TKK Dissertations 188
Espoo 2009

COMPUTATIONAL STUDIES ON VARIABLE DISTRIBUTED ENERGY SYSTEMS

Doctoral Dissertation

Jukka Paatero

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Faculty of Information and Natural Sciences
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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Information and Natural Sciences for public examination and debate in Auditorium K216 at Helsinki University of Technology (Espoo, Finland) on the 6th of November, 2009, at 12 noon.

Helsinki University of Technology
Faculty of Information and Natural Sciences
Department of Applied Physics

Teknillinen korkeakoulu
Informaatio- ja luonnontieteiden tiedekunta
Teknillisen fysiikan laitos

Distribution:
Helsinki University of Technology
Faculty of Information and Natural Sciences
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ISBN 978-952-248-124-5
ISBN 978-952-248-125-2 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)
URL: http://lib.tkk.fi/Diss/2009/isbn9789522481252/

TKK-DISS-2657

HSE Print
Helsinki 2009

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author	Jukka Veikko Paatero

Name of the dissertation

Computational Studies on Variable Distributed Energy Systems

Manuscript submitted	20.4.2009	Manuscript revised	7.10.2009
Date of the defence	6.11.2009		

☐ Monograph ☒ Article dissertation (summary + original articles)

Faculty	Faculty of Information and Natural Sciences
Department	Department of Applied Physics
Field of research	Engineering Physics, Advanced Energy Systems (F040Z)
Opponent(s)	Dr Stathis Tselepis
Supervisor	Professor Peter Lund
Instructor	Professor Peter Lund

Abstract

In this work the large-scale integration of distributed wind turbine and photovoltaic power generation to medium voltage power distribution grid have been explored. The effects of the integration were mainly evaluated by steady-state power flow analysis. Compensation of unwanted overvoltage events was tested with the use of energy storage, utilization of grid topology, and redirecting of photovoltaic panels. In addition, this work examines the use of energy storage to compensate short and long term fluctuations in the power output of variable distributed generation. For this purpose three different storage control strategies were applied.

For simulation purposes a detailed bottom-up consumer load model and a distribution grid power flow simulation model were developed. The stochastic approach in the load model is based on the classic bottom-up load model by Capasso *et al*. However, the emulation of the activities of individual people has been replaced by statistical use of household appliances where reference data is more readily available. The grid simulation model is based on established power flow computation methods. The model is especially designed for easy implementation of grid details as well as various types of distributed generation and storage and their control strategies.

The distribution grid simulation results indicate that in a hypothetical crowded urban distribution grid an approximate limit for not causing grid disturbances for private households is around 0.5 kW of grid-connected photovoltaic power generation per apartment building household in both southern (Lisbon) and northern (Helsinki) climates. Using storage schemes the amount can be increased up to over 1kW per household. However, grid details concerning storage size and siting topology greatly influence the exact limit. Further, the simulation results show that the integrated photovoltaic power generation can induce up to 34% reduction in the transmission losses of medium voltage distribution network. Corresponding analysis with wind power shows that if a MW-scale wind turbine is integrated to distribution grid the grid topology as well as the siting of distributed generation and storage are very important in avoiding unwanted overvoltage events. Overall, compensating power fluctuations of an individual MW-scale wind turbine needs to be viewed both on short and long time scales. Rapid minute-scale fluctuations can be most of the time smoothened by 50% with a storage unit in the capacity range of 25 kWh/MW. However, the long-term changes are difficult to compensate without large MWh-scale storage schemes. As a whole, the grid voltage issues proved to be much more crucial for the integration of variable distributed generation than the grid losses.

