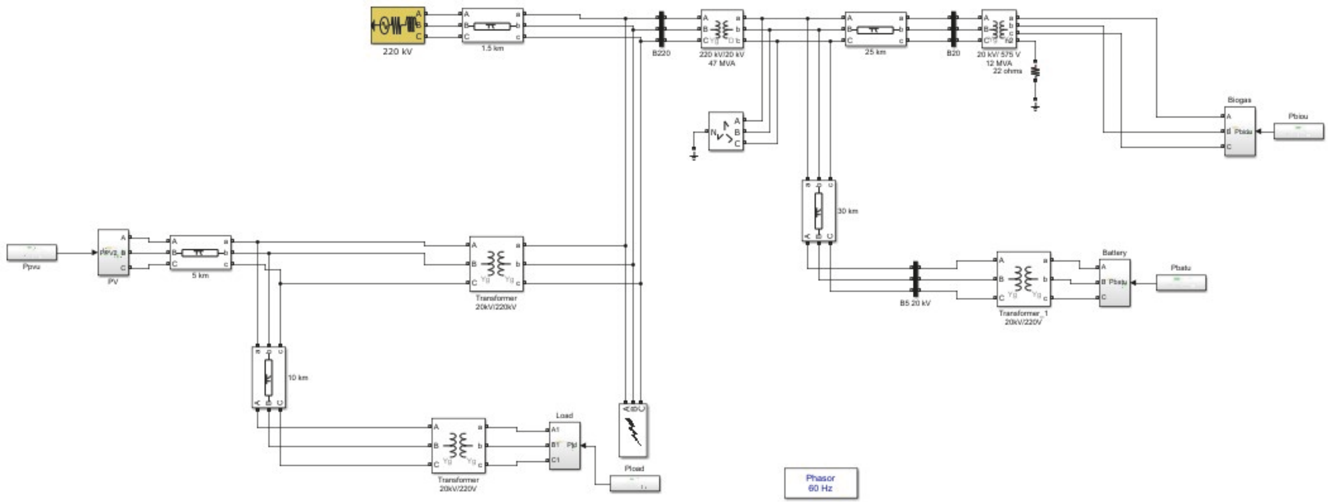


Figure 4.29. Representation of an electrical schematic diagram of RES-based DER on an IEEE-Bus system for optimal power flow optimization.

Source: Adapted from (The MathWorks, Inc, 2019).

The optimal energy-cost optimization $fte_i(t)$ model from three power plants i considers linear programming problem with coefficient vector as zeros $coef\_vector$ at time (t), cost unit per power plant $Cost_i(t)$ and their power $P_i(t)$:

$$fte_i(t)\,(coef\_vector) = min\,\sum_{i=1}^{n}(Cost_i(\mathrm{t})\,P_i(t))$$

Equation 4.27

subjected to:

-power balance constraints relative to load demand $Pload(t)$

$$\sum_{i=1}^{n}(P_i(\mathrm{t})) \geq Pload(t)$$

Equation 4.28

- power generation constraints with considering (upper $u_b(t)$ and lower bound $l_b(t)$), minimum $Pmin_i(t)$/ maximum $Pmax_i(t)$ generated power of each power plant, and number of power plants (PV *Npv(t)*, biogas *Nbio(t)*, BESS *Nbat(t)*)

$$Pmin_i(t) \leq P_i(t) \leq Pmax_i(t)$$

Equation 4.29

$$l_b(t) \leq fte_i(t) \leq u_b(t)$$

Equation 4.30

$$l_b(t) = [0,0,0]$$

Equation 4.31

$$u_b(t) = [Npv(t), Nbio(t), Nbat(t)]$$

Equation 4.32

- linear inequality constraints for optimized solution $fte_i(t)$ with considering usable energies (PV $Epvus(t)$, biogas $Ebious(t)$, BESS $Ebatus(t)$) and total of each maximum power plant energy $Emax_i(\mathrm{t})$

$$[Epvus(t), Ebious(t), Ebatus(t)](fte_i(t)) \;\leq\; \sum_{i=1}^{n}(Emax_i(t))$$

Equation 4.33

- linear equality constraints for optimized solution with considering usable energies and load energy $Eload(t)$

$$[Epvus(t), Ebious(t), Ebatus(t)](fte_i(t)) = Eload(t)$$

Equation 4.34

Optimal energy must be delivered by power plants (PV$Epvmust(t)$, biogas $Ebiomust(t)$, BESS $Ebatmust(t)$,) with their optimal solutions (PV $fte_{pv}(t)$, biogas $fte_{bio}(t)$, BESS $fte_{bat}(t)$) are

$$Epvmust(t) = Epvus(t)\big(fte_{pv}(t)\big)$$

Equation 4.35

$$Ebiomust(t) = Ebious(t)(fte_{bio}(t))$$

Equation 4.36

$$Ebatmust(t) = Ebatus(t)(fte_{bat}(t))$$

Equation 4.37

Optimum cost $Opticost(t)$is then calculated from each power plant cost (PV $Costupv(t)$, biogas $Costubio(t)$, BESS $Costubat(t)$) unit relative to their delivered energy

$$Opticost(t) = \frac{Costupv(t)Epvmust(t) + Costubio(t)Ebiomust(t) + Costubat(t)Ebatmust(t)}{Epvmust(t) + Ebiomust(t) + Ebatmust(t)}$$

Equation 4.38

4.2.6 Developing VPP's user interface

A user interface is an interface built for a VPP user/operator in order to handle the DER. Furthermore, a user interface provides flexibility for a VPP user/ operator to undertake Supervisory Control and Data Acquisition (SCADA) functionalities.

The development of the user interface started from the development of VPP servers and client concepts / architecture in virtualized machines (Figure 4.30.). Developing VPP Servers consists of the development of the application server and web server (incl. Database server). The application server manages information exchanges from local controllers of DER through PLCs. The web server manages a VPP visualization for a web environment user interface. The database servers manage data collection in the VPP.

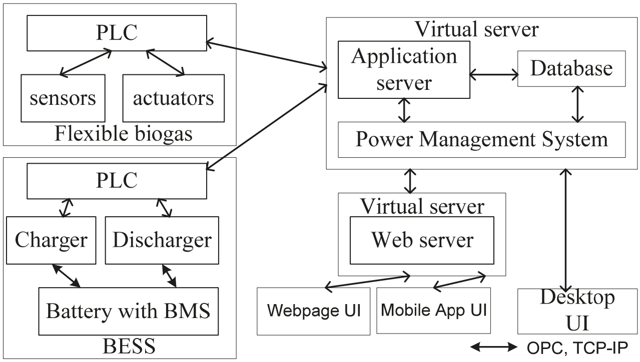


Figure 4.30. Virtualized VPP servers and its user interface environments (incl. back-end and front-end technologies used).

Source: Own Depiction.

In the development of user interface environments, back-end and front-end model categories were used (Table 4.3). An Object Linking Embedded for Process Control (OPC) was considered as as a smart grid standard as well as future requirements such as flexibility, scalability, reliability, functionality and interactivity. Technologies applied for user interface environments developments included OPC, Transfer Control Protocol-Internet Protocol (TCP-IP), Java Script Object Notification (JSON), Cascade Style Sheet (CSS), Hyper Text Markup Language (HTML) and Python.

Table 4.3. User interface environments developments based on back-end and front-end technologies.

Source: Own Depiction.

UI environments	Back-end technology	Front-end technology
Desktop	OPC, TCP-IP	Python-based UI using Kivy
Web	JSON, OPC, TCP-IP	JavaScript, CSS, HTML
Mobile application	JSON, OPC, TCP-IP	JavaScript, Multiplatform application using Apache Cordova

4.2.7 Analyzing a VPP performance and its boundaries

Analyzing a VPP performance will be done using the following ways:

- Analyzing behavior of DERs using the following ways:
  - Analyzing battery performance – undertaken by analyzing battery behavior in a VPP which refers to response and request, as well as battery SOC behavior as a single parameter were considered in this study.
  - Analyzing biogas performance – undertaken by analyzing the biogas dispatching strategy and the biogas feeding strategy.
  - Analyzing PV performance – undertaken by analyzing a VPP's ability to cover load demands.
- Analyzing a VPP's ICT performance. - conducted by analyzing the data exchange from request-response activities in a VPP.
- Investigating boundaries or limitations of DER on a VPP through:
  - Investigating a biogas plant boundary – undertaken by investigating flexible feeding
  - Investigating of the reaction time and gas production of a biogas plant

    A biogas plant will be measured quantitatively and qualitatively within standard techniques based on (Lehner et al., 2010). All the measured data is then monitored using a SCADA system. This investigation will help power management to determine a biogas plant contribution to answer load demand.
  - Investigating boundaries or limitations of a VPP from the PV plant mainly regarding power availability.

    This is done by analyzing trend performance of PV power availability. The method from (Monteiro et al., 2013) is adopted in order to find the PV power production behavior or profile. Forecast method used to determine the profile. Once the profile is found, the contribution of the PV plant to answer load demand can be determined. Comparing forecasted data to real data in order to optimize VPP performance. If forecasted data is under/ overestimate compared to real data than a re-forecast analysis will to be conducted. This is done by evaluating parameter inputs used in forecasting models.

- Investigating other parameters such as time response and technical limitations of a VPP.

4.2.8 Sensitivity analyses

In this sensitivity analyses, the capacity or size of DERs in a VPP platform will be adjusted and plotted for different market products (based on (Candra et al., 2018)). The DER will be adjusted to the different ratios. In addition, the DER ratio of PV:battery:biogas indicates the power capacity of each power plant.

A PV with a ratio factor of 1 means that the PV has a power capacity of 15 MW multiplied by a ratio factor 1, and so on. A battery with a ratio factor of 1 means that the battery has a power capacity of 7,5 MWh multiplied by a ratio factor of 1, and so on. A biogas with a ratio factor of 1 means that the battery has a power capacity of 15 MW (or 25 for base load and week futures) multiplied by a ratio factor of 1, and so on.

Total analyzed market products are 68 for Day-Ahead (DA) markets and 4 products of Week-Future (WF) markets (Appendix 10, Table 10.4.). Based on these sensitivity products, Monday is used to represent the beginning of the week, while Saturday is used to represent the beginning of the weekend. Market prices and magnitude of required power for each market are described by (Appendix 10, Table 10.6 and Table 10.7) which are derived from electricity market data from the (European Power Exchange, 2015).

The expected results from sensitivity analyses would be used to analyze:

- The impact of DER sizes to the technical economical VPP configuration to answer load demands
- The profit/ losses from the contribution margin CM_p for each market product p (see Appendix 10, Table 10.8) of the VPP by comparing marginal costs $Copt_p$ and market prices MP_p (according to (Candra et al., 2018)).

Table 10.8

$$CM_p = BP_p - Copt_p$$

Equation 4.39

This analysis adopted previous works done by (Müsgens, 2004). The use of marginal cost-based theory in the calculation of marginal costs is alligned to proposed features (Richter and Adigbli, 2014) for further EEX SPOT developments.

Table 4.4. DER sizes adjustments for sensitivity analyses in this study.
Source: Adapted from (Candra et al., 2018).

VPP configuration	**PV:battery:biogas**	**Properties**
1	1:1:1 (15 MW: 7.5 MWh:15 MW or 25 MW[1])	Assumed: - PV: max. 180 MW_{AC}, 20 years lifetime, 0 €/kWh marginal cost - Battery: max. 100 MWh, 10 years lifetime, marginal cost varies and depends on market prices +10%, efficiency 95% - biogas: max. 20 MW_{AC}, 10 years lifetime, 0,10 to 0,15 €/kWh[2] marginal cost, 40% efficiency
2	1:2:1	
3	1:3:1	
4	2:1:1	
5	2:2:1	
6	2:3:1	
7	3:1:1	
8	3:2:1	
9	3:3:1	

[1] only for baseload and Week Futures, [2] according to (Aschmann and Effenberger, 2013; Bofinger et al., 2010; BMWi, 2016; Dachs et al., 2006; Ruhnau et al., 2011; Schmid et al., 2009).

5 Results

5.1 Integrated power plants in VPP

This chapter describes the findings of the study including the results regarding the technical integration of VPP, the VPP balancing mechanism, the VPP components performances and the VPP limitations

5.1.1 Technical integration of RES in grid and power market

Implementing the MAS and the SGAM concepts enables a PV system, a battery, and a biogas power plant to be integrated into a VPP system. The results from the implementation of these methods (integration using MAS or integration using the SGAM concept or integration using the combined MAS- SGAM concept) generally show a sucessful integration of DERs.

This research shows that a different method of a DER integration lead to a different characteristic of a VPP implementation. Specifically, that the MAS concept is one of the simplest determination of how VPP is developed compared to the SGAM concept and the combined MAS & SGAM concept. However the MAS is relatively difficult to be interpreted into a real application than other methods due many assumptions that are required during the its implementation.

The VPP realization in this study also resulted in a bottom-up approach DER integration that enabled the application of a modularity approach for power plant models or agents. This result was relevant to the future requirements in the power generation, which consists of an increasing number of decentralized power plants in the grid. Furthermore, further research is recommended since this integration in the VPP using the MAS and SGAM concept was in its early stages, especially for flexible biogas implementation.

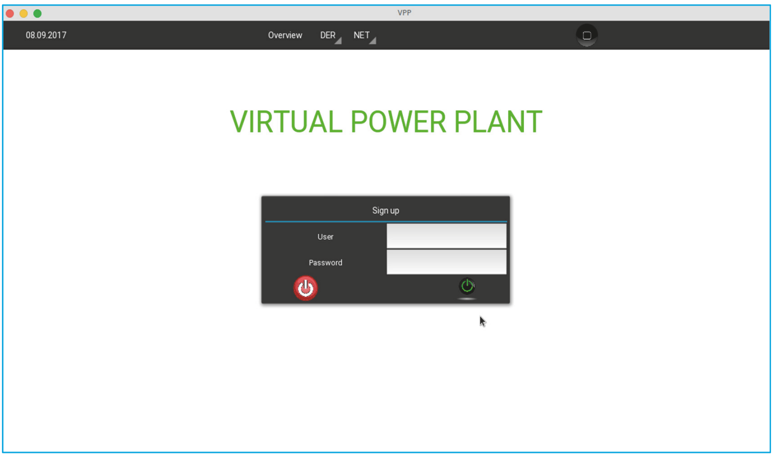
5.1.2 User interface

In the DER integration (PV-biogas-battery) process, the application of the Open Platform Communications (OPC) and the Transmission Control Protocol-Internet Protocol (TCP-IP) as back-end technology supported the ICT and data exchange for different user interfaces (desktop, web, mobile). On the back-end technology level, it was found that there is no difference in how the data was managed. Regardless of wether the MAS or SGAM concept was used, the back-end technology was able to minimize and adapt to the complex requirements in the control of power plants.

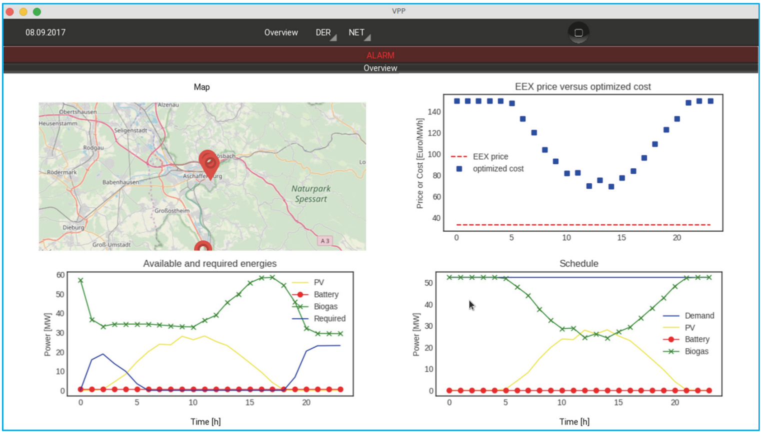
The application of OPC and TCP-IP also helped to reduce the complexity of the ICT development of the VPP by categorizing its requirements for the complex application in power generation.

On the front-end technology level, the VPP with selected programming languages (mainly Python and JavaScript) enabled the VPP's compatibility to be deployed to different Operating Systems (OSs). This application was classified as a multi-platform application (see also Appendix 10.5).

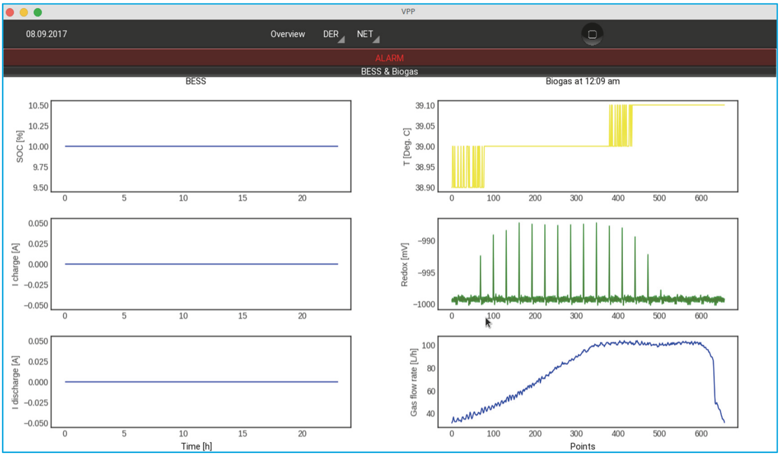
Moreover, regarding visualization, the VPP in this study was able to meet SCADA functionalities for VPP users.



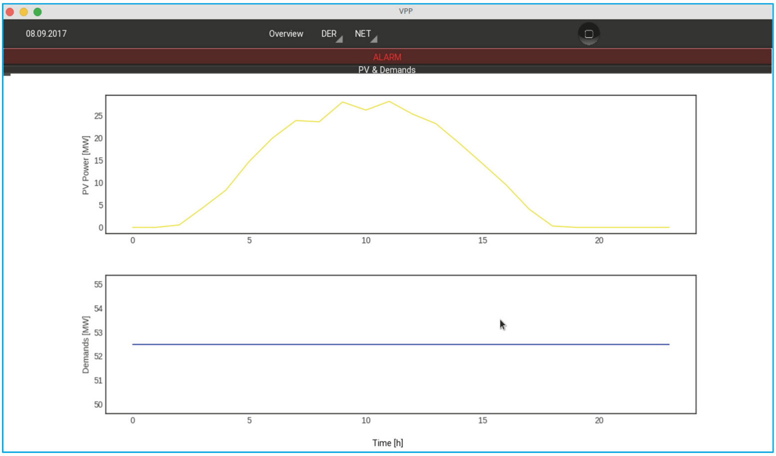
(a)


VPP
08.09.2017
Overview
DER
NET
ALARM
Overview
Map
EEX price versus optimized cost
Price or Cost [Euro/MWh]
EEX price
optimized cost
Available and required energies
Power [MW]
PV
Battery
Biogas
Required
Time [h]
Schedule
Power [MW]
Demand
PV
Battery
Biogas
Time [h]

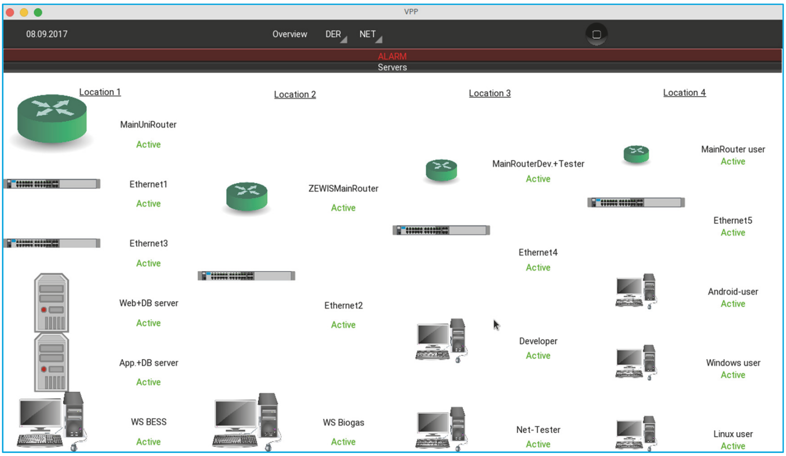
(b)


VPP
08.09.2017
Overview
DER
NET
ALARM
BESS & Biogas
BESS
Biogas at 12:09 am
SOC [%]
T [Deg. C]
I charge [A]
Redox [mV]
I discharge [A]
Gas flow rate [L/h]
Time [h]
Points

(c)


VPP
08.09.2017
Overview
DER
NET
ALARM
PV & Demands
PV Power [MW]
Demands [MW]
Time [h]

(d)