Keywords	distributed generation, network effects, simulation, photovoltaics, wind power, storage, consumption		
ISBN (printed)	978-952-248-124-5	ISSN (printed)	1795-2239
ISBN (pdf)	978-952-248-125-2	ISSN (pdf)	1795-4584
Language	English	Number of pages	86p. + app. 94p.
Publisher	Helsinki University of Technology		
Print distribution	Department of Applied Physics		

☒ The dissertation can be read at http://lib.tkk.fi/Diss/2009/isbn9789522481252/

VÄITÖSKIRJAN TIIVISTELMÄ	TEKNILLINEN KORKEAKOULU PL 1000, 02015 TKK http://www.tkk.fi

Tekijä Jukka Veikko Paatero

Väitöskirjan nimi

Vaihtelevan hajautetun tuotannon energiajärjestelmien laskennallisia tarkasteluja

Käsikirjoituksen päivämäärä	20.4.2009	Korjatun käsikirjoituksen päivämäärä	7.10.2009

Väitöstilaisuuden ajankohta 6.11.2009

☐ Monografia ☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)

Tiedekunta	Informaatio- ja luonnontieteiden tiedekunta
Laitos	Teknillisen fysiikan laitos
Tutkimusala	Teknillinen fysiikka, energiatieteet (F040Z)
Vastaväittäjä(t)	Tri Stathis Tselepis
Työn valvoja	Professori Peter Lund
Työn ohjaaja	Professori Peter Lund

Tiivistelmä

Tässä työssä tutkitaan hajautetun tuuli- ja aurinkosähkötuotannon laajamittaista liittämistä keskijännitejakeluverkkoon. Liittämisen vaikutuksia arvioitiin pääosin pysyvän tilan tehonvirtausanalyysillä. Ei-toivottujen ylijännitetilojen tasoittamisessa tutkittiin energiavaraston, verkkotopologian sekä aurinkopaneelien suuntaamisen hyödyntämistä. Lisäksi työssä perehdytään lyhytaikaisen ja pitkäaikaisen vaihtelevan tuotannon tehonvaihtelujen tasoittamiseen energiavaraston avulla. Tähän tarkoitukseen sovellettiin kolmea eri varastonohjausmallia.

Mallintamistyötä varten kehitettiin yksityiskohtainen sähkönkulutuksen ”bottom-up” -malli sekä sähkönjakeluverkon simulointimalli. Kulutusmallissa käytetty stokastinen lähestymistapa perustuu Capasso *et al.* klassiseen ”bottom-up” -malliin. Yksittäisten ihmisten toiminnan matkiminen on kuitenkin korvattu kodin sähkölaitteiden tilastollisella käytöllä, josta on helpompi saada vertailevaa tilastotietoa. Verkon simulointimalli perustuu tunnettuihin tehovirtojen laskentamalleihin. Malli on erityisesti suunniteltu verkon yksityiskohtien, monenlaisten hajautettujen tuotantolaitteiden ja varastojen, liittämiseen sekä niiden ohjaustapojen huomioimiseen.

Jakeluverkon simulointitulokset osoittavat, että hypoteettisen kuormitetun urbaanin jakeluverkon suurpiirteinen raja sille, ettei hajautettu tuotanto aiheuta verkkohäiriöitä, on kotitalouksille noin 0,5 kW verkkoon liitettyä aurinkosähkötuotantoa kerrostalohuoneistoa kohden. Tämä pätee sekä eteläisessä (Lissabon) että pohjoisessa (Helsinki) ilmastossa. Varastoja hyödyntämällä tuotantomäärää voidaan nostaa jopa yli tason 1 kW/ huoneisto. Verkon yksityiskohdat ja varastojen sijoittamisen topologia vaikuttavat kuitenkin suuresti tarkkaan raja-arvoon. Lisäksi simuloinnit osoittivat, että hajautetulla aurinkosähkötuotannolla jakeluverkon siirtohäviöitä voidaan leikata jopa 34 %. Vastaava tarkastelu tuulivoiman osalta on osoittanut, että kun megawattiluokan tuulivoimala liitetään jakeluverkkoon, sekä verkkotopologia että tuotannon ja varaston sijoittaminen ovat erittäin tärkeitä ei-toivottujen ylijännitetilanteiden välttämisessä. Kaikkiaan yksittäisen megawattiluokan tuulivoimalan tehovaihtelujen tasoittamista tulee tarkastella sekä lyhyellä että pitkällä ajanjaksolla. Nopeat, minuutin suuruusluokkaa olevat vaihtelut voidaan yleensä tasoittaa 50 %:sesti jo varsin pienellä, noin 25 kWh/MW varastolla. Toisaalta pitkän ajanjakson vaihteluiden kompensointi on vaikeaa ilman suuria MWh-kokoluokan varastoratkaisuja. Kaikkiaan vaihtelevan hajautetun tuotannon liittämisessä jakeluverkkoon verkon jännitekysymykset osoittautuivat paljon kriittisemmiksi kuin verkon häviökysymykset.