VPP
08.09.2017
Overview
DER
NET
ALARM
Servers
Location 1
Location 2
Location 3
Location 4
MainUniRouter
Active
Ethernet1
Active
Ethernet3
Active
Web+DB server
Active
App.+DB server
Active
WS BESS
Active
ZEWISMainRouter
Active
Ethernet2
Active
WS Biogas
Active
MainRouterDev.+Tester
Active
Ethernet4
Active
Developer
Active
Net-Tester
Active
MainRouter user
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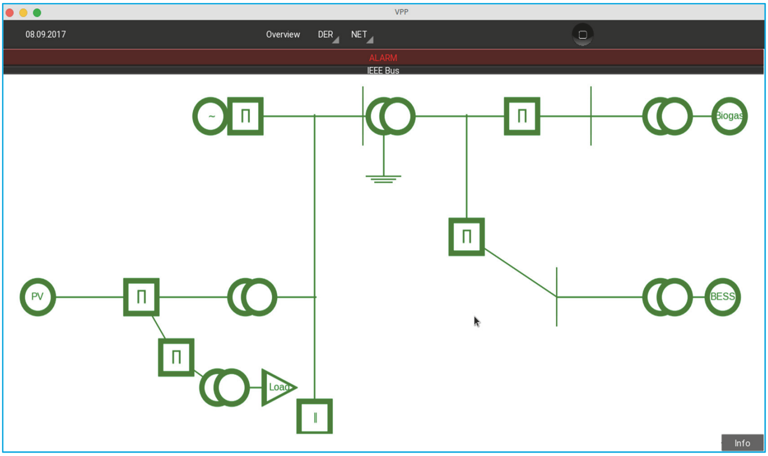
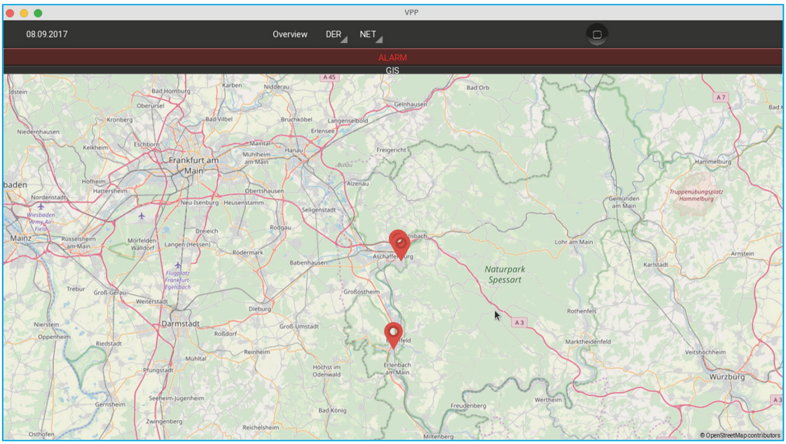
Ethernet5
Active
Android-user
Active
Windows user
Active
Linux user
Active

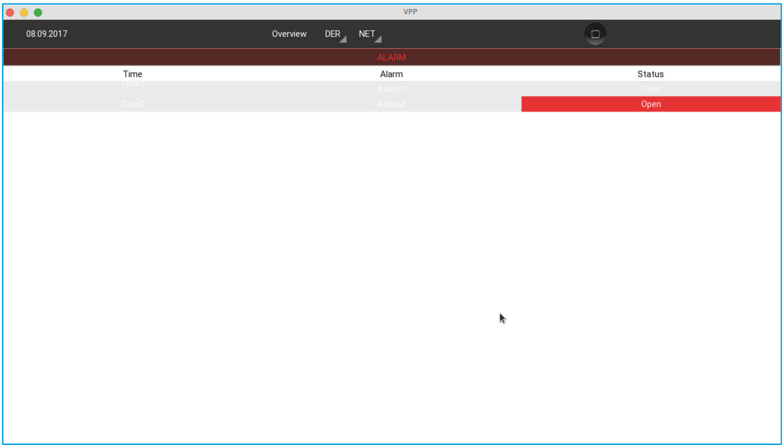
(e)


VPP
08.09.2017
Overview
DER
NET
ALARM
IEEE Bus
Biogas
PV
Load
BESS
Info

(f)


VPP
08.09.2017
Overview
DER
NET
ALARM
GIS
Frankfurt am Main
Darmstadt
Naturpark Spessart
Würzburg
© OpenStreetMap contributors

(g)



(h)

Figure 5.1. Virtualized VPP desktop user interface environments (a) login page, (b) overview page, (c) BESS and biogas page, (d) PV and demands page, (e) servers page, (f) IEEE bus page, (g) GIS page, (h) alarm page.

Source: Own Depiction.

5.1.3 VPP components interactions

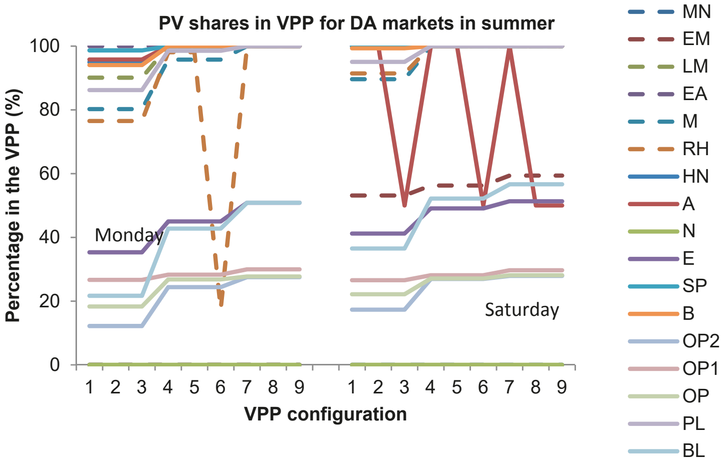
This sub-chapter shows findings which are related to interactions between VPP components through identifier mechanisms on the MAS concept and based on the SGAM. These findings show that the VPP is able to be deployed distributedly and autonomously within reliable processing times to support minimum time delays on the frequency regulation tasks. Therefore, the results are comparable to the decentralized, active and adaptive VPP developed by (Hossain and Mahmud, 2014).

5.2 VPP components performance

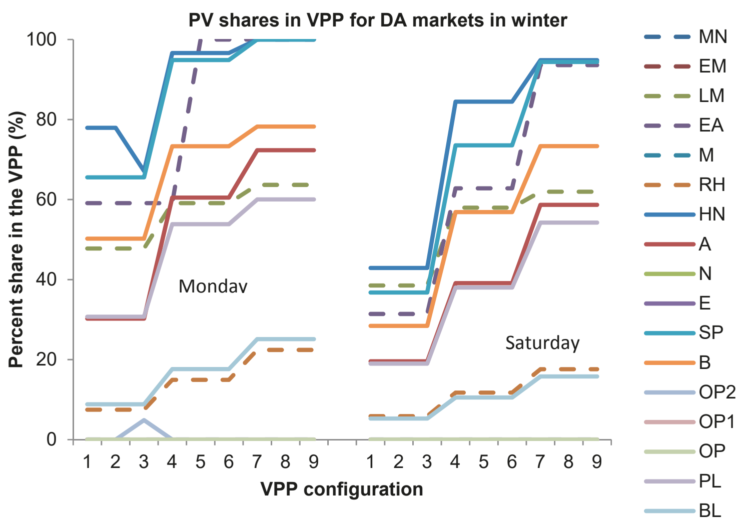
5.2.1 PV Performance

Through implementation of nine different configurations for different market types (DA and WF), the VPP in this study shows that trends of share of PV energy in VPP in summer or winter are increasing as the size of DER in the VPP configuration increased (Figure 5.2. (a) to (c)). However, in some cases such as in Rush-

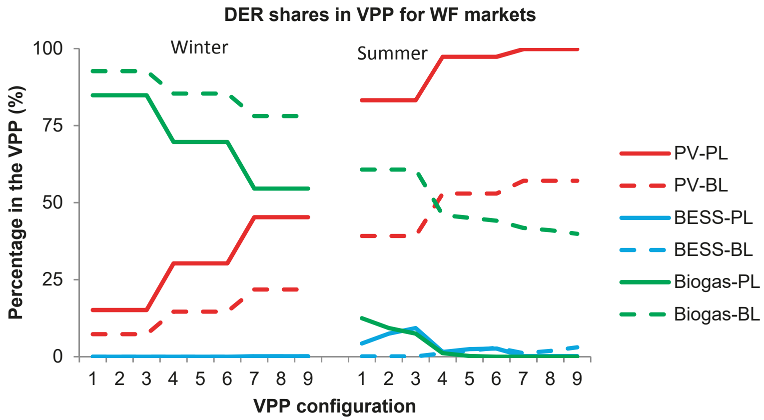
Hour (RH) and Afternoon (A) in summer (Figure 5.2. (a)), there was a fluctuation in the trend of this PV share in the VPP. The PV also did not contribute much power in winter at Noon (N) market (Figure 5.2. (b)).



(a)



(b)



(c)

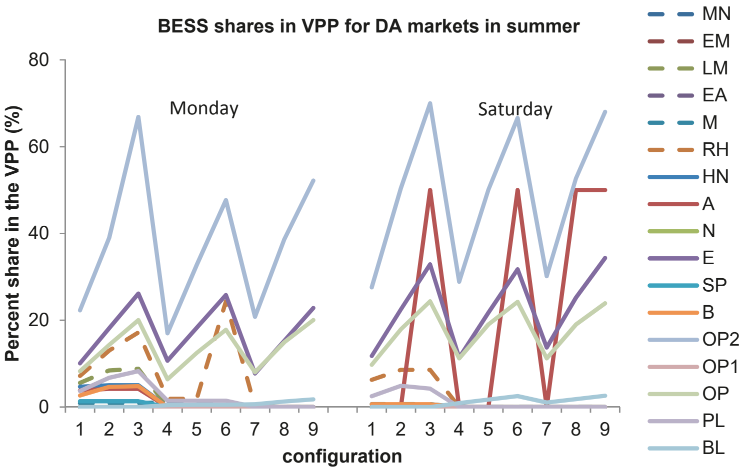
Figure 5.2. DER behavior at different VPP configurations: (a) PV in DA summer, (b) PV in DA winter, (c) PV-BESS-biogas in WF summer and winter.

Source: Own Depiction.

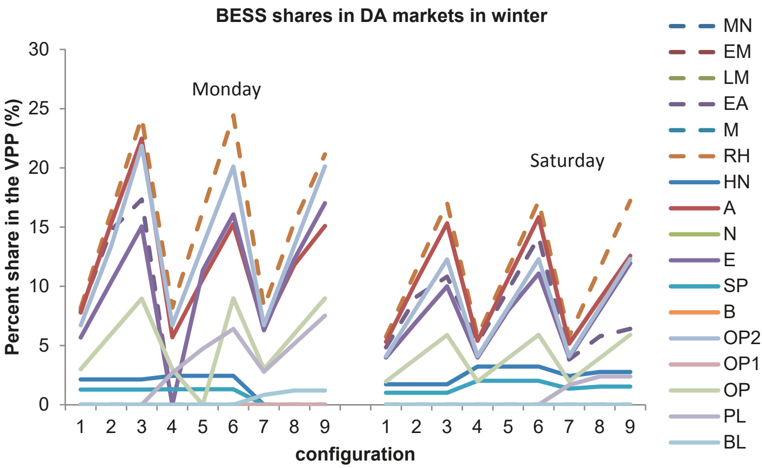
5.2.2 Battery performance

Battery in VPP

Findings regarding the contribution of BESS or the Battery in the VPP in (Figure 5.3. (a) and (b)) show that the Battery performance was fluctuating in winter or summer when DER sizes increased. It also means that increases in the DER sizes did not positively relate to the increasing share of battery in the VPP. These fluctuations then became much more stable when the Battery was deployed for Evening (E) market or Sun-Peak (SP) market. In these markets, the Battery contributed a relatively lower share in the VPP than on the other markets. Moreover, in summer, the Battery contributed at least twice as much more than in winter application. In WF markets (Figure 5.2. (c)), the Battery contributions were relatively low (the lowest among others) even when the DER size was increased.



(a)



(b)

Figure 5.3. Battery behavior in different market products on the DA market at different VPP configurations: (a) in summer, (b) in winter.

Source: Own Depiction.

Battery SOC performance

The results show that the performance of the battery was manageable within its safe operation levels indicated by its SOC level. It was assumed that the safe operation of this battery was between 10% to 100% of its total capacity (Figure 5.4.). The performance of the battery was managed by the MAS battery which simulated the battery behavior during different period, load demands, and seasons. In winter the battery's SOC level fluctuates more than in summer. Furthermore, the battery performance in the VPP was also limited by technical constraints of battery.

Since the impact of battery performance on longer-term application was not investigated during this study, it is recommended in the future to investigate other battery parameters such as the impact of battery temperature during the VPP operation.

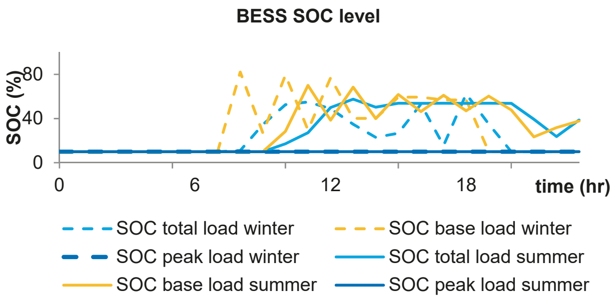


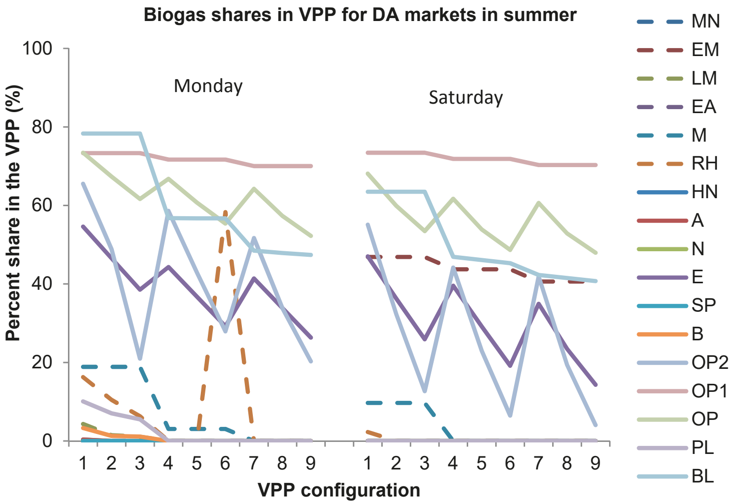
Figure 5.4. Sample of Battery SOC at summer and winter for DA market.

Source: Own Depiction.

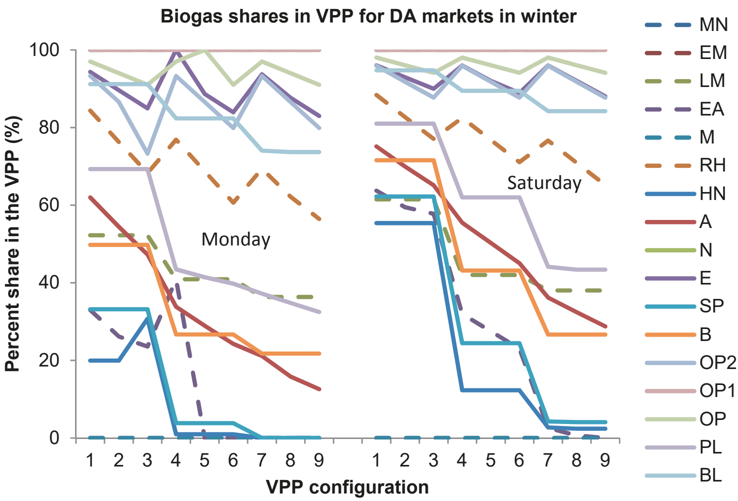
5.2.3 Biogas performance

Biogas in VPP

Regarding biogas performance in the VPP, the findings show that the performance of biogas to answer load demands in the VPP depended on the share of PV energy and battery energy. In DA markets, with increasing size of DER, the trend of share of biogas energy on Saturday was quite similar to the trend share of biogas energy on Monday with an offset value. In these markets, there was a fluctuated trend of share, a decreased trend of share or a relatively stable trend of share of biogas (Figure 5.5.). The stable trend of share of biogas occurred when the VPP was applied to Off-Peak 1 (OP1) with a value of at least 70%. In WF markets (Figure 5.2. (c)) as DER sizes increased, the trend of share of biogas decreased. The trend of biogas's share was mirroring the trend of PV's share.



(a)



(b)

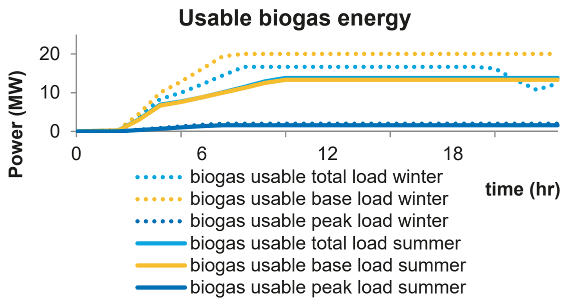
Figure 5.5. Biogas behavior at different VPP configurations: (a) in DA summer, (b) in DA winter.

Source: Own Depiction

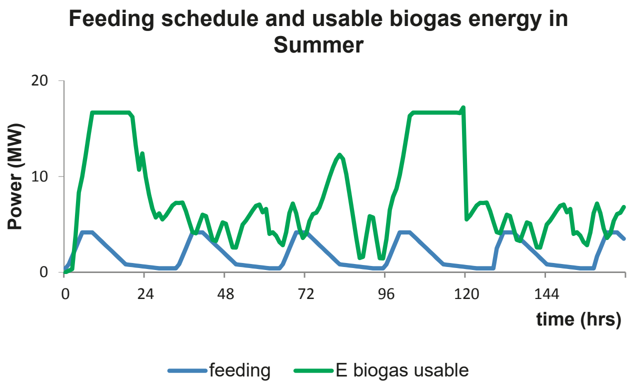
<u>Biogas feeding strategy</u>

Apart from the share of biogas in the VPP, the biogas performance can also be analyzed from its performance on feeding strategy When the biogas was fed at the beginning of the VPP application, the biogas would have generated usable power for the VPP (see example in Figure 5.6. (a If feeding was done for a longer-term, such as in the application to WF markets , the fluctuations of usable biogas potentials was remarkable (Figure 5.6. (b)). From the example in summer from (Figure 5.6. (b)) shows that six times feeding (at time of 0,34, 65, 96, 127 and 158 hour); it would not have always generated a similar biogas potential peak after feedings were done. In a real-world implementation, the biogas feeding strategy was converted to a signal of feeding and recorded on a data logger together with gas flowrate (Figure 5.6. (c)).

In addition to these findings, the generated gas from the flexible biogas in this study proved that it was able to produce flexible gas based on the requirements. Furthermore, the VPP was able to generate signals for flexible feeding and the biogas's local controller was also able to provide response or reaction to this signal and then answered the challenge in the future time. This finding is important regarding the integration and control different RES-based power plants in order to meet the grid requirements.



(a)



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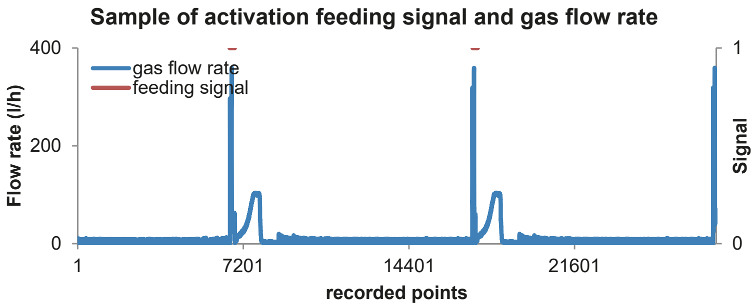


(c)

Figure 5.6. Biogas feeding strategy based on first VPP configuration: (a) For short term (24 hours) during one-time feeding strategy at the beginning of the experiment, (b) In summer in WF market, (c) Sample of feeding signal activation and gas flow rate (07.09.2017 to 11.09.2017 at 38.5 °C, ~ -999.1 mV redox for 20 l substrate with 600 g sugar).

Source: Adapted from (Candra et al., 2017b).

Monitored biogas parameters

Biogas performance seen through monitored parameters in the biogas controller is essential to understand the biochemical as well as the physical processes inside biogas. Some of the example monitored parameters were gas flow rate, redox value and fest bed temperature (Figure 5.7.). In this example, after feeding was done at a stable fest bed temperature, redox value began to climb up to a specific value and then began to climb down once gas flow rate had reached its maximum value. In this case, gas flow rate was gradually increased until reached its peak value for some hours and then suddenly went down. The time required for the whole process was at least 2.5 hours.

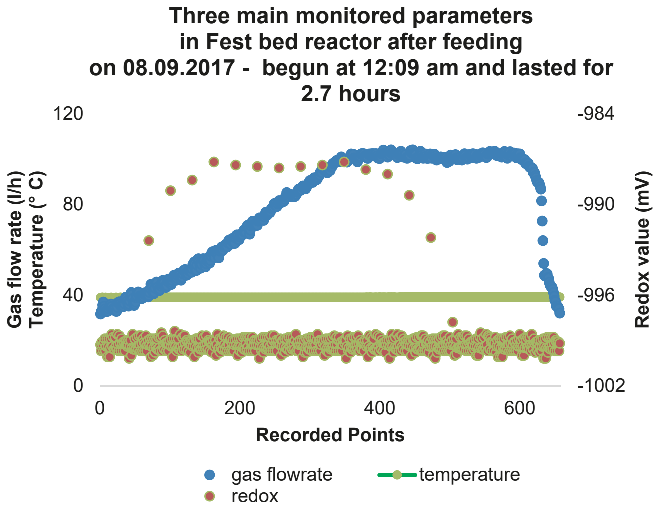


Figure 5.7. Sample of controlled biogas parameters – with addition of 600 g sugar to the substrate (Experiment was conducted on 08.09.2017, begun at 12:09 am and lasted for 2.7 hours.).

Source: Own Depiction

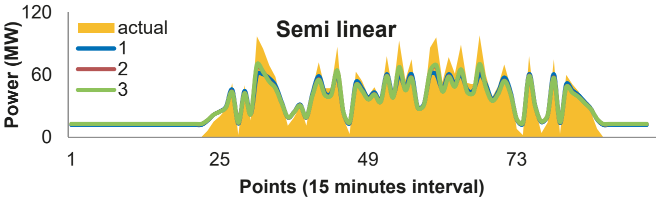
5.2.4 Forecasting system (PV Power and Demand)

The results for the sub-chapter of the forecasting system shows that various models of the forecasting systems developed in this study successfully generated predicted and then forecasted values of PV power production and load demands. Those predicted and forecasted values were close to the historical/ actual data.

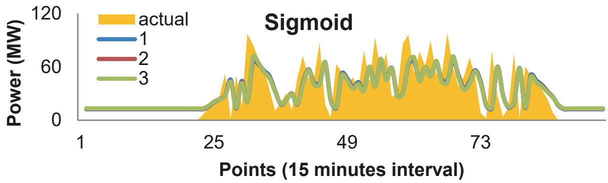
<u>Predicted vs Historical Value of PV Power Production Step - A(1)</u>

The PV power production's prediction using ANN activation functions ((a) semi linear activation (b) sigmoid activation, (c) bipolar sigmoid activation and (d) Hyperbolic tangent activation) show for configuration numbers 1 to number 3 a similar result. There are still gaps, especially in the value at peak and at valley, between the predicted and historical values of PV production.(Figure 5.8.).

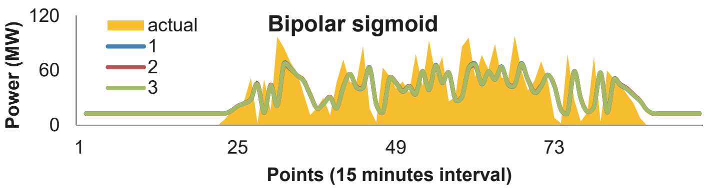
However, the result of configuration number 3 using (d) Hyperbolic tangent activation shows that there were fewer errors at the beginning and end of the prediction process compared to other configurations. Configuration number 3 using functions of Hyperbolic tangent consists of one piece of learning data, 47 hidden layers and one output layer.



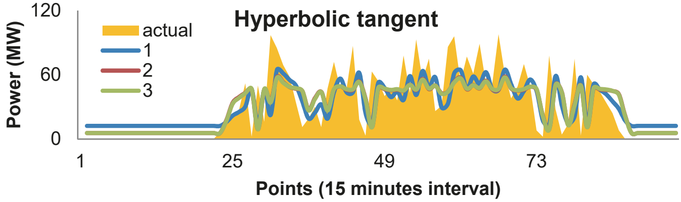
(a)



(b)



(c)



(d)

Figure 5.8. Predicted and actual PV power for 1st to 3rd ANN configuration with : (a) semi linear activation (b) sigmoid activation, (c) bipolar sigmoid activation, (d) hyperbolic tangent activation.

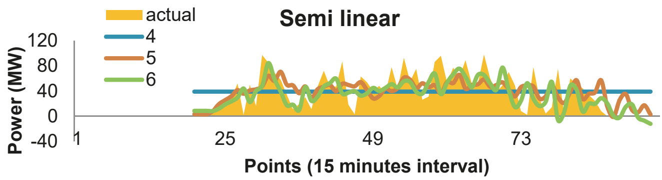
Source: Own Depiction

Predicted vs actual PV Power Production - Step A(2)

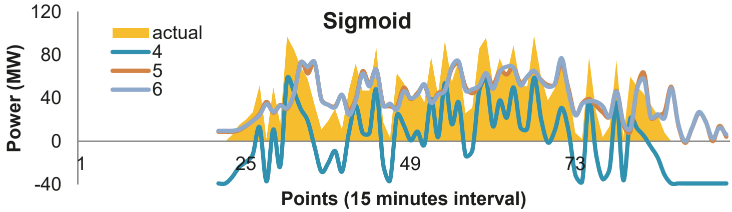
The results show that if learning data was increased to 20 (4th to 6th configuration) and the hidden layer was fixed at one (4th ANN configuration), the prediction system would have generated: a flat trend of predicted value (Figure 5.9. (a)), a trend where predicted value was bigger than historical value (Figure 5.9. (b)) and/or possible combination of those two trends(Figure 5.9. (c) and (d)).

When using semi linear and sigmoid functions, increasing both the number of inputs and hidden layers led to a trend, where predicted values were smaller than historical value. Using these functions, the result would have been the same, even the number of hidden layers was increased two times.

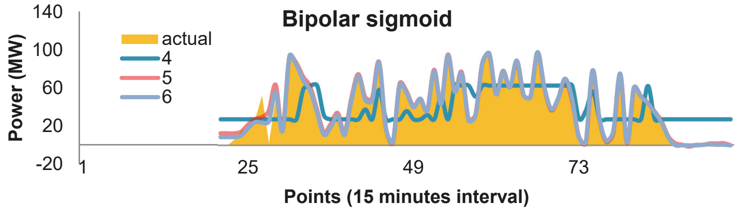
The preferred results of PV power prediction were achieved when Bipolar sigmoid and Hyperbolic tangent functions were used (Configuration number 5 and 6). The number of the input layer and hidden layer for those configurations was 20 of 95 total observed pieces of data (Chapter 4.2.4).


Semi linear
actual
4
5
6
Power (MW)
120
80
40
0
-40
1
25
49
73
Points (15 minutes interval)

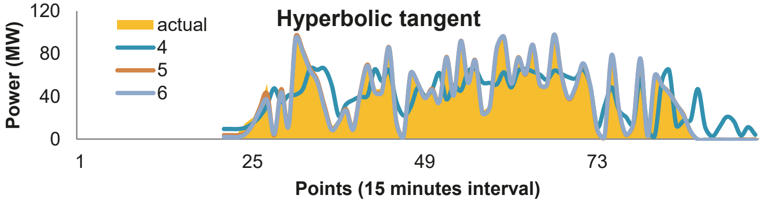
(a)


Sigmoid
actual
4
5
6
Power (MW)
120
80
40
0
-40
1
25
49
73
Points (15 minutes interval)

(b)


Bipolar sigmoid
actual
4
5
6
Power (MW)
140
100
60
20
-20
1
25
49
73
Points (15 minutes interval)

(c)



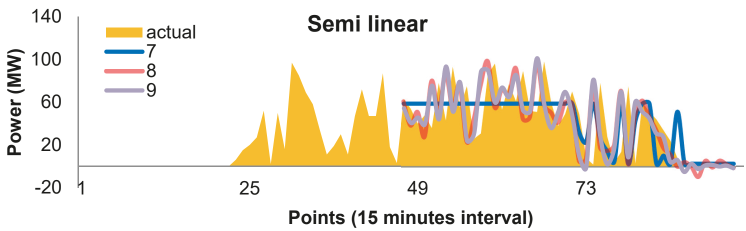
(d)

Figure 5.9. Predicted and historical/actual PV power for 4th to 6th ANN configuration with : (a) semi linear activation (b) sigmoid activation, (c) bipolar sigmoid activation, (d) hyperbolic tangent activation.

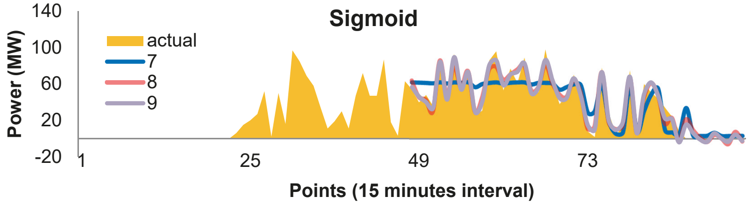
Source: Own Depiction

Predicted vs Actual Value of PV Power Production - Step A(3)

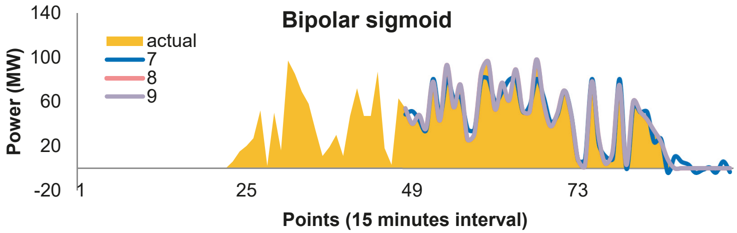
If the number of the input layer was a half of total historical PV value and when using the hyperbolic tangent function, predicted values would be considerably closer to the value of the actual/ historical PV data. This also only happened in other approaches if the number of the hidden layer was also increased to a value at least 20 of 95 total observed pieces of data (Chapter 4.2.4) (Figure 5.10. (a) to (c)).



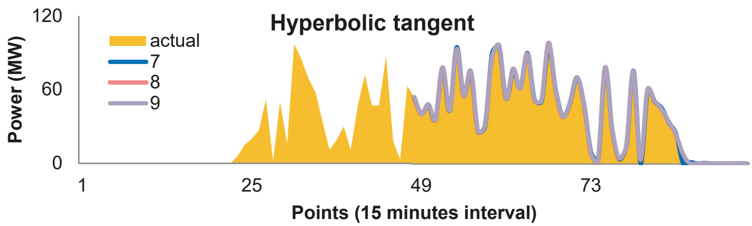
(a)



(b)



(c)



(d)

Figure 5.10. Predicted and historical/actual PV power for 7th to 9th ANN configuration with : (a) semi linear activation (b) sigmoid activation, (c) bipolar sigmoid activation, (d) hyperbolic tangent activation.

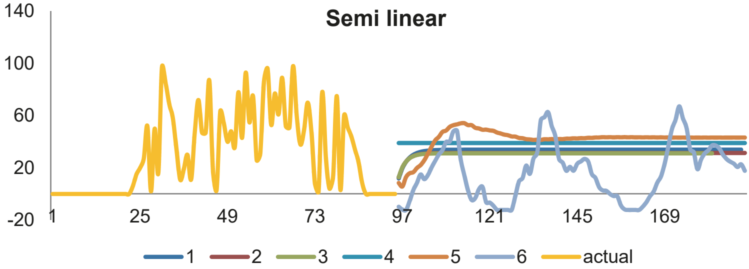
Source: Own Depiction

Forecasted vs Historical PV Power Production - Step B

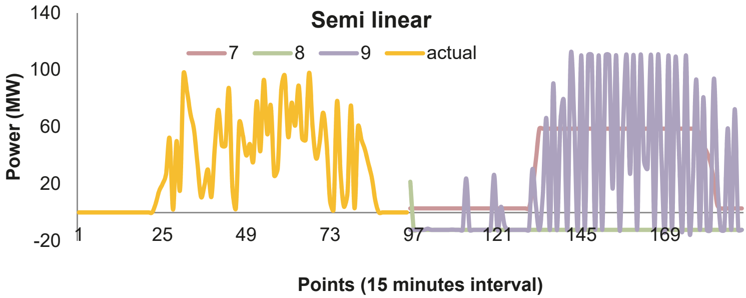
The results show that the forecasting system of VPP developed in this study is able to generate a preferable value of future PV potential. Through conducting tests using nine different configurations and four functions, it was found that two of the several functions developed in the forecasting system in this VPP were able to produce data that were close to the value of future PV power potential.

In detail, (Figure 5.11.) represent the model of (e) bipolar sigmoid 5th ANN configuration and Figure 5.11. (f) bipolar sigmoid 9th ANN configuration which produced considerable forecasted value. This therefore shows that the bipolar sigmoid function was considerable approach both for predicting and forecasting PV power.

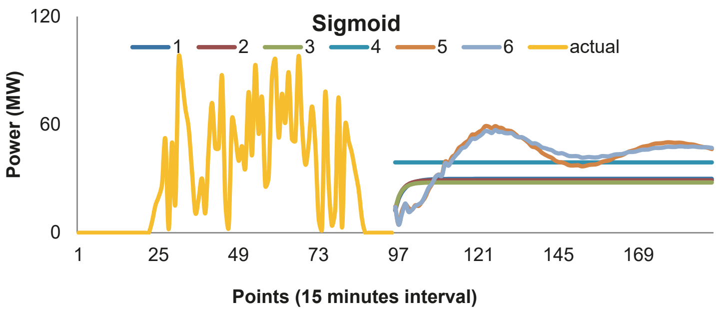
On the other hand, other functions presented in Figure 5.11. , including (b) at 9th ANN configuration, Figure 5.11. (f) at 7th ANN configuration and Figure 5.11. (g) at 5th and 6th ANN configuration) generated under-forecasted or over-forecasted values. In addition, the hyperbolic tangent approach was found to be not suitable enough in forecasting the PV power even though it was the most reliable approach for PV power prediction.


Semi linear
140
100
60
20
-20
1
25
49
73
97
121
145
169
1
2
3
4
5
6
actual

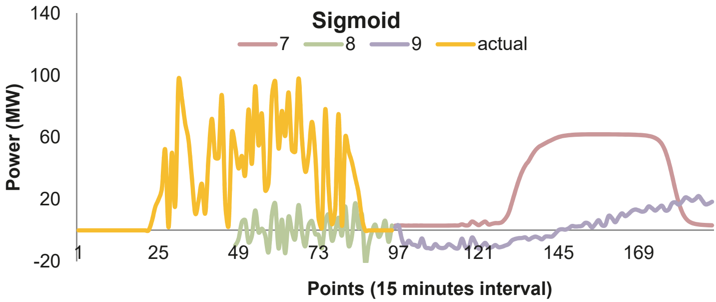
(a)


Semi linear
7
8
9
actual
Power (MW)
140
100
60
20
-20
1
25
49
73
97
121
145
169
Points (15 minutes interval)

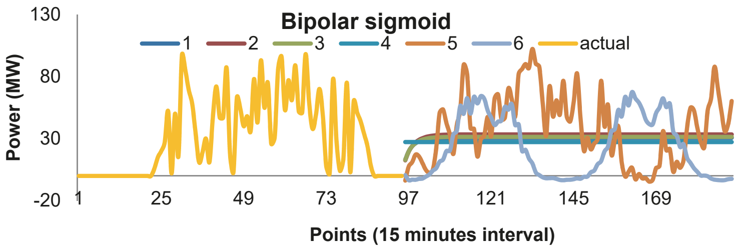
(b)


Sigmoid
1
2
3
4
5
6
actual
Power (MW)
120
60
0
1
25
49
73
97
121
145
169
Points (15 minutes interval)

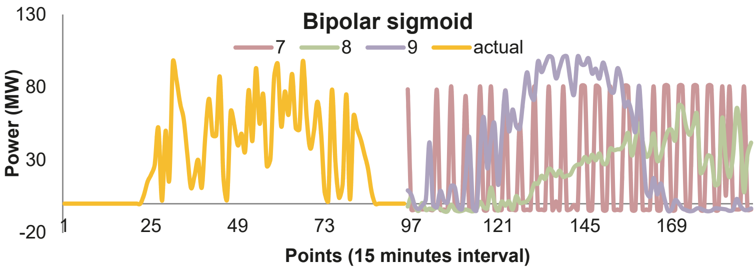
(c)


Sigmoid
7
8
9
actual
140
100
60
20
-20
Power (MW)
1
25
49
73
97
121
145
169
Points (15 minutes interval)

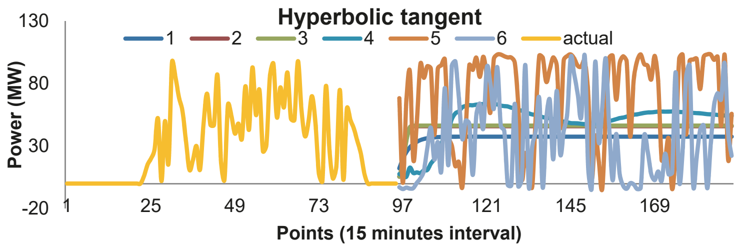
(d)


Bipolar sigmoid
1
2
3
4
5
6
actual
130
80
30
-20
Power (MW)
1
25
49
73
97
121
145
169
Points (15 minutes interval)

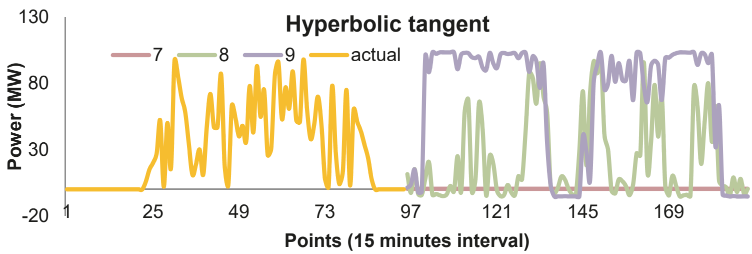
(e)


Bipolar sigmoid
7
8
9
actual
130
80
30
-20
Power (MW)
1
25
49
73
97
121
145
169
Points (15 minutes interval)

(f)



(g)



(h)

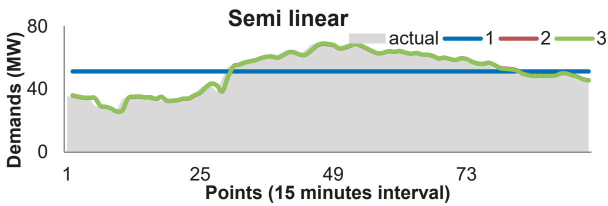
Figure 5.11. Predicted and historical/actual PV power: (a) 1st to 6th ANN configuration with semi linear activation, (b) 7th to 9th ANN configuration with semi linear activation, (c) 1st to 6th ANN configuration with sigmoid activation, (d) 7th to 9th ANN configuration with sigmoid activation, (e) 1st to 6th ANN configuration bipolar with sigmoid activation, (f) 7th to 9th ANN configuration with bipolar sigmoid activation, (g) 1st to 6th ANN configuration with hyperbolic tangent activation, (h) 7th to 9th ANN configuration with hyperbolic tangent activation.

Source: Own Depiction

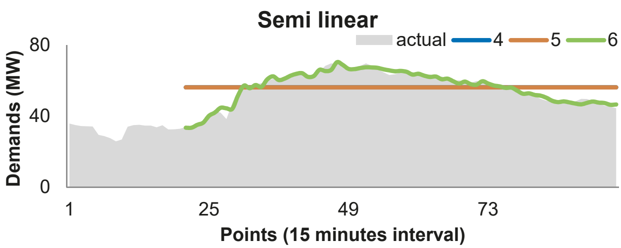
Predicted vs actual load demands- Step A

Results of load prediction in (Figure 5.12.) show that the increase in the number of the hidden layer to point 47 of the 95 total number observed pieces of data in all applied funtions (Semi Linear, Sigmoid, Bipolar Sigmoid and Hyperbolic Tangent) leads the prediction system to generate ‘’a copy’’ of actual load demands. This is presented in configuration numbers 3, 6, and 9.

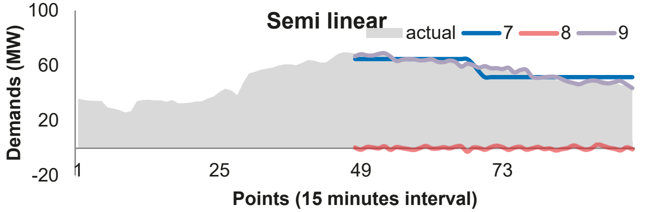
In addition, the predicted results would have been under-predicted or even over-predicted when the humber hidden layer is less than 49% of the total number of pieces of observed data. The under or over prediction was shown by a linear line, a curved line across the x-axis, a curved line over actual load demands or combination of both. The prediction system will generate "a copy of" actual load demands when the number of the hidden layer is increased.