Asiasanat hajautettu tuotanto, verkkovaikutukset, simulointi, aurinkosähkö, tuulivoima, varasto, sähkönkulutus

ISBN (painettu)	978-952-248-124-5	ISSN (painettu)	1795-2239
ISBN (pdf)	978-952-248-125-2	ISSN (pdf)	1795-4584
Kieli	Englanti	Sivumäärä	86s. + liit. 94s.

Julkaisija Teknillinen korkeakoulu

Painetun väitöskirjan jakelu Teknillisen fysiikan laitos

☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2009/isbn9789522481252/

Foreword

The work presented in this thesis was carried out at the New and Renewable Energy Systems group (NRES)[1], Department of Applied Physics at Helsinki University of Technology (TKK). Fortum Foundation, Research Foundation of TKK, and Natural Gas Fund of Gasum Ltd. are gratefully acknowledged for funding the work. In addition, VTT Technical Research Centre of Finland, VVO-Group, Winwind Ltd., Central Cooperative Oulun Seudun Sähkö, and Ålands Vindenergi Cooperative are acknowledged for providing access to the wind power generation data and domestic electricity consumption data used in this thesis.

I am deeply grateful to Professor Peter Lund for giving me the possibility to work as a post-graduate researcher in the laboratory. Without his far-reaching support this thesis would not have been possible. It was his persistent but kind guidance that kept me going towards the goal despite the challenges that were on the way.

All my current and former colleagues at NRES I thank for the good research environment we shared. Dr. Petri Konttinen I appreciate for his friendship and the many discussions we had. Dr. Janne Halme taught me a lot with his dedicated work from Master’s Thesis to creating a prosperous group of researchers. Dr. Pertti Aarnio I thank for the many friendly discussions and his helpful attitude. To Dr. Mikko Mikkola I have special gratitude due to his ability to bring attention to problems and defected modes of operation. Furthermore, I am grateful to Mr. Arto Lehtolainen and Mr. Tuomo Sevón for their valuable contribution in developing the tools I applied in this thesis.

To Professor Pekka Pirilä I am grateful for the encouragement he gave to finalize this thesis. All my colleagues at the Department of Energy Technology I thank for providing such a welcoming working environment. I am also very grateful to my thesis pre-examiners Dr. Eero Vartiainen and Professor Timo Vekara for their valuable feedback.

Of the people close by I have sincere gratitude to Mrs. Ann Sofie Luba Hjerp (Paatero). Without her encouragement I most likely would not have embarked on this journey to strive for my doctoral dissertation. Concerning my sons Daniel and Kristian Paatero, I deeply appreciate all the joy, wonder, and beauty their presence has brought to my life during these years. Also, the many forms of support by my parents Aino Rahikainen and Heikki Paatero are gratefully acknowledged.

The Reverend Sun Myung Moon I thank for all the inspiration, guidance, and insights he has given me through his teachings. Most of all, however, I thank God for all the faith, love, and truth I have discovered during this journey. My life has been such a precious adventure!

“We should serve in newness of spirit, and not in the oldness of the letter.”
- Romans 7:6

Espoo, September 2009
Jukka Paatero

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[1] Part of the former Laboratory of Advanced Energy Systems

Table of Contents

List of Publications

This thesis is an introduction to the following five publications:

I. J.V. Paatero, P.D. Lund.
"*A model for generating electricity load profiles*"
International Journal of Energy Research 30 (2006), p. 273-290.