(a)

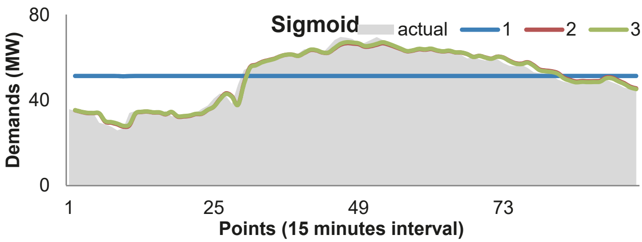


(b)



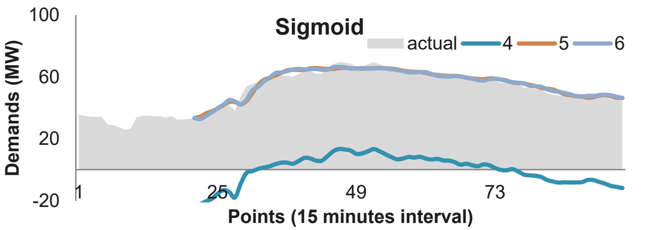
Semi linear
actual
7
8
9
100
60
20
-20
1
25
49
73
Demands (MW)
Points (15 minutes interval)

(c)



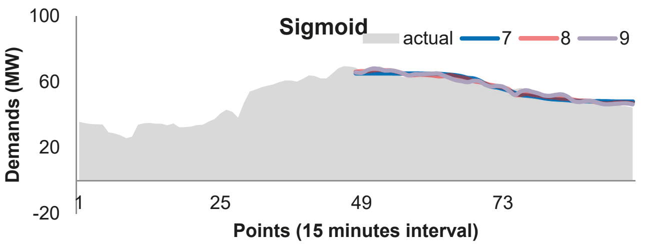
Sigmoid
actual
1
2
3
80
40
0
1
25
49
73
Demands (MW)
Points (15 minutes interval)

(d)



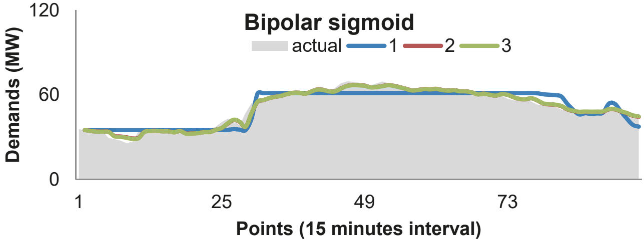
Sigmoid
actual
4
5
6
100
60
20
-20
1
25
49
73
Demands (MW)
Points (15 minutes interval)

(e)

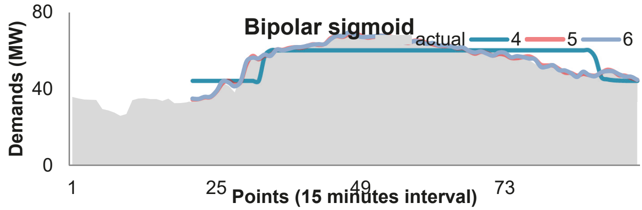


Sigmoid
actual
7
8
9
100
60
20
-20
1
25
49
73
Demands (MW)
Points (15 minutes interval)

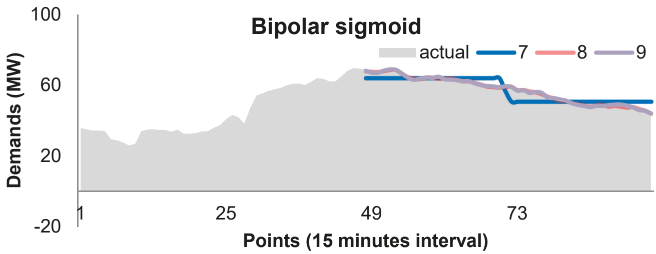
(f)


Bipolar sigmoid
actual 1 2 3
120
60
0
Demands (MW)
1
25
49
73
Points (15 minutes interval)

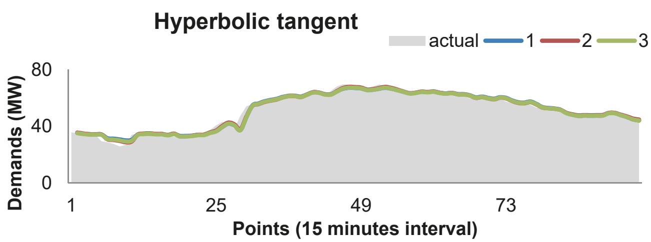
(g)


Bipolar sigmoid
actual 4 5 6
80
40
0
Demands (MW)
1
25
49
73
Points (15 minutes interval)

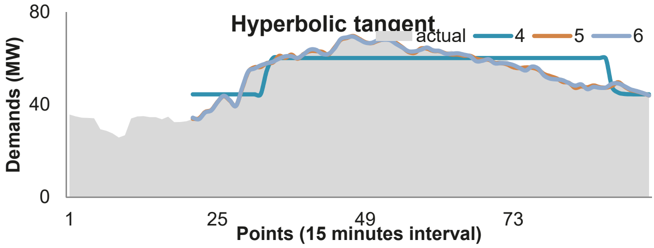
(h)


Bipolar sigmoid
actual 7 8 9
100
60
20
-20
Demands (MW)
1
25
49
73
Points (15 minutes interval)

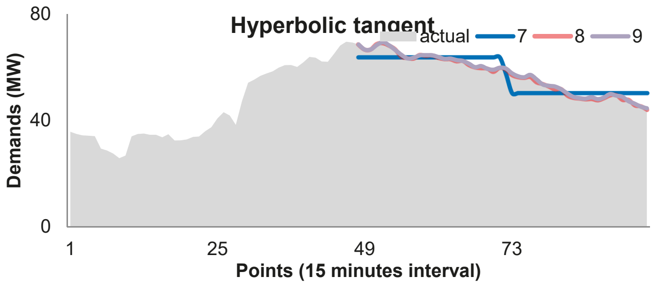
(i)


Hyperbolic tangent
actual 1 2 3
80
40
0
Demands (MW)
1
25
49
73
Points (15 minutes interval)

(j)



(k)



(l)

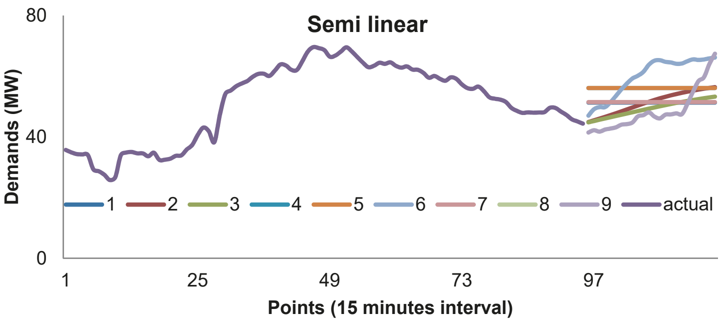
Figure 5.12. Predicted and historical/actual load demands with: (a) semi linear activation for 1st to 3rd ANN configuration, (b) semi linear for 4th to 6th ANN configuration, (c) semi linear (d) sigmoid activation for 1st to 3rd ANN configuration, (e) sigmoid activation for 4th to 6th ANN configuration, (f) sigmoid activation for 7th to 9th ANN configuration, (g) bipolar sigmoid activation for 1st to 3rd ANN configuration, (h) bipolar sigmoid activation for 4th to 6th ANN configuration, (i) bipolar sigmoid activation for 7th to 9th ANN configuration, (j) hyperbolic tangent activation for 1st to 3rd ANN configuration, (k) hyperbolic tangent activation for 4th to 6th ANN configuration, (l) hyperbolic tangent activation for 7th to 9th ANN configuration.

Source: Own Depiction

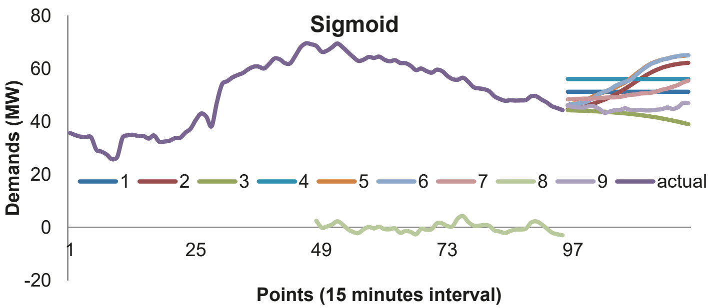
Forecasted vs actual load demands- Step B

There are 4 types of trends of forecasted load demands: fluctuated under actual value, linearized, ramped-up and ramped-down (Figure 5.13. (a) to (d)).

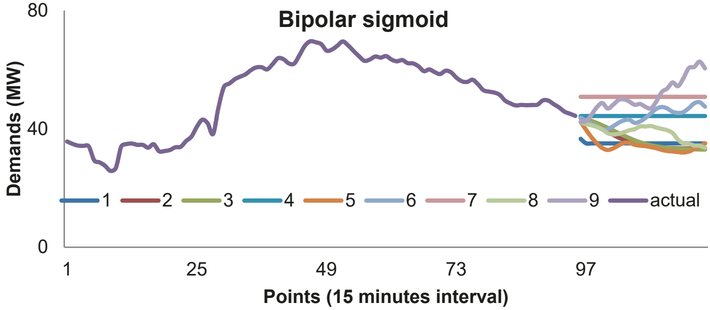
Ramped up and ramped-down trends were generated by most of the ANN activation functions. Fluctuated trends were generated when sigmoid AF with 47 input layers and 20 hidden layers (8th ANN configuration) was activated. In addition, functions include semi linear AF with 20 input layers and 20 hidden layers or 47 input layers and 1 hidden layer (5th and 7th ANN configuration), sigmoid AF with 1 input layer and 1 hidden layer or 20 input layers and 1 hidden layer (1st and 4th ANN configuration), bipolar sigmoid AF with 1 input layer and 1 hidden layer or 20 input layers and 1 hidden layer or 47 input layers and 1 hidden layer (1st, 4th, and 7th ANN configuration) produced a linear trend of forecasted load.



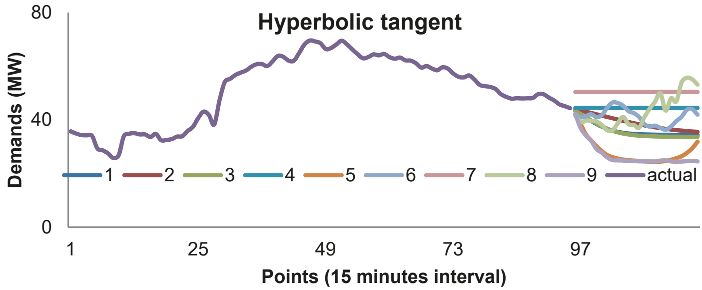
(a)



(b)



(c)



(d)

Figure 5.13. Predicted and actual/ historical load demands for 1st to 9th ANN configuration with: (a) semi linear activation (b) sigmoid activation, (c) bipolar sigmoid activation, (d) hyperbolic tangent activation.

Source: Own Depiction

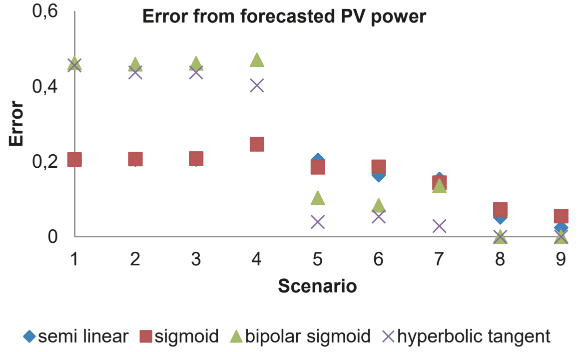
Error value and processing time of PV and load demands (1)

Errors in the forecasting system show (Figure 5.14. (a) and (b)) the relative distance between the trained value in the ANN and the actual desired output (refers to actual PV power or load demands). MSE and MSA were calculated from this errors. In this study, providing errors from the forecasting system was expected to provide more concise explanations of the forecasting system's behavior than representing its MSE and MSA (Figure 5.14. (c)). In (Figure 5.14. (c)) the first 36 data was MSA and MSE from load demands forecasting system, whereas the second 36 data was MSA and MSE from PV power forecasting system (see Appendix 10.6, Table 10.3).

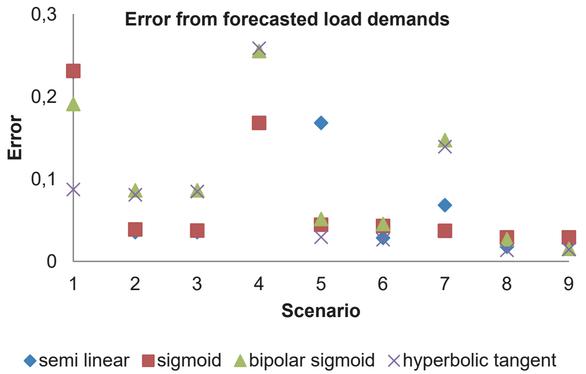
Errors in the forecasting system of actual PV power and load demands are fairly low. It was varied from 0% (using bipolar sigmoid or hyperbolic tangent AF with 8^{th}-9^{th} ANN configurations) to a maximum of approximately 0,5% (using bipolar sigmoid AF with 5^{th} ANN configurations) (Figure 5.14. (a)). However, it was clearly seen that then error trend (due to varying ANN configurations) between actual PV power and actual load demands were quite different.

In the forecasting system of actual PV power, as soon as the total number of input layers as well as the total number of hidden layers was increased, the error gradually decreased. In the sigmoid and bipolar sigmoid AF, however, increasing input layers to 20 but keeping hidden layers at one could lead to a higher error value than with ANN using one or 47 input layer(s) with any number of hidden layers. In addition, the configuration with 20 input layers and one hidden layer, plus its weighting, did not do enough to minimize error.

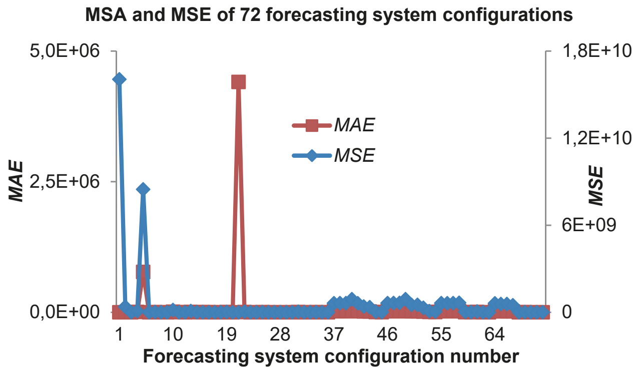
Errors in the forecasting system of actual load demands did not gradually decreas as soon as the total number of input and hidden layers was increased (Figure 5.14. (b)). The effect of decreasing errors from these sensitivity analyses could have been seen if both a combination of input and hidden layers was increased. If number of input layers was kept constant whereas the number hidden layers was increased,the error from this forecasting system was relative un-changed (Figure 5.14. at 2^{nd}-3^{rd} or 5^{th}-6^{th} or 8^{th}-9^{th} ANN configurations). The error was between 0,3% (4^{th} ANN configuration) and 0,01% (9^{th} ANN configuration) when bipolar sigmoid AF or hyperbolic tangent AF was applied.


Error from forecasted PV power
Error
0,6
0,4
0,2
0
1
2
3
4
5
6
7
8
9
Scenario
semi linear
sigmoid
bipolar sigmoid
hyperbolic tangent

(a)


Error from forecasted load demands
Error
0,3
0,2
0,1
0
1
2
3
4
5
6
7
8
9
Scenario
semi linear
sigmoid
bipolar sigmoid
hyperbolic tangent

(b)



(c)

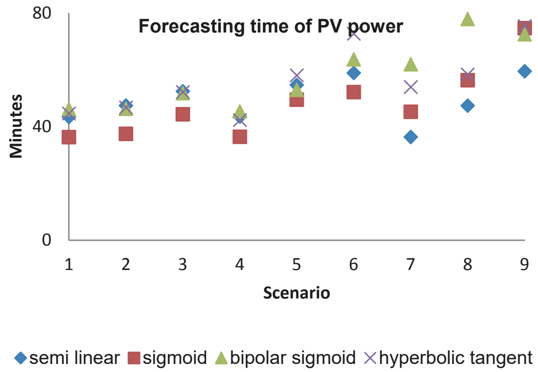
Figure 5.14. Error value (a) error on PV forecasting, (b) error on load demands forecasting, (c) *MSA* and *MAE* of 72 forecasting system configurations.

Source: Own Depiction

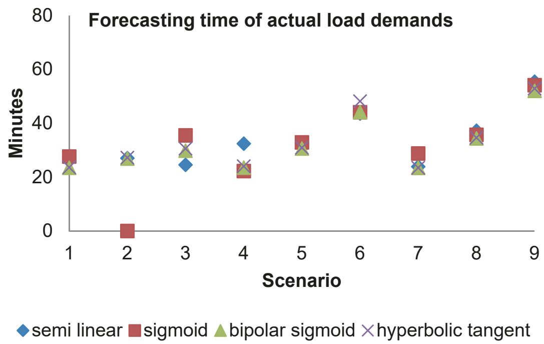
<u>Error value and processing time of PV and load demands (2)</u>

The time required by the forecasting system mainly depends on the forecasting machine and the complexity of forecasted data. Forecasting in this study was applied on i5th processor generation with 2,5 GHz frequency and 4 cores processor machine. If the forecasting system of this study was applied on other higher processing computational machines, the forecasting time required would have changed but the trend would have been similar.

The result shows that the time required by the forecasting systems for actual PV power was about two times higher than the time required for forecasting systems for actual load demands (Figure 5.15.). It can also be seen that for both of PV power and load, that as soon as the number of input layers and/ or hidden layers was increased, the time needed by the forecasting system to do the calculations also increased (by one more time).



(a)



(b)

Figure 5.15. Forecasting time of PV and load demands: (a) processing time on PV forecasting, (b) processing time on demands forecasting.

Source: Own Depiction

5.2.5 ICT performance

This thesis showed that the ICT performance of the VPP was influenced mainly by the implementation of the MAS communication concept. The effect of the implementation of asynchronous mode of MAS communications was detected from the client-server side of the VPP performance. In order to process a single task, the VPP required about 2,5 ms time in total and the VPP received a response in less than 2 ms (Table 5.1).

Table 5.1. Required times for different process in VPP activities.

Source: Own Depiction

Event handle (ms)	**Receive response (ms)**	**Finish loading (ms)**	**Send request (ms)**	**Receive data (ms)**
2,5	1,7	0,9	0,3	~0

In the server-side, the response data from the local controllers were possibly colliding with each other (Figure 5.16.), but were still received by the VPP server.

Figure 5.16. Screenshot of server-side response of VPP using asynchronous mode with possible colliding data.

Source: Adapted from (Candra et al., 2017a).

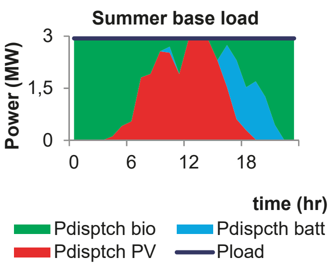
5.3 Techno-economic optimal balancing mechanism from high share of RES in VPP

5.3.1 VPP dispatching strategy

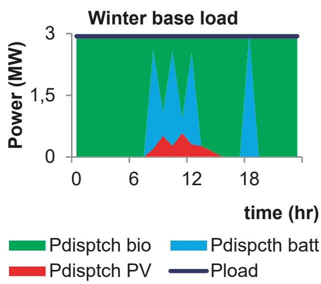
The behavior of dispatching strategies of DA and WF market applications are in principle describing the DER timing and allocation in the VPP application. The PV will mostly be used during the day, followed by the BESS and lastly biogas during the night. The figure on the DER allocation could however have been slightly different if the VPP was deployed in summer or winter and on different types of load demands. The differences could clearly have been seen for instance, when the VPP was applied to Day-Ahead market in the base configuration or 1st configuration (Figure 5.17.) or for the other VPP configurations in chapter 5.2.1 to 5.2.3.

In summer time, a PV power plant generates for almost the whole day and covers for more than 50% of load. In winter time, however, the load coverage done by a PV is smaller. In this study, for base load and total load applications with the same battery SOC level, as soon as generated power from the PV reached its capacity limit, the BESS and the biogas took over the residual load.

In peak load in summer and winter (Figure 5.17. (c) and (d)), the VPP preferred to use a combination of the PV and the biogas to cover peak load demands. In summer, it was still possible to cover more than 60% peak load by the PV since the required energy and generated energy from the PV between 8 am to 8 pm were met. But in winter, almost 90% of the residual load from the PV was covered by the biogas.



(a)



(b)

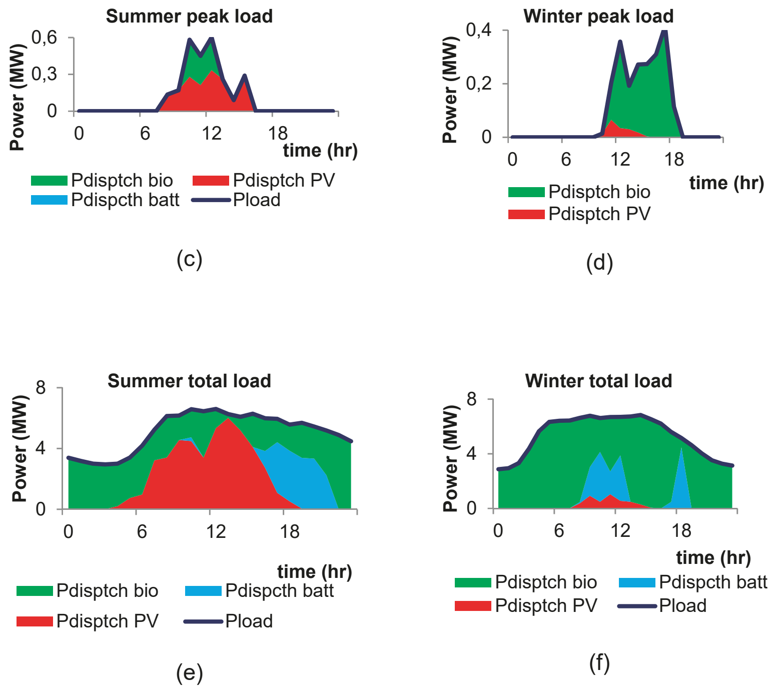


Figure 5.17. Sample dispatching strategy for 1st configuration: (a) summer base load, (b) winter base load, (c) summer peak load, (d) winter peak load, (e) summer total load, (f) winter total load.

Source: Adapted from (Candra et al., 2017b).

5.3.2 DER shares

This study developed nine different scenarios of DER configurations in order to conduct sensitivity analysis (Table 4.4). Detailed properties of the configurations are presented in (Table 4.4).

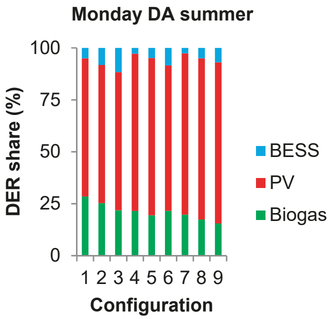
In the DA market in summer, the minimum share of the PV is found to be from 50%. It then increased to about 80% as the PV configuration was increased (Figure 5.18. (a) and (c)). It was found that by increasing a PV power capacity by a factor of 3 did not contribute a linear impact to the share of PV contribution in order to answer load demands. Unlike the PV, the increase in the BESS capacities by a factor of 3 would have increased the BESS share contribution at the same multiplication factor. In addition, regarding the total power generation in the

VPP, the trend of the biogas contribution followed the expected behavior which decreased as PV and BESS capacity increased.

For both DA markets on Monday and Saturday, at base configuration (1st configuration), the VPP still depended on about 25% of biogas power for both markets. This percentage would be minimized as soon as the share of PV and BESS increased.