II. J.V. Paatero, P.D. Lund.
"*Effects of large-scale photovoltaic power integration on electricity distribution networks*"
Renewable Energy 32 (2007), p. 216-234.

III. J.V. Paatero, P.D. Lund.
"*Impacts of energy storage in distribution grids with high penetration of photovoltaic power*"
International Journal of Distributed Energy Resources 3 (2007), p. 31-45.

IV. J.V. Paatero, P.D. Lund.
"*Effect of energy storage on variations in wind power*"
Wind Energy 8 (2005), p. 421-441.

V. P.Lund, J.Paatero.
"*Energy storage options for improving wind power quality*"
Proceedings of the Nordic Wind Power Conference, Espoo, Finland, 2006. 7p.

Summary of Publications

I. A bottom-up load generation model is introduced in this article. The model is used to generate realistic domestic electricity consumption data on an hourly basis from a few up to thousands of households. This consumption data is used for demand side management (DSM) case studies in this article and later for case studies of large-scale distributed generation (DG) in the articles II, III and V. The model uses input data that is available in public reports and statistics. Two measured data sets from apartment buildings are also applied for statistical analysis, model training, and verification. The analysis shows that the generated load profiles correlate well with real data. As the data allows different types of consumption to be observed separately, it enables the authors to perform detailed DSM case-studies. With a mild DSM scheme using cold loads, a 7.2% reduction can be achieved in the daily peak loads. On the other hand, a sudden loss of supply can be compensated with an average of 66% reduction in the mean load.

II. In this article, the effect of large-scale photovoltaic (PV) generation in medium voltage (MV) distribution network is investigated. Case studies with different network topologies, PV penetration levels and PV panel orientation strategies have been analyzed. The emphasis was put on static phenomena, like voltage drop, network losses and grid benefits. All the network types could handle PV without problems with an amount of PV equaling at least up to the load (1 kWp/household), while the comb type network with strong main cable showed the best performance. The PV is unable to shave the domestic load evening peak, but by orienting the panels to east and west the middle day PV generation peak can be reduced by 30%. The PV contributes to reducing the network losses until a penetration level of 1kWp/household.

III. This article investigates the influence of energy storage on the network impacts from large-scale PV schemes. Additionally the influence of PV and storage siting in the network is considered. Special emphasis is given to avoiding network overvoltage events. The results show that 30-100% of the PV induced overvoltages can be compensated with storage, depending on case. With careful placing of the PV units in the grid, even greater benefits can be achieved than those with storage. The gained storage benefits were more distinguished in a southern climate, while in a northern climate the mismatch between solar power generation and domestic consumption is strongly seasonal.

IV. In this article, the effects of energy storage to reduce wind power fluctuations are investigated. The model used for the integration of a storage unit to a wind power unit is based on a filter, whose time constant corresponds to the capacity of the physical energy storage. The studies show, that a relatively small storage unit, with a 3 kWh storage capacity per MW of wind reduces the short term power fluctuations of the turbine by 10%. Smoothening out the power fluctuation of the wind turbine on the annual level would necessitate large storage, e.g. a 10% reduction requires 2-3 MWh per MW wind. This is due to the relatively long periods of low production that are typical to individual wind turbines on the annual level.

V. In this work the needs and options for peak shaving storage are investigated in local networks with variable DG. The intermittency of wind may in some cases limit the applicability of wind power when integrated directly into the distribution network, while the energy storage technologies can provide a local solution either through peak shaving or increasing temporal stability of the power generation. Through case studies it is demonstrated that roughly one MWh of storage per MW of wind power is enough to reduce at least 10% of the local voltage rise in weak networks. The weaker the network is, the more the storage influences the local network voltages.

Author's Contribution

A large part of this thesis work is based on the load simulation model discussed in Publication I and the system simulation tool DESIGEN discussed in Publication II. Both the load model and DESIGEN have been designed together by J. Paatero and P. Lund. However, the practical implementation of the load model has been completely done by J. Paatero, while the practical implementation of DESIGEN has been done by J. Paatero and A. Lehtolainen together.