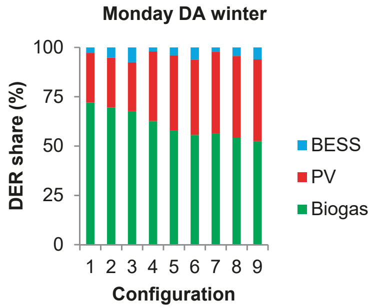
In addition, in the DA market in winter (Figure 5.18. (b) and (d)), at base configuration (1stconfiguration), it was found that most of the energy generated in the VPP came from biogas (almost 72%). The share of biogas was then decreased as soon as capacity of PV and BESS . However, the biogas still contributed more than half of the power generation in the VPP. The minimum share of biogas found was 53% on Monday at configuration 9. The PV, on the other hand, could only contribute up to approximately 42% of required energy by VPP (Figure 5.18. (b)). Furthermore, the BESS contribution's trend was linear like in DA summer and it depended on its multiplication factor. But in winter, it had less contribution than in summer.

In the Week Future market (Figure 5.18. (e)), specially in winter, for example based on the basic VPP configuration, the majority if energy came from biogas (about 90%). By increasing capacity of other DERs (the PV and the BESS) up to 3 times, the needs of biogas power in the VPP could be reduced by up to 30%. When the PV could only have contributed a maximum 30% of generated power in the VPP (when its capacity 3x increased), the BESS contributions are hard to be seen in this case. However, this condition was different in summer. In summer, the VPP could rely on 60 to 80% of its energy from the PV in order to answer the load. The share of the BESS could be seen significantly in summer, especially at 1st to 3rd VPP configurations and it was independent to the BESS capacity enlargements. The BESS had up to 5% share in the total VPP power generation for VPP configuration number 1 and 3. The rest of the required energy was then supplied by biogas. Morever, due to the load behavior on weekends, the PV and the BESS did not contribute energy as much as in the business day. In this case, VPP needs more energy from biogas.



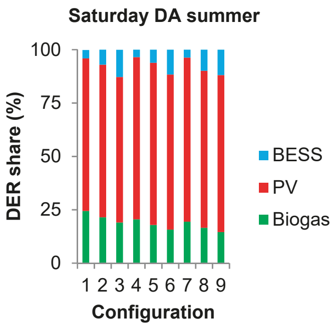
Monday DA summer
DER share (%)
100
75
50
25
0
1 2 3 4 5 6 7 8 9
Configuration
BESS
PV
Biogas

(a)



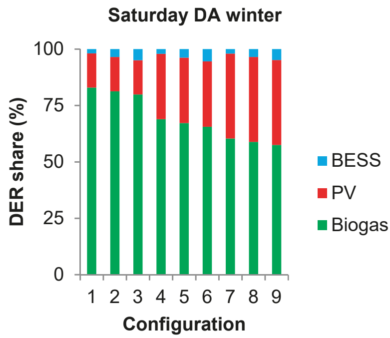
Monday DA winter
DER share (%)
100
75
50
25
0
1 2 3 4 5 6 7 8 9
Configuration
BESS
PV
Biogas

(b)



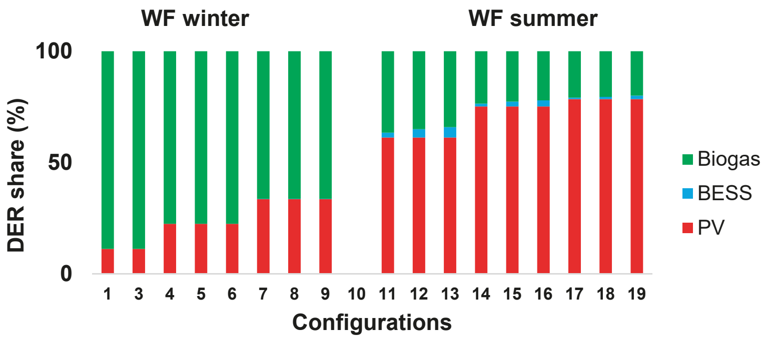
Saturday DA summer
DER share (%)
100
75
50
25
0
1 2 3 4 5 6 7 8 9
Configuration
BESS
PV
Biogas

(c)



Saturday DA winter
DER share (%)
100
75
50
25
0
1 2 3 4 5 6 7 8 9
Configuration
BESS
PV
Biogas

(d)



(e)

Figure 5.18. The average share of PV, BESS, and biogas in the VPP: (a) on Monday DA summer, (b) on Monday DA winter, (c) on Saturday DA summer, (d) on Saturday DA winter, (e) in WF winter and WF summer.

Source: Own Depiction

5.3.3 Optimum cost of VPP

The optimum costs to generate energy in the VPP, or called as the VPP generation costs, cannot be separated by the VPP dispatching strategy. From these costs, the manner of the VPP to deploy the available energy from its components can be proven. In addition, the VPP dispatching strategy is determined by considering the optimum generation cost of combined power plants in the VPP.

In the VPP, it was found that trends of average marginal costs in summer or in winter and for DA or WF market due to sensitivity analyses (9 VPP configurations) were quite similar (Figure 5.19.). The average marginal costs would have decreased as soon as the DER size increased. In summer, these costs would have been competitive enough in comparison to market prices in winter.

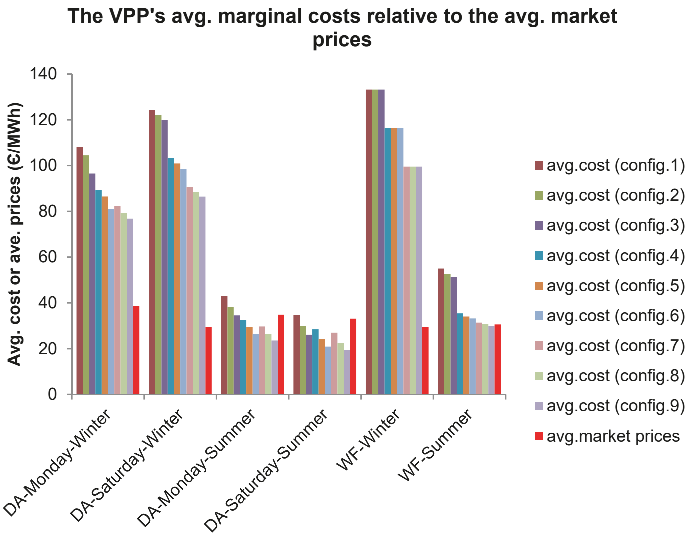


Figure 5.19. The average VPP's marginal costs and market prices over different VPP configurations.

Source: Adapted from (Candra et al., 2018).

The costs in (Figure 5.19.) from the average of hourly optimized VPP costs. Examples of the hourly optimized costs at basic VPP configuration in winter and summer (1st configuration) are described in (Figure 5.20.). In summer for base and total load, the trend would have been like a basin at 5 am to 8 pm with a small peak at 11 am. In winter, the VPP relied on biogas, therefore, with regard to base and total load, the costs for most of the time in a day would have been between 110 €/MWh and 140 €/MWh. The optimized costs would have reached its maximum level in winter peak load until 150 €/MWh which would be two-fold more than the maximum optimized costs for peak load in summer.

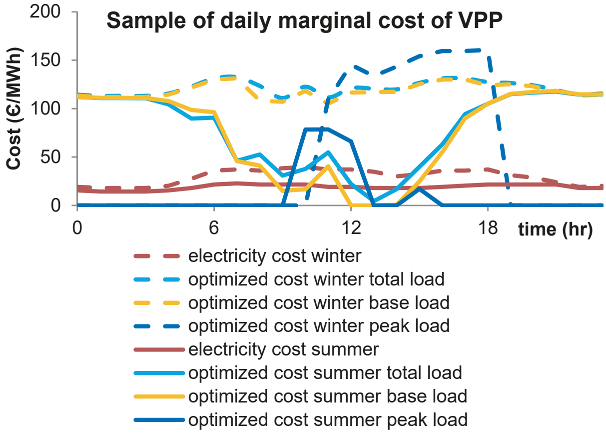


Figure 5.20. Sample of daily marginal costs in summer and winter.
Source: Adapted from (Candra et al., 2017b).

5.3.4 VPP's Contribution Margins

The Contribution Margin (CM) of VPP in this study emphasized a margin earned by the VPP which is calculated from the difference between the VPP's average marginal cost and its average market price. In this study, the VPP's contribution margins is found to vary from positive to negative values, from −105 €/MWh (WF in winter) to 14 €/MWh (DA in summer) (Figure 5.21.).

Findings in this thesis also show that increasing the DERs sizes would have increased VPP's contribution margins. In winter and in summer for both DA and WF markets, by increasing the DERs size by a factor of 3 led the CM to increase by up to two times.

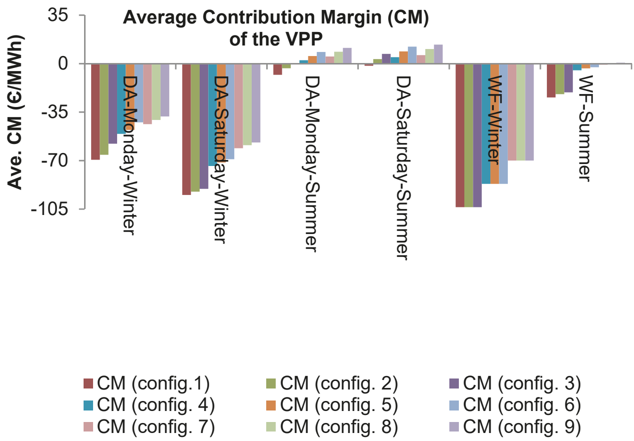


Figure 5.21. Average VPP' CM for different market products at different VPP configurations.

Source: Adapted from (Candra et al., 2018).

5.4 Technical constraints

Experiment in developing a VPP which has been undertaken in this study has identified at least four technical limitations in the VPP implementation. These limitations were coming from the biogas, the ICT, the optimization part and the User Interface which occurred during the VPP implementation.

<u>Biogas boundaries</u>

These technical constraints were based on the following points:

- error measurements from biogas
  In the data logging process, error measurement data was found (Table 5.2) from the signal sensors in biogas.

Table 5.2. Technical constraints of the Biogas due to error measurements (a) before data logger calibration, (b) after data logger calibration.

Source: Own Depiction

(a)

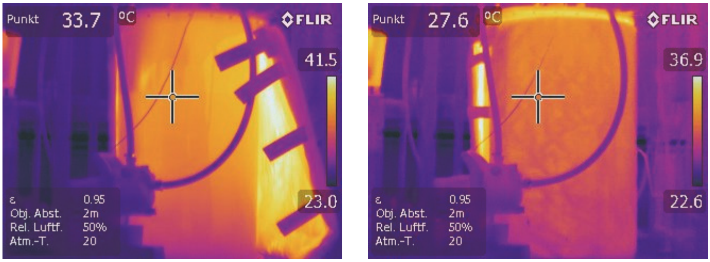
Date/Time	**Tvorlage**	**Tfestbed**	**P festbed**	**Redox Festbed**	**pH Fee-ding Reactor**
	°C	**°C**	**mbar**	**mV**	**pH**
01.08.2016 10:50	262.914	372.796	0.1174	-5.216.711	86.919
01.08.2016 10:55	263.028	382.911	0.1185	-5.125.828	87.373
01.08.2016 11:00	263.164	383.056	0.1185	-5.072.729	87.640

(b)

Tfestbed	**Low=**	**0.0**	**High=**	**100.0**	**Units=**	**°C**
Redox Festbed	**Low=**	**-1000.0**	**High=**	**1000.0**	**Units=**	**mV**
Gas flowrate	**Low=**	**0.0**	**High=**	**361.0**	**Units=**	**l/h**
Date/Time		**Tfest-bed**	**Redox Festbed**	**Gas flowrate**		
		°C	mV	l/h		
06.08.2016 12:21		38.8	-999.8	6,6		
06.08.2016 12:21		38.8	-999.4	6,6		
06.08.2016 12:21		38.8	-998.8	7,4		

- Digester/Fest bed temperature

  The optimum temperature in order to reach optimum biogas process was set to be 40 °C based on (Eder and Krieg, 2012). However at the beginning of the experiments, it was hard to reach stable heating temperature for the digester (Figure 5.22.). As an example in summer, maximum intern digester temperatures were less than 35 °C. The temperature of the biogas system should be controlled because it would have been influencing the biogas stability process (Weiland, 2008).



(a) (b)

Figure 5.22. Fest bed reactor temperature (measured by FLIR camera on Monday, 29th June 2016 at 08:27 AM) at the beginning of biogas experiments: (a) internal temperature, (b) external temperature.

Source: Own Depiction

- fixed setting of mixer frequency in mixing tank
  It was assumed that the percolate had homogeneous characteristic contents. Therefore, for different percolate volumes in the mixing tank, the experiment used a fixed setting frequency converter (Figure 5.23. (a)). This setting for dynamic percolate volume should be optimized by PLC with the help of level information from the laser volume measurement.

(a)

(b)

Figure 5.23. Mixer in mixing tank: (a) set mixing frequency, (b) laser sensor (above) and its measurement point (red point -bottom).

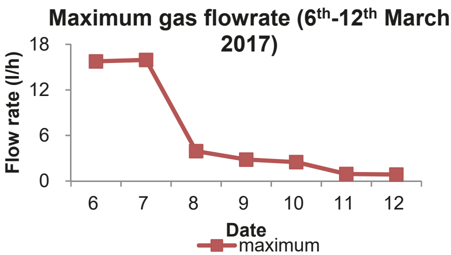
Source: Own Depiction

- Unpredictable gas production due to a heterogeneous percolate quality
  The variation of percolate contents and the quality of the percolate provided by the local waste management office influenced quality and quantity of the biogas power produced in the fest bed reactor (indicated by gas flow rate and gas composition on biogas process) (Figure 5.24. (a) and (b)).
  It was found that within a seven period (Figure 5.24. (a)), by using constant feeding volume per day of 20 L at the same experiment temperature, the redox value and trend of the generated gas from the fed substrate were unpredictable. Maximum gas flowrate was gradually decreasing from 16 l/h (between 6th-7th, March), to 4 l/h (between 8th, March), to 3 l/h (between 9th, March), to 2 l/h (on 10th, March), and to 1 l/h (between 11th-12th, March). The increasing and decreasing of gas flowrate in the experiment

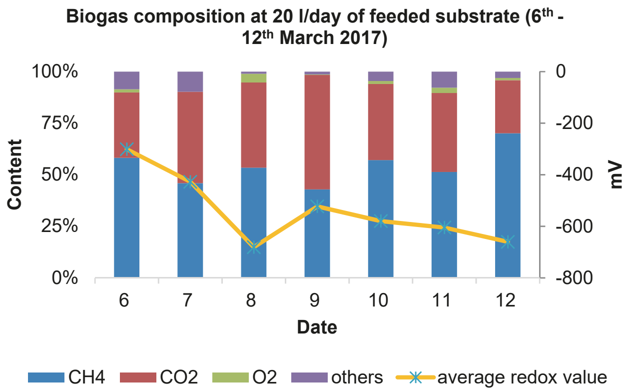
occurred between 1 - 3 hours. In each day of period, there were at least three experiments that had been conducted.

The share of CH_4 in biogas compositions that were produced during these seven days were also fluctuated (Figure 5.24.). It is difficult to find the relationship between redox potential or gas flowrate and generated CH_4 contents. The findings show that during the seven days period,biogas produced varied CH_4 contents between 40% and 70%. CO_2 contents were also fluctuating between 15 to 40%, whereas the rest resultant between CH_4 contents and CO_2 contents were other biogas components (O_2 or others).

It was also interesting that for relatively similar redox potential, the digester generated the highest CH_4 contents (on the 6^{th} day of interation) or medium CH_4 contents (on the third day). But gas flowrate on the 6^{th} day was less than gas flow rate on the third day of iteration. If results from (Figure 5.24. (a)) and from (Figure 5.24. .(b)) are compared, an interesting finding is found when feeding was done on the first day of iteration. On this date, biogas generated a maximum flow rate with the least value (least negative value) of redox and therefore the 2-nd most optimum CH_4 contents during the experiments.



(a)



(b)

Figure 5.24. Biogas properties before sugar-based content influence: (a) gas production and process time: (b) biogas compositions and average redox value.

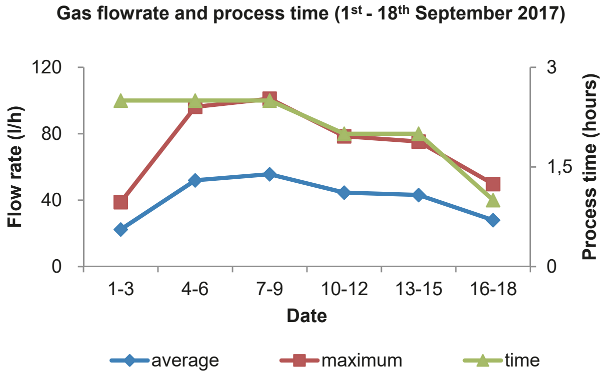
Source: Own Depiction

Further experiments

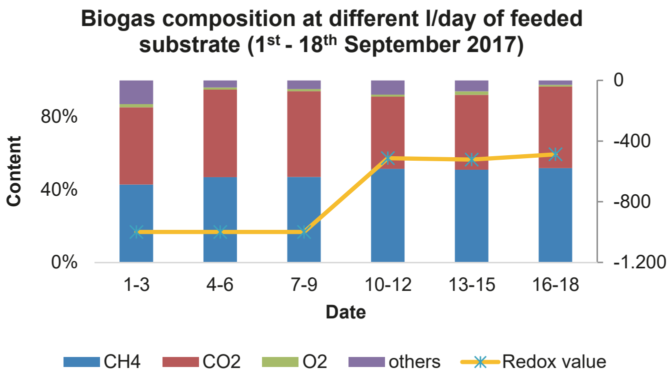
The further experiments were conducted in order to minimize the influence of the various substrates contents on the biogas quality and quantity by introducing sugar-based contents from 0 g to 1000 g with a step of 200 g (adapted from (List, 2017)). The findings show that biogas quantity and quality was then more predictable and it led to a reduction in its digestion time.

The results show (Figure 5.25. (a)) that biogas flowrate was gradually increased from about 40 l/h to 100 l/h after sugar was added until 400 g. Until these points, the required time for the digester in digesting added sugar was quite similar, approximately 2,7 hours. CH_4 contents were slightly increased at the same time (Figure 5.25. (b)). At these conditions, redox values were quite stable.

However, if more sugar was added (more than 400 g), gas flowrate would went down again gradually until maximum 60 l/h (Figure 5.25. (a)). This gradual trend was followed by the reduction of the required time trend for the biogas plant in order to digest the added substrates. At these conditions, redox values were changed to the less negative value for some time and then they remained unchanged (Figure 5.25. (b)). Concomitantly, CH_4 contents were just slightly increased from its previous conditions. However, it was clear that other biogas contents were reduced gradually when step by step sugar was added.



(a)



(b)

Figure 5.25. Biogas properties after sugar-based content influence: (a) gas production and processing time: (b) biogas compositions and average redox value. *Source: Adapted from (List, 2017).*

<u>Secondary data</u>

The analyzed secondary data showed that the performance of the Biogas was found technically to be limiting the VPP operations (Table 5.3). Biogas has about 42% electrical efficiency and constrained time on start-up and shut-down processes.

Table 5.3. Technical constraints of Biogas and intermittent RES to provide services in a VPP.

Source: Adapted from (Alet et al., 2017; Hossain and Ali, 2015; IEA, 2014; Peter et al., 2015; Romero and Hughes, 2015; Wellinger et al., 2013).

Biogas and intermittent RES constraints for VPP services				
Services	**Biogas**	**PV**	**Wind power plants**	**Battery**
Congestion management, Reactive Power or Voltage control, Ancillary services and frequency control	eff. CHP machine on average +/- 42%. engine constraints (Wellinger et al., 2013) :i.e. gas engine: start-up within seconds.	capacity factor (2014) 11% (Peter et al., 2015). Increased reactive/active power and voltage when increasing PV penetration (Alet et al., 2017). Solar irradiation dependents ,depends on forecast quality, low efficiency (IEA, 2014).	capacity factor (2014) up to 17% (Peter et al., 2015). Generators types dependents performance (Hossain and Ali, 2015), weather dependents (EA, 2014).	Capacity is limited (Romero and Hughes, 2015).

ICT and networking boundaries

During the research, the use of ICT and networking was by design only limited to be applied at the Technical University of Applied Sciences Aschaffenburg networking area. It was not yet applied and tested for the external or public networking area.

Optimization boundaries

Optimization by default was set to process three power plants (PV, battery, and biogas) and depended on the accuracy of the forecasting system. Whenever VPP participant is changed, for example a new power plant is introduced into this VPP, then the then the new optimization method or strategy should be set up in order to avoid failures in dispatching schedules.

User interface boundaries

The use of user interface environment in the VPP was limited to desktop, web and mobile application (see Appendix 10.5). The only part that was not applied was mobile development for iOS-based mobile application.

6 Discussion

6.1 Concept and implementation to integrate a flexible biogas plant and a PV system including a battery storage system into a VPP

Technical integration of DER

A successful integration of DER in the VPP depends on VPP's components’s characterizations and determinations. The MAS concept creates a modularity concept of VPP components. Each VPP is seen as an entity which has its own special functionalities. However, implementing the MAS itself, if applied in the VPP without SGAM application, would be challenging due to its modular characteristics. These results are in line with research done by (Dimeas and Hatziargyriou, 2007; Yan et al., 2015) that aimed to place the agents in different layers: dispatching center, energy management, local controller or enterprise layer. The MAS implemented in this study was bottom up, autonomous, decentralized, and adaptive. and is relevant to application done by (Hossain & Mahmud, 2014).

The SGAM concept on the other hand describes the VPP components in more detail than the MAS concept. Implementation of the SGAM concept in the VPP application would enable the flexibility of VPP development. Thus, combining both concepts enables the VPP to utilize the modularity concept from the MAS and the detailed VPP components and determinations from the SGAM concept. A combination of modularity and flexibility in the DER integration into the VPP is relevant to the future grid supply structure requirements which are adaptable and controllable with any further changes.

User interface

The User Interface in the VPP determines the data management and data visualization in the VPP. Regarding the back-end technology development, the VPP should be able to handle the ICT and power data. The actual data is related to the data properties from DER such as generated power. The ICT data is related to the transfer and communication mechanism of all data, including the database and power data from the VPP components. Among many back-end technologies, the use of the TCP-IP and the OPC as the two main back-end technologies enables the VPP to manage its data handling. Depending on which power application is required, implemented back-end technologies are not limited to these two technologies in the VPP application. IEC 104 or IEC 61850 are two other common back-end standards used in the power application. This result is relevant to the study done by (Dimeas & Hatziargyriou, 2007; Yan et al., 2015). In addition, it made the VPP easier to control the power plants in order to respond to future grid structure requirements.This finding is in line with the previous research conducted by (Hossain & Mahmud, 2014).

On the front-end technology, there are some differences on how the data on the VPP is visualized. The reason is that for different UI environments, and the VPP has different requirements for its user interfaces. On the desktop application, the data from OPC and TCP-IP technologies are ready to be visualized by the Python-based front-end technology. But for some others for example for web and mobile application, JavaScript-based front-end technology is required. Both Python and JavaScript support multi-platform user interface VPP applications. The multi-platform application in the VPP was comparable to previous applications from (Heitkötter et al., 2013) that were based on NET framework-based on Windows. In addition, the combination of JavaScript, HTML and MATLAB for the VPP in this study is comparable to previous works from (Corera, José and Maire, 2009; Decker and Lyngby, 2008; Lukovic et al., 2010).

VPP component interactions

Management of VPP components's interactions are also an important part in the DER integration in the VPP. VPP components would not automatically communicate to each other without a mechanism which handles the interactions. Identifier principle in this VPP is a simplified interaction mechanism among VPP components. VPP components are identified and based on the specific number and functionalities in the VPP. If a specific function in the VPP is required, for example, reading of DER's generated power, VPP main controller would call the identifier of DER and its generates power properties.

6.2 VPP performance from a combined flexible biogas plant and PV system

The VPP performance is influenced by the technical limitations of the VPP components. The VPP performance is not related to market orientations of the VPP, but rather to the technical application of the VPP. Moreover, the performance of the VPP was also influenced by the performance of the machine and the power converter installed in the power plants.

6.2.1 PV power plants performance to cover load demands through VPP

The performance of PV power plants highly depends on the availability of the PV power, which is related to the availability of solar irradiation. Increasing DER size, including PV size, enables the VPP to optimally use the PV potential in answering the load demands.

However, in the case of Noon market during winter, Rush-Hour and Afternoon in summer, increases in the PV size are not always followed by significant change to the PV performance in the VPP. This is due either to intermittent characteristics of the PV or the availability of other energy from other DER which costs less.

6.2.2 Battery performance to cover load demands through VPP

Battery in VPP

The Battery performance fluctuated both in winter and in summer as the DER size increased. This indicates that changes on the DER size is not always positively followed by an increase share of the battery in the VPP. The performance of the battery is more stable in type of markets where its share is expected to be lower, for example in the Evening (E) market, the Sun-Peak (SP) market and the Week Future (WF) market.

Battery SOC

There are two factors that influence the battery's SOC performance, including the excess power from the PV and the "must" delivered power from the battery to the grid.

The level of the PV excess power used to charge the battery would directly influence the battery's SOC. In addition, the battery's SOC level fluctuates more in winter than in summer because there is a difference in charging and discharging battery activity between these periods. In winter, the charge rate of excess power from the PV is lower than the discharge rate.

On the other hand, the battery's SOC is found to be relatively stable in summer because there was enough excess energy from PV in order to maintain the battery at a specific SOC level, which was found in this study to be approximately 60 to 75 %. This finding is relevant to the previous research done by (Romero and Hughes, 2015), which shows that the battery BESS is costly and capacity limited. Moreover, further investigation about SOC models considering the technical limitation of batteries, such as the degradation model by (Xu, 2013) should be conducted to increase the calculation of SOC accuracy.

6.2.3 Biogas performance to cover load demands through VPP

The Biogas in VPP

The share of biogas energy in DA or WF market is a result of the share of the PV and the battery. The requirement of biogas power on Monday would be slightly similar to the biogas requirement on Saturday for both winter and summer in the DA market. The reason is that, the contribution of the PV potential in order to cover load demands on Monday and on Saturday is not very greatly different.

The stability of biogas's share trends is possible to see, for example in the application of Off-Peak 1 (Table 2.4 (Number 10)), due to relative stability in the trend of PV's share and the battery share. Moreover, in the WF market, when the share of battery shares is unnoticeable, then the share of biogas would be likely mirroring the trend of the share of PV energy.

Biogas feeding strategy

The feeding strategy of the biogas has a significant contribution to the performance of the biogas plant. The characteristics of the demand of the VPP towards power generated by the biogas would also determine the feeding strategy of the biogas. If feeding is conducted in order to participate in the WF market, for example, then the fluctuations of usable biogas potentials is significant. Nevertheless, the biogas is able to produce flexible gas based on the requirements. The VPP is able to send a signal to the biogas for a flexible feeding and the the biogas's controller reacts to the signal and enables the Biogas to generate the amount power requested. This is relevant to the research done by (Ganagin et al. 2014), which concluded that the future balancing requirement from the biogas to meet load demands by manipulating the biological processes in the Biogas power plants.

Monitored biogas parameters

When feeding is done, fresh substrates are added to the biogas which lead to increasing growth of bacteria thus increasing redox value (to the less negative voltage). This process is then followed by forming more biogas in the digester. As soon as no more freshly-added substrates are left to be digested, the redox value would be back to its previous conditions (when there are no feeded substrates).

6.2.4 Forecasting system

Predicted vs historical/actual PV Power Step A (1)

The trend of predicted PV generated by the Forecasting System in the VPP is influenced by the total number of input layers, the total number of hidden layer and the type of ANN function that is applied.

Configurations that use only one input layer would generate unreliable predicted values. The configuration which used hyperbolic tangents (the total number of hidden layers is at least half of the total number of observed pieces of historical data) would produce predicted values that are only reliable at the beginning and at the end of the series/period.

Predicted vs actual PV Power Step A (2)

The second step of generating predicted PV values is through adding more hidden layers. When the number of input layers for all configurations is 20, the Forecasting System would generate different types of predicted values. The flat trend of predicted value, which is unreliable, is generated when the configuration uses only one hidden layer. The result improves when the configuration greater number of hidden layers. The Bipolar sigmoid function and Hyperbolic Tangent function could produce a preferable predicted value for configuration which has 20 input layers and at least 47 input layers (which is equal to half of the total number of actual observed pieces of data).

Predicted vs actual PV Step A (3)

The last step undertaken by the Forecasting system is conducting three configurations using various ANN functions (Semi Linear, Sigmoid, Bipolar Sigmoid and Hyperbolic Tangent) where all configurations have 47 input layers (this is equal to half of the total number of the observed actual data). The result shows that all of those configurations which have at least 20 hidden layers could generate a trend of a predicted value that is very close to the actual data no matter what type of function is used.

Based on the three steps tested by the Forecasting System using ANN, it is argued that when a configuration has a total number of input layers and hidden layers which are equal to half of the total number of observed pieces of actual data, then a predicted data with minimal errors would be generated.

In addition, a preferred predicted data still can be generated as long as a configuration has a total number of input layers which is one fourth of the total number of observed pieces of actual data and total number of hidden layers which is equal to half of the total number of the observed pieces of actual data. The configuration, however, must be applied using Hyperbolic Tangent.

Forecasted vs historical/actual PV Step B

The Forecasting System shows that ANN activation functions which have excessive or extremely low number of derivative functions would produce either under-forecasted values or over-forecasted values. A Semi-Linear and a Sigmoid approach have fewer numbers of derivative functions than Bipolar Sigmoid and Hyperbolic Tangent. Configurations that use Semi-Linear or Sigmoid produce under-forecasted values and they are therefore not flexible enough to respose the high variability of the actual data of PV power. On the other hand, configurations that use Hyperbolic Tangent (which has the highest number of derivative functions) generate over-forecasted values. Lastly, configurations which use a Bipolar Sigmoid approach produce a reliable trend of forecasted PV power, as long as the configurations have a number of input and layer data that is equal to one fourth of the total number of observed pieces of data

Predicted vs actual load demands

The increase in the number of hidden layers to a half of the total number pieces of observed data for all configurations led to the prediction system to generate predicted values that was very close or collided with the actual data. This was applied to the Semi Linear, Sigmoid, Bipolar Sigmoid and Hyperbolic Tangent functions.

Forecasted vs actual load demands

Increasing the number of trained pieces of data (represented by increasing the number of input layers) without increasing the number of hidden layers would affectthe quality of frecasting of the actual load demands.

If the number of hidden layer does not meet the minimum requirement in the prediction system, the prediction system does not have large enough comparable sum of weighted data in the hidden layer. Thus, it could generate a saturated calculation in the prediction model. The prediction system will see it as the end of the calculation in the prediction system. Moreover, as the actual load demands have less data variability (in terms of magnitude) characteristics in comparison with actual PV data, there will be fewer re-trigger actions in the prediction system to re-calculate its sum of weighted data. This would be again led to saturation in the prediction system.

Error value and processing time of PV Power and load demands (1)

The Bipolar sigmoid or the hyperbolic tangent are more compatible in generating fewer errors in the ANN for the forecasting system. The derivative function of bipolar sigmoid or hyperbolic tangent has a relatively higher (non-linear margin) than semi linear and sigmoid function.

Regarding the high variability of data of the actual PV power, an increase in the number of inputs and hidden layers would cause the Forecasting System to have more trained data and more complex calculations in its hidden layer. Thus, more reduced errors would be achieved.

With fewer fluctuation in desired data (actual load demands), a forecasting system with the bipolar sigmoid or the hyperbolic tangent function generates converged data that is relatively faster than in the actual PV power forecasting system. In this case, an increase in the number of hidden layers and input layers does not lead to a change of convergence level between actual and predicted data, so the error would be relatively similar.

Error value and processing time of PV and load demands (2)

The time required by the Forecasting System to process the data of the actual PV power is higher than the data of the load demands, since the data of the actual PV power has a higher degree of variability than the data of the actual load demand. By increasing the complexity of the calculations as well as the trained data, the processing time will require a double duration (compared to a less complex trained data set and functions).

6.2.5 ICT performance of VPP

Regarding technical application of the ICT in the VPP, it enables the VPP's performance to have a successful communication among its components. In addition, the VPP shows that the ICT performance of the VPP is mainly results from the implementation of the asynchronous mode in the MAS communications process.

In the client-server side, the ability of the VPP to reduce processing time creates an increase in the readiness of VPP to provide time-based grid services, e.g. for example frequency control services. This positive performance is very important so that a power plant can provide frequency control and also acts as balancing power plant.

Nevertheless, the MAS concept has number of drawbacks. It is still challenging for the VPP servers to guarantee that all controllers could respond to him, since not all controllers in the VPP will provide their responses for the requested commands. This could imply unanticipated time data or failure in data exchange. This study recommends future research to investigate the asynchronous mode that manage the response data from local controllers.

6.3 Techno-economic optimal configurations to cover load demands considering the current Germany's power markets conditions VPP's operational strategy

In terms of techno-economic optimization of the VPP operation, there are two important technical aspects that should be considered, namely the operational strategy of VPP and share of DER in the VPP. The operational strategy of VPP is related to the distribution of the energy strategy for DER. In addition, The share of DER indicate the level of availability and the capability of DER in answering load demands through VPP. Optimum costs and marginal costs of VPP mainly depend on how these two technical aspects are optimized. The more DER is implemented with low marginal costs , the more economic VPP is.

6.3.1 VPP dispatching scenario

The VPP dispatching strategy is influenced by two variables; namely DER characteristics (its marginal costs, capability and availability to answer loads) and load or market types. At different VPP configurations for different markets (1 to 9), VPP generates different dispatching strategies. It enables the VPPto follow the priorities in the VPP management system and DER characteristics.

The dispatching strategies in the VPP in various type of markets (especially in DA or WF market)use, in principle, the PV during the day and the BESS – the Biogas - for the rest of day, when the power from PV is not readily available Through its different configurations, the VPP has the possibility to dispatch their power to the grid using different options, whether it is only from the PV or from the BESS or from the Biogas or a combination of those DERs.

In cases of peak load, a DER combination in the VPP's dispatching strategies depend on the availability of potential power delivered from the PV and the Biogas. Despite BESS being more responsive in delivering power and has fewer marginal costs than biogas, the VPP through its optimization could detect if the energy content in the BESS is at its minimum level. In addition, increases in the DER sizes does not help BESS have the opportunity to receive enough energy from the PV and deliver economically to the grid. In contrast, biogas is adjustable and readily available to handle the residual load left by the PV.

6.3.2 Share of DERs

The different configurations of the VPP (detailed in Table 4.4) lead to a different DER shares in the VPP. These configurations (sensitivity analyses)

influence the VPP in distributing its power. Share of DERs are developed as a function of power plants' capacity, market types (DA or WF) and seasonal time. In addition, increases in the capacity of DERs that have fewer marginal costs (the PV and the BESS) would increase the share of those DERs in the VPP.

Furthermore, PV has its own limitation. Even though it has increased by a factor of three, its contribution to the VPP is limited due to its algorithm of power optimization.

The reason is that the optimization algorithm in the VPP follows the rule that VPP should deliver power from biogas if there is no more available power from the PV or battery to cover the loads.In addition to that, the available power in summer is different in comparison with winter, thus also influencing the contribution of each DER in the VPP.

Seasonally, the PV generates less energy in VPP in winter than in summer. This condition happens due to a lack of solar irradiation in winter. Therefore, the PV does not generate much energy to charge the BESS in winter, thus the BESS stays most of the time at its minimum SOC level. This is the reason why biogas is needed more in winter than in summer.

The share of DER is also as an indicator in how the VPP manage its resources in covering the load in different types of market. In addition, the VPP is able to determine it constraints or priority. The constrains can only rely on the lowest marginal cost of power plants or the most available power plants or combine low cost and the most available power plants.

6.3.3 VPP’s optimum cost

The average marginal cost of VPP components is also an important factor to consider in the implementation of the VPP since it reveals marginal costs required by the VPP in generating its power to cover load demands.

The VPP still could not compete against available conventional power plants in the grid. The marginal costs of the VPP is not competitive enough and cannot be used as an alternative in providing power to cover load demands. In this case, the application of the VPP in the grid therefore cannot increase the economic value of DERs which join the VPP. It is therefore required in the future to find the method to allow power plant technology, especially RES-based power plants as VPP components, to be more economically competitive to the fossil fuel-based power plants.

In order to achieve more optimal configurations leading to lower generation costs, it is necessary to increase the size of low-cost energy and integrate more low-cost RES-based power sources. For example, the use of the PV with marginal costs of 0 €/MWh or Wind power plants and Hydropower plants with 0 €/MWh marginal costs. As a result, the marginal costs of the VPP is expected to be able to compete with market prices since the VPP's marginal costs are lower than market prices. This phenomenon can be seen at some points in summer in the findings in the third part of this thesis.

However, increasing the size of power plants could increase the surplus of generated power in the grid. If this surplus energy becomes higher in the future, then the market prices would decrease. The question remains which method should be applied in order to manage this surplus energy in order to achieve a benefit that is more economical to the VPP.

Related to this, the determination of battery size in this study considers the reduction of surplus power generated by the combined power plants in the VPP. However, further investigations of the battery's role regarding this impact has yet to be investigated. There must be further analysis on the economic value from surplus power in the VPP, so that the VPP can benefit more from it

Other points also emphasized in this study are as follows:

- The economic optimal implementation of the VPP could vary and it depends on: different type of time - weekday/weekend time, seasons components size, and the type of power markets. The sensitivity analyses undertaken by adjusting power plant size for different power market products influences the economic optimal configurations of VPP components (VPP components share) and VPP's average marginal costs (represents the costs of power generation from VPP).
- The VPP, from combined biogas and a PV system with a battery system, is able to provide secure power at all times of the year. The VPP has comparatively low prices with marginal costs of 20–80 €/MWh (summer–winter, best configuration). The lowest price is met in the VPP when the total generated power from PV exceeds a certain level, such as in summer in the

Day-Ahead market. In this case, the VPP's marginal costs would be lower than the market prices but still expensive enough considering the economic participation of the VPP in the power markets in general.

- Current marginal costs of the VPP with combined biogas and a PV system with battery storage system are. in general higher. compared to the current market prices (EPEX and EEX) in different seasons and times (winter or summer for weekend or weekdays). This is caused by the use of non-competitive prices from RES-based power plants in the VPP. The generated power in current market prices is provided by low-cost fossil-based power plants as well as low-cost power from surplus energy in the power markets.

6.3.4 Contribution margin of VPP

The Contribution Margin (CM) of the VPP in this study emphasized the margin earned by the VPP that results from the difference between the VPP's average marginal cost and the average market price. The VPP CM varies in all types of power market: from positive to negative values (from − 105 €/MWh to 14 €/MWh). It is mainly influenced by the reliability of the DER. For example, due to the high availability of power from the PV in summer, the VPP has positive or close to break-even point of the CM, that reaches up to 14 €/MWh in summer in the Day-Ahead market. In winter, the VPP will have a negative CM in all types of power markets due to there being less available power from low-cost power plants, especially from the VP, in the VPP. The findings are comparable to the CM of gas power plants in the EPEX market.

The CM resulted from this VPP can still, at the moment, be applied to the power markets on the SPOT and Future market at current market prices (even though with higher generation costs than the status quo) as long as the security of generated power from VPP can be guaranteed. Thus, the implementation of the VPP in covering standardized load demands in the power markets enables the transformation of fluctuated power from RES-based power plants into a controllable and secured power, which leads to more predictable prices in the power markets, and the reduction of grid control from RES-based power plants.

6.4 Technical constraints and implications of VPP application

Technical constraints

The technical limitations of theVPP in this study include the Biogas, the ICT, the Networking, the Optimization and the User Interface.

(a) Biogas boundaries

- error measurements
  Error measurements in the biogas were caused by error calibration in the sensors and measurements.
- fest bed temperature
  The temperature stability of the biogas system resulted from a function of outside temperature of the system (room temperature) and the inside temperature of the system (generated by a heating system). For instance, in summer, it is hot, and in winter, is too cold for biological processes in the fest bed reactor. By adjusting the temperature controller, the expected temperature value can be achieved.
- fixed setting mixer frequency in mixing tank
  It would be recommended for future application of biogas that the homogeneity of percolate or substrate is kept stable in order to maintain a digestion rate of substrates at the same level. The alternative is that biogas would flexibly adjust their mixer frequency based on different measured substrate contents.
- Unpredictable gas production due to heterogenous percolate quality
  It was difficult to determine or to predict the quality and the quantity of the biogas since different quality and contents of substrates exist. However, this study recommends a further research in order to analyse ‘‘unidentifed factors’’ that influence the biogas quality and quantity trough its impact on the changes of the biogas flow rate, CH_4 and redox potential values within a seven days of experimentation.

- further experiments

  When sugar-based substances are gradually added to substrates, it provides more ‘food’ for bacteria to live and grow. When the bacteria is healthy enough, it produces more predictable biogas quantity and quality. The time to digest is also gradually minimized.

  The change in redox potential during the experiments happened in dates 7^{th}-9^{th} to 10^{th}-12^{th} (or second-fourth and sixth - seventh days of the experiment) was caused by increasing bacteria growth and activities in the digester.

- secondary data

  Regarding to to grid services, the analysis of the biogas based on the the secondary shows that there is engine constraints, especially to the Biogas response time, could have limited the possibility of flexible biogas to participate in ancillary services such as the primary frequency control. Findings from (Wickwire 2007; Darrow et al. 2017; Wellinger et al. 2013) show that biogas response time and its efficiency depend on the prime movers technology in this case from Combined Heat and Power (CHP) machine.

(b) ICT and networking boundaries

Since the VPP in this study by design was implemented in the closed networking area (the Technical University of Applied Sciences Aschaffenburg networking area), the requirements for networking security should further be considered if VPP is applied in public networking area. In the future, it is suggested to test the security, scalability, and capability of VPP in the non-educational networking system area.

(c) Optimization boundaries

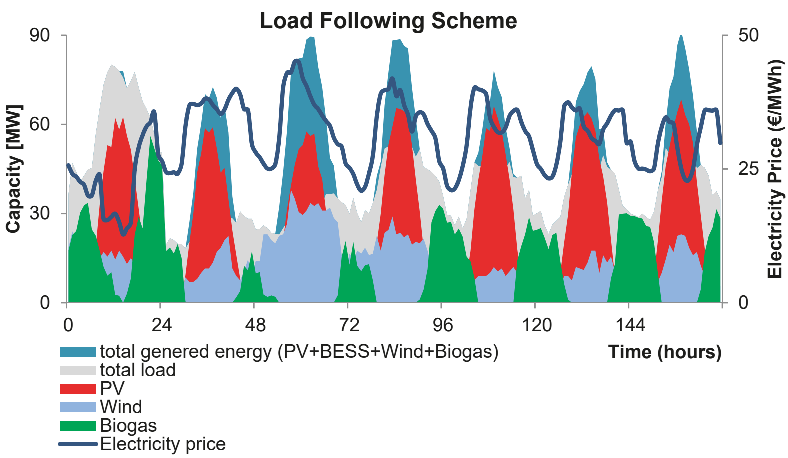
If a new DER is introduced to the VPP, the characteristic of this DER should be modeled in the VPP. Since the MAS concept is limited to the DER characterization, VPP could not automatically by itself determine and integrate a newly introduced DER without informing the characteristic of the new DER to its optimization agent. However, regarding the security manner, the MAS concept limitation provides a secured filtration model to the VPP against the intrusion of uncontrolled new VPP participants.

(d) User interface boundaries

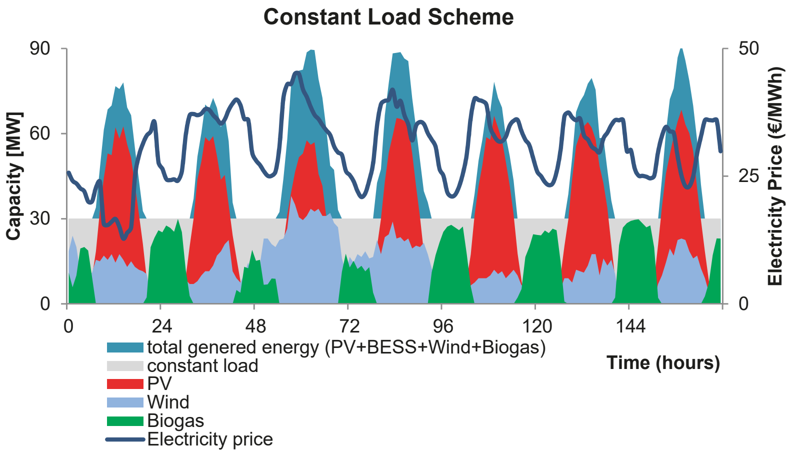
Due to the complexity of multi-platforms and multi application environments and their developmental requirements, user-interface environments in this VPP are not yet developed for iOS based mobile application.

Implications

The ability of the VPP in this study in answering fluctuated load demands opens up the possibility of a VPP of combined intermittent power (PV) and flexible generations (battery and biogas) to provide secured power generations in the power markets which is compatible with different power trading requirements (Figure 6.1.).



(a)



(b)

Figure 6.1. Possible implication from this VPP for future flexible power generation for (a) variable load demands; b) defined load demands.
Source Adapted from (Candra et al., 2019).

In addition to this, combining biogas, battery and PV system into a VPP provides support in the realization of reliable supply developments in the grid. According to (Banshwar et al., 2017; Li et al., 2010; Olejnczak, 2011, pp. 44–48; Rodrigues and Estanqueiro, 2011; Thrän et al., 2015; Zwaenepoel, 2016) biogas and batteries have the potential to produce flexible energy and to balance power, whereas intermittent RES such as PV has the potential to regulate voltage or frequency in the grid (Table 6.1).

Table 6.1. Possible potential grid services from VPP in this study which is based on combined biogas, battery and PV.

Source: Adapted from (Banshwar et al., 2017; Li et al., 2010; Olejnczak, 2011, pp. 44–48; Rodrigues & Estanqueiro, 2011; Thrän et al., 2015; Zwaenepoel, 2016).

Possible potential VPP services from combined biogas and intermittent RES	
Electricity tradings	√
Ancillary markets	√
Congestion management	√
Power flow control	√
Voltage control /reactive power	√
Fault ride through	√
Black start	√
Wholesale market participation	√
Frequency control	√

7 Conclusion and outlook

This study has developed an integrated solution to respond to current RES developments issues in the grid and power markets through a VPP using MAS and SGAM concept. It has also integrated different technologies of flexible biogas, energy storage and VPP. The technical concept and implementation of a Virtual Power Plant from a combined flexible biogas plant, PV system and battery storage system to answer fluctuating load demands shows an applicable solution to cope with RES development's challenges and in a wider scope is able to support further RES developments.

Based on this study, the following conclusions can be drawn:

- (How can flexible energy generations (biological flexible biogas and a battery storage) and intermittent RES (PV) be combined in a Virtual Power Plant (VPP) and to what extent is this combination able to answer load demands in the power markets?)

  In this study, battery,biogas,and a PV system have been combined into a VPP by applying the MAS and the SGAM concept. The MAS approach enables all components in the VPP to be determined as agents and they collaborate with each other in covering load demands. As an alternative the SGAM concept provides a desktop concept to application design in greater detail.

- (Which methods, components, and developments are needed to combine flexible energy generations (biological flexible biogas and a battery storage) and intermittent RES (PV) in a VPP?)

  The MAS and the SGAM concept are suitable to be adopted as an applicable method in providing an integrated solution for different power plants with a high share RES in the grid.

The MAS and the SGAM concept are handling the most challenging parts of power plant's integration concept, e.g. technic-economical optimization and visualitation of the VPP: It is achievable by modeling and transferring the model of the VPP into the local controller of power plants. The MAS application of the VPP is able to optimize combined power plants in the VPP in finding its optimized VPP' generation costs and dispatching strategy of each power plants, including the feeding strategy of biogas.
Moreover, the VPP from both combined approaches has an optimization model which is able to determine power generation strategy for power market products.

- (How are the behaviors of integrated flexible energy generations (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP) able to cover load demands?)

  The combination of flexible biogas and intermittent RES-based in a power plant is one of the keys to providing reliable supply by considering **power stability and balancing mechanism issues** from a RES to answer load demands.
  The implementation of flexible biogas in the VPP to answer load demands using the agent concept has provided a reliable supply to the grid. Biogas balances power from PV together with the battery storage. The intermittent power from weather-based RES is minimized and a stable power the supply can be established. As a result, technical risks to supply power in the grid can be minimized. However, since biogas has relatively expensive marginal costs in comparison to other power plants, biogas should be managed in a way that could affect the optimized cost of VPP on its balancing mechanism algorithm. For instance by reducing the biogas share and increasing the share of low-cost power plants in the VPP.

- A VPP implementation from flexible biogas and intermittent RES using the MAS concept provides an effective solution, especially in handling the coordination of RES and power market integrations issues.

- (What are the technical and economic optimum combinations flexible energy generations (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP) to provide a reliable energy supply, an adaptable power to the future energy requirements and an accessible power with competitive price in the electricity market?)

  With regard to current market prices, the products from these VPP configurations are **applicable and competitive enough to be marketed, but** only if secured power can be provided.
  If the products from VPP are reliable, these products are still marketable in the current power market conditions, even though, the VPP products prices are more expensive compared to current market prices. However, in the future, due to a liberalized market and high share of RES in the grid, there are furtherpossibilities that these products will be competitive with other power suppliers in the power market.

- (What are the technical limitations of integrated flexible energy generations (biological flexible biogas and a battery storage) and intermittent RES (PV) in a Virtual Power Plant (VPP)?)

  The technical boundaries of implemented flexible energy generations and intermittent RES in this study are based on the performance of biogas power plants (error measurements and digestion process stability), ICT and DER model dependents (see 5.4).

<u>Scientific contributions and future research recommendations</u>

The scientific contributions of this study are:

(1) Implementation of the MAS and the SGAM in the VPP with identifier-based concept.
The concept and implementation of the MAS and the SGAM concept especially in a VPP area, are, up to now to be developed. This study has shown the possibility of developing a VPP by implementing the MAS with identifier-based concept in enhancing the MAS interactions fit in the SGAM architecture. The identifier-based on the MAS communication concept enables the VPP to support grid services with reduced time.

(2) Plug-n-play and the modularity concept to integrate different power plants through VPP.

The implementation of the MAS concept in this study has opened the possibility of integrating different power plants in a VPP with plug-n-play and modularity concept. This concept will be relevant in the future as there will be more decentralized energy resources installed in the grid. The plug-n-play concept provides a method for the power plants to join or leave a VPP. Whereas, the modular concept allows power plants to be combinable. These concepts are required to bring a VPP up to date wit the future requirements such as upgradeable and reconfigurable requirements.

(3) The implementation of the MAS for power management systems with remote power plant's controller, e.g. for a flexible biogas feeding scenario in Day-Ahead market.

This study developed a power management system - MAS with remote power plants controller using a power plant parameters model approach for its model. This is to ensure the quality of a power plants' profile characterization. Additionally, the energy management was modeled and transferred to the local controller of power plants, so that it is possible to control the power plants directly from a VPP. For instance, a VPP would be able to control pump and manage the feeding strategy of biogas in the Day-Ahead market. This concept provides the opportunity in the future to minimize site dependency of a power plant's operator.

(4) Economic optimal implementations of the VPP to the German power market.

In the liberalized market in the future, power plants will be required to be able to deliver economic optimal implementation to the German power market in order to compete with fossil-based power plants. This study has shown the economic optimal configuration and implementation of VPP from different power plants to cope with this issue.

The applied VPP in this study still has some technical limitations, thus further innovations and improvements are required when applying the MAS and the SGAM with current ICT developments for VPP. In the future, it is recommended to conduct further research with regard to the topics, which are aimed at answering problems found in this study especially to improve VPP performance:

(1) Minimizing technical limitations of the developed VPP, for example by investigating data management in the asynchronous mode of MAS communication to reduce data collision.
(2) Investigating the impact and performance of the implemented MAS on ICT security and possible different grid services that could be supported by VPP.
(3) Investigating the impact of combined biogas with various RES power plants in a VPP to the technical-economical VPP configurations and performance considering various implemented areas, time scale (short-term, mid-term, long-term regarding the energy transition), and share of the RES in the grid.
(4) Implementing the market model for biogas implementation based on the current Renewable Energy Act model.
(5) Investigating the biological influence of biogas with regard to finding its impact on VPP implementation and its optimization.
(6) Improve the model of VPP by implementing fuzzy model in the biological biogas forecasting.

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9 Thesen

9.1 Motivation and Objectives

This study investigated the integration of a Photovoltaic (PV)-system, batteries, and a biologically flexible biogas adapted from (Ganagin et al. 2014) in a VPP. The theoretical and technical aspects in this study were identified by considering the following objectives:

- to investigate the integration and implementation concept of demand driven biogas and an intermittent RES from a Photovoltaic (PV)-system by applying a Multi Agent-based System (MAS) and Smart Grid Architecture Model (SGAM) concept. The development of a VPP applied an advanced Information and Communication Technology (ICT) to support RES and power market integration.
- to analyse a VPP performance/behaviour from integrated power plants (biogas, battery, PV) to answer load demands in the power markets.
- to investigate techno-economic optimal configurations, possibilities, and limitations of a VPP considering the current Germany power markets products i.e. Day-Ahead (DA) and Week Futures (WF) markets.
- to investigate the developed VPP boundaries.

9.2 Results

1. The adoption and deployment of the MAS and the SGAM concept into a VPP are yet to be developed. This study found that there is the possibility of implementing of these concepts to provide an integrated solution for different power plants with high share of RES in the grid. In this study, a flexible biogas plant, batteries and a PV system were combined by applying the MAS and the SGAM concept.
2. The MAS concept allows all components in the VPP to be determined as VPP agents and they collaborated with each other in answering the load demands. On the other hand, the SGAM concept contributes by providing a desktop concept of a detailed application design in the VPP: The other results are as follows:
   - The identifier-base of the MAS communication concept enables the VPP to support grid services with reduced time.

- The VPP from both combined approaches has an optimization model which is able to determine the power generation strategy for power market products.
- The implementation of the MAS concept in this study has opened the possibility to integrate different power plants in a VPP with the plug-n-play and the modularity concept. This concept is relevant in the future as there will be more decentralized energy resources installed in the grid. The plug-n-play concept provides a method for power plants to join or leave a VPP. Whereas, the modular concept allows power plants to be combinable. These concepts are required to bring a VPP up to date to the future requirements such as upgradeable and reconfigurable requirements.

3. The implementation of flexible biogas in the VPP to answer load demands using the MAS concept has provided a reliable supply to the grid. Biogas balances power from PV together with battery storage. The intermittent power from weather-based RES is minimized and a stable power supply can be established. As a result, technical risks to supply power to the grid can be minimized. However, since biogas has relatively expensive marginal costs than other power plants, biogas should be managed in a way, especially through the ability of the VPP in controlling the feeding strategy, that it could affect the optimized cost of VPP on its balancing mechanism algorithm. For instance, by reducing the share of biogas and increasing the low-cost power plants' share in the VPP.
4. Products generated by the VPP are still marketable to the current power market conditions, even though, their prices in general are more expensive compared to current market prices. However, in the future, due to a liberalized market and a high share of RES in the grid, there are open possibilities that these products will be competitive with other power suppliers in the power market.
5. The technical boundaries of the implemented flexible energy generations and intermittent RES on this study are based on the performance of biogas power plants (error measurements and digestion process stability), ICT and DER model dependency. The recommendation for further research is as follows:

- Investigating data management in the asynchronous mode of MAS communication to reduce data collision in order to minimize the technical limitations of the developed VPP.
- Investigating the impact of the application of an ICT security on the performance VPP with MAS concept on different grid services.
- Analyzing impact of combined biogas with various RES power plants in a VPP to the technical-economical VPP configurations and performance considering various implemented areas, time scale (short-term, mid-term, long-term in regards to the energy transition) and the share of RES in the grid.
- Implementing the market model for biogas based on the current Renewable Energy Act model.
- Investigating the influence of the biological substance of biogas on VPP implementation and its optimization.
- Developing improved models of VPP such as by implementing fuzzy model in the biological biogas forecasting.

10 Appendices

10.1 Sample of recorded biogas properties in a gas analyzer.

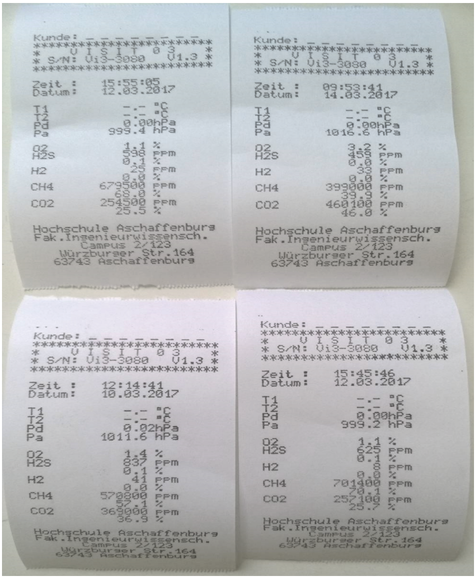


Figure 10.1. Recorded biogas properties in a gas analyzer from different quality of percolate.

Source: Own Depiction .

10.2 Sample of biogas behaviors

A data logger recorded biogas behaviors during the study (Figure 10.2.). In this study, the flexible feeding was done by manually or automatically using Siemens PLC through VPP.

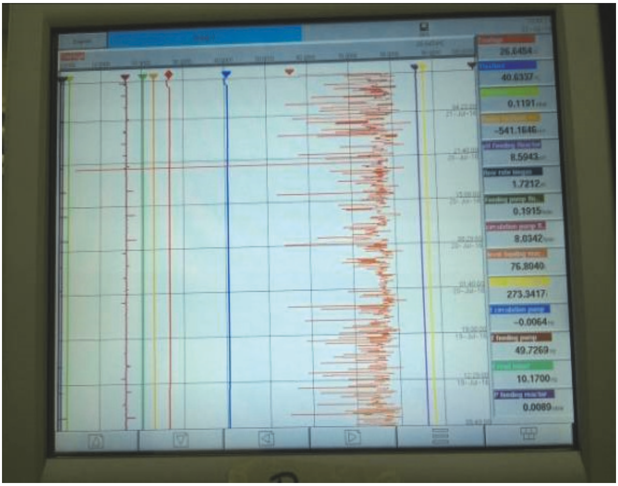


Figure 10.2. Sample of recorded biogas behaviors in a data logger.

Source: Own Depiction

10.3 Biogas power plant under testing specifications

Table 10.1. Biogas components specifications.

Source: Own Depiction

Components	Specifications	Descriptions
Feeding Tank	140 Litre max., Diameter: 600 mm, height 660 mm	Typ CPF-210, Polyethylen
Mixer with frequency converter	230 V input, propeller, 0.12 kW/230 V motor, 0.4 kW/230 V freq. converter	SIMIX-Schnellmischer Typ:SR 1/0,12-63/6 with 1 x 230 V 0.4 kW frequency converter, continuous operation
Feeding pump	15 – 64 - 100 l/h, 12 – 50 - 77 H, 0.37 kW, 230/400V, cavity pump	Controllable based on task from VPP through biogas local controller, Typ MR0.4I10 with Typ SK01F-71L/4 motor and freq. converter Hitachi TypSJ200-007HFE2 from PCM Deutschland GmbH
Fest bed reactor	1 m height, 630 mm diameter	-
Gas analyzer	measuring with CH4 = 100%, CO2 = 100%, O2 = 25 %, H2S = 5.000ppm, H2 = 10.000ppm, H2S sensor flushing, with difference pressure +/- 100 hPa, measuring for 2 temperatures,	Visit 03 Profi incl. measuring gas throttling for Visit 03
Gas counter	Max. 50 mbar for 10 - 600 l/h	Drum-type Gas Meter, TG5-PVC-PVC Typ: TG5/5 incl. Pulse Generator V 3.2"Smart-PG 200" Typ: PG V 3.2 and Electronic Display Unit Typ: EDU 32 FP
Heat exchanger	230 V input, 60 ° C, 600 W	NE00302 Silicon heating mate with HTMC 2 controller from Horst GmbH
Pressure transmitter	Max. 10 mBar	by Ritter Apparatebau GmbH & Co. kG
Thermometer	TG-G/TG 0-50/0,1, Thermometer (Gas) - 0-50/0,1°C	by Ritter Apparatebau GmbH & Co. kG

Gas storage bag	406 x 406 mm, 10 Litre	Typ: GSB-P/10, by Ritter Apparatebau GmbH & Co. kG
Over pressure safety	Max. 50 mBar	by Ritter Apparatebau GmbH & Co. kG
Additional gas flow meter	MV -104, PiPS-MV(7.03.424), standard 1/2" OD(5.06.025), pre-installed gas CH4	Mass flow meter from Wagner Mess- und Regeltechnik GmbH
Flow meter for substrate	0,2...50,0 l/min / 0,01...3,00 m^3/h, 4 – 20 mA/0 – 10 V output	SM7000 from ifm electronic
Biofilm	BT 20 density 0,96	Biofilm for fest bed reactor by Ratz Aqua & Polymer Technik
Data logger	Inputs 18 Channels, 12.1”, Trend speed 8 Hz	Graphikschreiber 6180A from Eurotherm
Level transmitter in fest bed reactor	9.35 m, 4..20 mA output	Liquicap T FM 121 from Endress+Hauser Messtechnik GmbH+Co.KG
Level transmitter for feeding tank	10 m , 4-Leiter , DC PNP ,18...30 V DC input	O1D300 laser transmitter from ifm electronic
Redox sensor	-1000...+1000 mV	RHEK-Pt-S from Ahlborn Mess- und Regelungstechnik GmbH
pH sensor	pH 0 to 14	PHER-112-SE with FY96PHER from Ahlborn Mess- und Regelungstechnik GmbH
Temperature sensor	- 40...+ 500°C	FPA30L0250 from Ahlborn Mess- und Regelungstechnik GmbH
Measurement transmitter	4 Channels for sensors, 10 – 30 V DC input	Measurements transmitter ALMEMO 2490-2 from Ahlborn Mess- und Regelungstechnik GmbH
Local controller	(varied)	PLC Siemens S7-1200 with additional required modules

10.4 Battery storage under testing specification

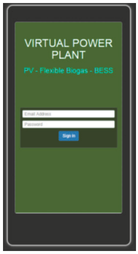
Table 10.2. Battery components specifications.

Source: Own Depiction

Components	Specifications	Descriptions
Battery	24V DC, 108 Ah, 2.7 kWh	IS 24.1 from BMZ
Charger	Input: 340 - 460 V Multi phase Output: 0 - 5 kW, 0 – 80 V, 0 - 170 A Programmable: U, I, P Protections: OVP, OCP, OPP, OTP Efficiency: ~ 93%	EA - PS 9080 - 170 3U
Inverter	Input: 1-, 2-, or 3- phase supply (230 V or 400 V), Output: 0 - 3.5 kW, 0 – 80 V, 0 - 170 A Programmable: U, I, P Efficiency: ~ 93%	EA - ELR 9080 - 170 3U
Local controller	(varied)	PLC Siemens S7-1200 with additional required modules

10.5 VPP user interface

(1) Mobile appUI (Android OS)



(a)

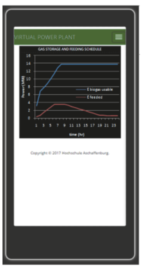
(b)

(c)

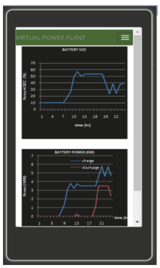
(d)

Figure 10.3. Mobile App UI: (a).VPP's login page (Android OS), (b).Home page, (c). Home page when it is scrolled, (d) When it is scrolled again.

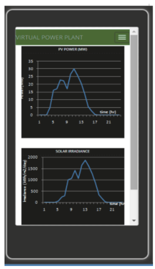
Source: Adapted from (Candra et al., 2017b).



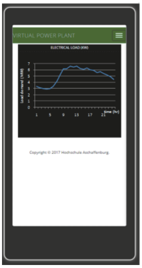
(a)



(b)



(c)



(d)

(e)

(f)

Figure 10.4. Mobile App UI: (a).Biogas page, (b).Battery page, (c). PV page, (d) Load demand page, (e).Report page, (f).Alarm page.

Source: Adapted from (Candra et al., 2017b).

(2) Web page UI

The contents in web site form are similar with the contents in application form.

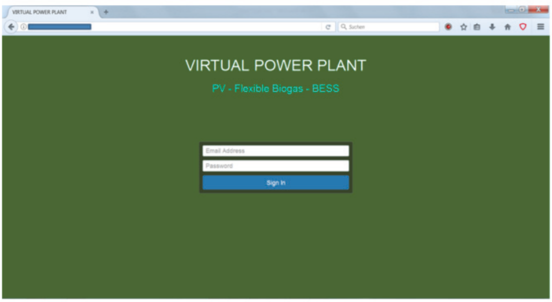


Figure 10.5. Web page UI.

Source: Own Depiction

(3) Desktop UI (see chapter 5.1.2)

10.6 VPP forecasting sensitivity analyses

Table 10.3. Forecasting analyses scenarios.

Source: Own Depiction

Scenario	PV	Load demand	Semi linear	Sigmoid	Bipolar sigmoid	Hyperbolic tangent	Input layer	Hidden layer	Output layer	Iteration
1		√	√				1	1	1	10000
2		√	√				1	20	1	10000
3		√	√				1	47	1	10000
4		√	√				20	1	1	10000
5		√	√				20	20	1	10000
6		√	√				20	47	1	10000
7		√	√				47	1	1	10000
8		√	√				47	20	1	10000
9		√	√				47	47	1	10000
10		√		√			1	1	1	10000
11		√		√			1	20	1	10000

12	√	√		1	47	1	10000
13	√	√		20	1	1	10000
14	√	√		20	20	1	10000
15	√	√		20	47	1	10000
16	√	√		47	1	1	10000
17	√	√		47	20	1	10000
18	√	√		47	47	1	10000
19	√		√	1	1	1	10000
20	√		√	1	20	1	10000
21	√		√	1	47	1	10000
22	√		√	20	1	1	10000
23	√		√	20	20	1	10000
24	√		√	20	47	1	10000
25	√		√	47	1	1	10000
26	√		√	47	20	1	10000
27	√		√	47	47	1	10000

28		√		√	1	1	1	10000
29		√		√	1	20	1	10000
30		√		√	1	47	1	10000
31		√		√	20	1	1	10000
32		√		√	20	20	1	10000
33		√		√	20	47	1	10000
34		√		√	47	1	1	10000
35		√		√	47	20	1	10000
36		√		√	47	47	1	10000
37	√		√		1	1	1	10000
38	√		√		1	20	1	10000
39	√		√		1	47	1	10000
40	√		√		20	1	1	10000
41	√		√		20	20	1	10000
42	√		√		20	47	1	10000
43	√		√		47	1	1	10000

44	√	√			47	20	1	10000
45	√	√			47	47	1	10000
46	√		√		1	1	1	10000
47	√		√		1	20	1	10000
48	√		√		1	47	1	10000
49	√		√		20	1	1	10000
50	√		√		20	20	1	10000
51	√		√		20	47	1	10000
52	√		√		47	1	1	10000
53	√		√		47	20	1	10000
54	√		√		47	47	1	10000
55	√			√	1	1	1	10000
56	√			√	1	20	1	10000
57	√			√	1	47	1	10000
58	√			√	20	1	1	10000
59	√			√	20	20	1	10000

60	√	√		20	47	1	10000
61	√	√		47	1	1	10000
62	√	√		47	20	1	10000
63	√	√		47	47	1	10000
64	√		√	1	1	1	10000
65	√		√	1	20	1	10000
66	√		√	1	47	1	10000
67	√		√	20	1	1	10000
68	√		√	20	20	1	10000
69	√		√	20	47	1	10000
70	√		√	47	1	1	10000
71	√		√	47	20	1	10000
72	√		√	47	47	1	10000

10.7 VPP-market sensitivity analyses

Table 10.4. Market analyses scenarios.

Source: Adapted from (Candra et al., 2018).

Scenario	Market Types	Bid Types	Season	Day(s)	Date(s)	x
1	Day-Ahead (SPOT market)	Middle-Night Block	Winter	Monday	26 January 2015	1
2	Day-Ahead (SPOT market)	Early Morning Block	Winter	Monday	26 January 2015	2
3	Day-Ahead (SPOT market)	Late morning Block	Winter	Monday	26 January 2015	3
4	Day-Ahead (SPOT market)	Early Afternoon Block	Winter	Monday	26 January 2015	4
5	Day-Ahead (SPOT market)	Rush Hour Block	Winter	Monday	26 January 2015	5
6	Day-Ahead (SPOT market)	Off-Peak 2 Block	Winter	Monday	26 January 2015	6
7	Day-Ahead (SPOT market)	Baseload Block	Winter	Monday	26 January 2015	7
8	Day-Ahead (SPOT market)	Peakload Block	Winter	Monday	26 January 2015	8

9	Day-Ahead (SPOT market)	Night Block	Winter	Monday	26 January 2015	9
10	Day-Ahead (SPOT market)	Off-Peak 1 Block	Winter	Monday	26 January 2015	10
11	Day-Ahead (SPOT market)	Business Block	Winter	Monday	26 January 2015	11
12	Day-Ahead (SPOT market)	Off-Peak Block	Winter	Monday	26 January 2015	12
13	Day-Ahead (SPOT market)	Morning Block	Winter	Monday	26 January 2015	13
14	Day-Ahead (SPOT market)	High Noon Block	Winter	Monday	26 January 2015	14
15	Day-Ahead (SPOT market)	Afternoon Block	Winter	Monday	26 January 2015	15
16	Day-Ahead (SPOT market)	Evening Block	Winter	Monday	26 January 2015	16
17	Day-Ahead (SPOT market)	Sun Peak Block	Winter	Monday	26 January 2015	17
18	Day-Ahead (SPOT market)	Middle-Night Block	Winter	Saturday	31 January 2015	18

19	Day-Ahead (SPOT market)	Early Morning Block	Winter	Saturday	31 January 2015	19
20	Day-Ahead (SPOT market)	Late morning Block	Winter	Saturday	31 January 2015	20
21	Day-Ahead (SPOT market)	Early Afternoon Block	Winter	Saturday	31 January 2015	21
22	Day-Ahead (SPOT market)	Rush Hour Block	Winter	Saturday	31 January 2015	22
23	Day-Ahead (SPOT market)	Off-Peak 2 Block	Winter	Saturday	31 January 2015	23
24	Day-Ahead (SPOT market)	Baseload Block	Winter	Saturday	31 January 2015	24
25	Day-Ahead (SPOT market)	Peakload Block	Winter	Saturday	31 January 2015	25
26	Day-Ahead (SPOT market)	Night Block	Winter	Saturday	31 January 2015	26
27	Day-Ahead (SPOT market)	Off-Peak 1 Block	Winter	Saturday	31 January 2015	27
28	Day-Ahead (SPOT market)	Business Block	Winter	Saturday	31 January 2015	28

29	Day-Ahead (SPOT market)	Off-Peak Block	Winter	Saturday	31 January 2015	29
30	Day-Ahead (SPOT market)	Morning Block	Winter	Saturday	31 January 2015	30
31	Day-Ahead (SPOT market)	High Noon Block	Winter	Saturday	31 January 2015	31
32	Day-Ahead (SPOT market)	Afternoon Block	Winter	Saturday	31 January 2015	32
33	Day-Ahead (SPOT market)	Evening Block	Winter	Saturday	31 January 2015	33
34	Day-Ahead (SPOT market)	Sun Peak Block	Winter	Saturday	31 January 2015	34
35	Day-Ahead (SPOT market)	Middle-Night Block	Summer	Monday	6 July 2015	35
36	Day-Ahead (SPOT market)	Early Morning Block	Summer	Monday	6 July 2015	36
37	Day-Ahead (SPOT market)	Late morning Block	Summer	Monday	6 July 2015	37
38	Day-Ahead (SPOT market)	Early Afternoon Block	Summer	Monday	6 July 2015	38

39	Day-Ahead (SPOT market)	Rush Hour Block	Summer	Monday	6 July 2015	39
40	Day-Ahead (SPOT market)	Off-Peak 2 Block	Summer	Monday	6 July 2015	40
41	Day-Ahead (SPOT market)	Baseload Block	Summer	Monday	6 July 2015	41
42	Day-Ahead (SPOT market)	Peakload Block	Summer	Monday	6 July 2015	42
43	Day-Ahead (SPOT market)	Night Block	Summer	Monday	6 July 2015	43
44	Day-Ahead (SPOT market)	Off-Peak 1 Block	Summer	Monday	6 July 2015	44
45	Day-Ahead (SPOT market)	Business Block	Summer	Monday	6 July 2015	45
46	Day-Ahead (SPOT market)	Off-Peak Block	Summer	Monday	6 July 2015	46
47	Day-Ahead (SPOT market)	Morning Block	Summer	Monday	6 July 2015	47
48	Day-Ahead (SPOT market)	High Noon Block	Summer	Monday	6 July 2015	48

49	Day-Ahead (SPOT market)	Afternoon Block	Summer	Monday	6 July 2015	49
50	Day-Ahead (SPOT market)	Evening Block	Summer	Monday	6 July 2015	50
51	Day-Ahead (SPOT market)	Sun Peak Block	Summer	Monday	6 July 2015	51
52	Day-Ahead (SPOT market)	Middle-Night Block	Summer	Saturday	11 July 2015	52
53	Day-Ahead (SPOT market)	Early Morning Block	Summer	Saturday	11 July 2015	53
54	Day-Ahead (SPOT market)	Late morning Block	Summer	Saturday	11 July 2015	54
55	Day-Ahead (SPOT market)	Early Afternoon Block	Summer	Saturday	11 July 2015	55
56	Day-Ahead (SPOT market)	Rush Hour Block	Summer	Saturday	11 July 2015	56
57	Day-Ahead (SPOT market)	Off-Peak 2 Block	Summer	Saturday	11 July 2015	57
58	Day-Ahead (SPOT market)	Baseload Block	Summer	Saturday	11 July 2015	58

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Table 10.5. Bid classifications.

Source: Adapted from (Candra et al., 2018).

No.	Market Types	Bid Types	Block Times (h)
1	Day-Ahead	Middle-Night Block	01–04
2	Day-Ahead	Early Morning Block	05–08
3	Day-Ahead	Late morning Block	09–12
4	Day-Ahead	Early Afternoon Block	13–16
5	Day-Ahead	Rush Hour Block	17–20
6	Day-Ahead	Off-Peak 2 Block	21–24
7	Day-Ahead	Baseload Block	01–24
8	Day-Ahead	Peakload Block	08–20
9	Day-Ahead	Night Block	01–06
10	Day-Ahead	Off-Peak 1 Block	01–08
11	Day-Ahead	Business Block	09–16
12	Day-Ahead	Off-Peak Block	01–08 & 21–24
13	Day-Ahead	Morning Block	07–10
14	Day-Ahead	High Noon Block	11–14
15	Day-Ahead	Afternoon Block	15–18
16	Day-Ahead	Evening Block	19–24
17	Day-Ahead	Sun Peak Block	11–16
18	Week Futures	Peakload Block	08–20 (Monday–Friday)
19	Week Futures	Baseload Block	01–24 (Monday–Sunday)

Table 10.6. Bid prices.

Source: Adapted from (Candra et al., 2018; European Power Exchange, 2015).

Bid Ty-pes	Prices (€/MWh)	Bid Ty-pes	Prices (€/MWh)	Bid Ty-pes	Prices (€/MWh)	Bid Types	Prices (€/MWh)
MWMN	26	SWMN	26.64	MSMN	22.52	SSMN	35.23
MWEM	37.5	SWEM	25.4	MSEM	28.12	SSEM	29.84
MWLM	48.3	SWLM	29.14	MSLM	37.16	SSLM	30.43
MWEA	44.28	SWEA	28.5	MSEA	27.52	SSEA	28.26
MWRH	41.42	SWRH	40.39	MSRH	47.15	SSRH	33.65
MWOP 2	27.51	SWOP2	28.81	MSOP 2	59.86	SSOP 2	41.88
MWBL	37.5	SWBL	29.81	MSBL	33.21	SSBL	37.05
MWPL	44.67	SWPL	32.68	MSPL	30.78	SSPL	37.28
MWN	26.15	SWN	26.11	MSN	21.61	SSN	33.06
MWOP 1	31.75	SWOP1	26.02	MSOP 1	25.32	SSOP 1	32.54
MWB	46.29	SWB	28.82	MSB	32.34	SSB	29.34
MWOP	30.34	SWOP	26.95	MSOP	36.83	SSOP	35.65
MWM	49.4	SWM	27.35	MSM	38.76	SSM	31.28
MWHN	46.23	SWHN	28.84	MSHN	30.58	SSHN	29.25
MWA	42.4	SWA	33.12	MSA	31.84	SSA	28.11
MWE	31.84	SWE	33.62	MSE	59.16	SSE	40.7
MWSP	44.97	SWSP	28.78	MSSP	29.43	SSSP	28.59
MWF_WBL	37.50	MWF_WPL	44.67	MWF_SBL	37.05	MWF_SPL	37.28
TWF_WBL	32.94	TWF_WPL	40.21	TWF_SBL	49.02	TWF_SPL	53.83
WWF_WBL	28.18	WWF_WPL	30.19	WWF_SBL	29.57	WWF_SPL	27.98
ThWF_WBL	26.24	ThWF_WPL	32.7	ThWF_SBL	28.7	ThWF_SPL	28.5

FWF_ WBL	38.24	FWF_W PL	46.04	FWF_S BL	32.14	FWF_ SPL	31.62
SWF_ WBL	29.81	SuWF_ WBL	29.23	SWF_S BL	33.21	SuWF _SBL	27.9

Table 10.7. Total volume of each bid types.

Source: Adapted from (Candra et al., 2018).

Bid Ty-pes	**Total Voume (MWh)**	**Bid Ty-pes**	**Total Voume (MWh)**	**Bid Ty-pes**	**Total Voume (MWh)**	**Bid Ty-pes**	**Total Voume (MWh)**
MWMN	44.09	SWMN	56.83	MSMN	0	SSMN	0
MWEM	0	SWEM	0	MSEM	0	SSEM	14.38
MWLM	29.65	SWLM	43.62	MSLM	86.47	SSLM	49.62
MWEA	78.79	SWEA	131.34	MSEA	95.49	SSEA	63.16
MWRH	95.95	SWRH	136.58	MSRH	82.63	SSRH	57.32
MWOP2	89.29	SWOP2	146.11	MSOP2	35.67	SSOP2	24.60
MWBL	792.41	SWBL	1255.6 3	MSBL	1259.6 3	SSBL	766.42
MWPL	227.47	SWPL	347.67	MSPL	277.05	SSPL	189.36
MWN	66.14	SWN	85.24	MSN	0	SSN	0
MWOP1	88.18	SWOP1	113.65	MSOP1	32.62	SSOP1	28.76
MWB	124.82	SWB	204.20	MSB	181.96	SSB	112.77
MWOP	200.08	SWOP	304.41	MSOP	92.50	SSOP	66.13
MWM	0	SWM	0	MSM	41.87	SSM	30.35
MWHN	49.99	SWHN	85.26	MSHN	105.20	SSHN	60.88
MWA	96.33	SWA	141.90	MSA	90.38	SSA	63.45
MWE	132.53	SWE	208.68	MSE	74.46	SSE	54.06
MWSP	93.61	SWSP	153.15	MSSP	148.25	SSSP	93.61
WF_WB L	6379.9 4	WF_WP L	2129.3 9	WF_SB L	4817.1 5	WF_SP L	1398.6 6

Table 10.8. Market categories.

Source: Adapted from (Candra et al., 2018).

No.	**Market Categories**	**p**
1	Day-Ahead Monday Winter	1
2	Day-Ahead Monday Summer	2
3	Day-Ahead Saturday Winter	3
4	Day-Ahead Saturday Summer	4
5	Week Futures Winter	5
6	Week Futures Summer	6

List of Publications

This dissertation was based but not limited on these following publications:

1. Candra, D.I.; Hartmann, K.; Nelles, M. Conceptual and Practical Implementation of Integrated Flexible Biogas-Intermittent RE-Battery Storage for Reliable and Secure Power Supply to Meet Actual Load Demand at Optimal Cost. In Proceedings of the 25th European Biomass Conference and Exhibition, Stockholm, Sweden, 12–15 June 2017; p. 1863–1872. DOI: 10.5071/25thEUBCE2017-5CO.4.3, ISBN: 978-88-89407-17-2.
2. Candra, D.I.; Hartmann, K.; Nelles, M. Development of a Virtual Power Plant to Control Distributed Energy Resources for Future Smart Grid. In Proceedings of the NEIS 2017 Conference on Sustainable Energy Supply and Energy Storage Systems, Hamburg, Germany, 21–22 September 2017; p. 229.
3. Candra, D.I.; Hartmann, K.; Nelles, M. Economic Optimal Implementation of Virtual Power Plants in the German Power Market. Energies 2018, vol. 11(9), 2365; p. 1-24. DOI: 10.3390/en11092365
4. Candra, D.I.; Hartmann, K.; Nelles, M. Erneubare Energie: Von flukturiender zu verlässlicher Elektrizität? Ew-Magazin 2019; vol. 4

Furthermore, findings of this study also have been published in the following publications:

1. Hartmann K., Candra D.I.: Einsatz derivativer instrumente für die Integration erneuerbarer Energien in bestehende Strommärkte, Working paper, 2017, DOI 10.13140/RG.2.2.36571.36645
2. Hartmann K., Candra D.I.: Use of derivative instruments to integrate renewable energies into the electricity market, working paper, 2017, DOI 10.13140/RG.2.2.32377.06242
3. Hartmann K., Candra D.I.: Think and Produce instead of Produce and Forget - Integration of RES into an economic market system, presentation at EUBCE, 12.-15.06.2017 (Stockholm)

Declaration of Primary Authorship

I declare, that I have written the present thesis for doctorate and without help of others. Other than the presented references were not used and quoted results were always marked with the relevant reference. The present thesis was never either abroad or in Germany submitted for examination in the present or a similar version.

Selbstständigkeitserklärung

Ich erkläre, dass ich die eingereichte Dissertation selbständig und ohne fremde Hilfe verfasst, andere als die von mir angegebenen Quellen und Hilfsmittel nicht benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Die vorgelegte Dissertation wurde bisher weder im Ausland noch im Inland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Aschaffenburg, 23.06.2020

Dodiek Ika Candra

Proof of Individual Contribution

Publications	Author **Candra, D.I.**	Co-Authors
Candra, D.I, Hartmann, K., Nelles, M., Conceptual and Practical Implementation of Integrated Flexible Biogas-Intermittent RE-Battery Storage for Reliable and Secure Power Supply to Meet Actual Load Demand at Optimal Cost Proceedings of the 25th European Biomass Conference and Exhibition (2017), p. 1863-1872. DOI: 10.5071/25thEUBCE2017-5CO.4.3, ISBN: 978-88-89407-17-2	Idea, collecting and analysing data, writing the article	**Hartmann, K., Nelles M.:** generating idea
Candra, D.I, Hartmann, K., Nelles, M., Development of a Virtual Power Plant to Control Distributed Energy Resources for Future Smart Grid Proceedings of the NEIS 2017 Conference on Sustainable Energy Supply and Energy Storage Systems (2017), p.229	Idea, collecting and analysing data, writing the article	**Hartmann, K., Nelles M.:** generating idea
Candra, D.I, Hartmann, K., Nelles, M., Economic Optimal Implementation of Virtual Power Plants in the German Power Market Energies 2018, vol. 11(9), 2365, p. 1-24. DOI: 10.3390/en11092365	Idea, collecting and analysing data, writing the article	**Hartmann, K., Nelles M.:** generating idea
Candra, D.I, Hartmann, K., Nelles, M Erneubare Energie, Von einer fluktu-rienden zur verlässlichen Stromerzeugung ew-Magazin (2019), vol.4,	Idea, collecting and analysing data, writing the article	**Hartmann, K., Nelles M.:** generating idea

Publications	Author	Co-Authors **Candra, D.I.**
Hartmann K., Candra D.I. Einsatz derivativer instrumente für die Integration erneuerbarer Energien in besteheende Strommärkte Working paper, DOI 10.13140/RG.2.2.36571.36645	**Hartmann, K.:** Idea, collecting and analysing data, writing the article	Collecting and analysing data
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Curriculum Vitae

Persönliche Informationen

Nationalität	Indonesisch
Familienstand	Verheiratet, 1 Kind
Geburtsdatum	9. March 1984 in Tulungagung, Indonesien

Ausbildung

10/2011 - 02/2013	M.Sc. Renewable Energy Carl von Ossietzky Universität Oldenburg, Deutschland
08/2002 - 08/2006	B.Sc. Engineer in Applied Technology Sepuluh Nopember Institute of Technology, Indonesien

Berufserfahrung

Seit 01/2014	Technische Hochschule Aschaffenburg, Deutschland Doktorand und wissenschaftlicher Mitarbeiter in einem Forschungsprojekt zur Solar-Biogas-Batterie- Kombikraft-werk
Seit 10/2007	Indonesien Institute of Sciences, Indonesien Forscher für Elektrische Energie und Mechatronik

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