For Publications I-IV, the planning and developing of the ideas have been done together by J. Paatero and P. Lund. However, the practical work and analysis, as well as the writing of the publications have been done by J. Paatero alone while many useful comments and feedback for the analysis and manuscripts have been provided by P. Lund.

The planning and developing of ideas for Publication V was mostly done by P. Lund, with minor contributions from J. Paatero. The simulation work described in chapters V and VI of Publication V have been done by J. Paatero, based on the plan and ideas by P. Lund. The manuscript of the publication has been reviewed and commented by J. Paatero, while the basic writing was done by P. Lund.

Nomenclature

A	Appliance or group of appliances.
A_{air}	Area that the rotor of wind turbine sweeps.
A_{module}	Solar module area (m^2).
C_p	Wind turbine power coefficient.
d	Day of the week.
d_W	Storage self-discharge factor.
f	Mean daily starting frequency, models the mean frequency of use for an appliance [1/day].
h	Hour of the day.
H_{mn}	$H_{mn} = \partial P_m / \partial \delta_n$.
$\bar{I}_{ij}^{t}$	Current between nodes i and j as a complex vector at time t.
I_{solar}	Incident solar irradiance.
L_{mn}	$L_{mn} = \partial Q_m / \partial U_n$.
$L_{ref,t}$	Local reference load or consumption at time t.
M_{mn}	$M_{mn} = \partial Q_m / \partial \delta_n$.
n	Number of data points or nodes.
N_{mn}	$N_{mn} = \partial P_m / \partial U_n$.
$P_{ch,t}$	Power used to charge or discharge storage at time t.
P_{down}	Lower power limit in storage control.
p_{hour}	Hourly probability factor, models the activity levels during the day.
P_{loss}	Power loss caused by Joule heating.
P_{nom}	Nominal power of wind turbine.
P_{PV}	Electric power generated by photovoltaic array or system.
$P_{ref,t}$	Reference power at time t.
$P_{sd,t}$	Self discharging power of storage at time t.
p_{season}	Seasonal probability factor, models the seasonal changes.
p_{social}	Social random factor, models the weather and social factors influencing the communal behaviour.
p_{start}	Probability for appliance to be switched on during a time period.
p_{step}	Step size scaling factor, scales the probabilities according to Δt_{comp}.
P_t	Real power at time t.
$P_{turbine}$	Electric power generated by wind turbine.
P_{up}	Upper power limit in storage control.
Q_t	Reactive power at time t.
R_{ij}	Ohmic resistance between nodes i and j.
r_m	Autocorrelation function for a given lag m.
$\bar{S}_{ij}^{t}$	Power flowing from the node i to node j at time t. One or several of the following can at times be omitted from the notation: the vector sign or index i, j, or t.
$\bar{S}_{ij,loss}$	Power loss between nodes i and j. One or several of the following can at times be omitted from the notation: the vector sign or index i or j.
t	Time or time index.
T_a	Ambient temperature.
t_{disch}	Length of discharge period in time.

$\overline{U}_i^t$	Voltage at node *i* at time *t*. One or several of the following can at times be omitted from the notation: the vector sign or index *i* or *t*.
U_t	Voltage at time *t*.
V_{wind}	Wind velocity.
w	Week of the year.
W_t	Energy at storage at time *t*.
$\overline{Z}_{ij}$	Impedance between nodes i and j. One or several of the following can at times be omitted from the notation: the vector sign or index *i* or *j*.

Δ	Small change in a variable.
$\Delta\delta_t$	Phase angle at time *t*.
ε	Tolerance level in iterative computation.
η_{inv}	Efficiency of the DC to AC conversion efficiency including cabling losses.
η_{PV}	Efficiency of a photovoltaic module.
η_{sto}	Storage system efficiency, charging or discharging.
$\eta_{sto,0}$	Constant part of storage system efficiency, charging or discharging.
$\eta_{sto,P}$	Linear part of storage system efficiency, charging or discharging.
η_{syst}	Efficiency of a photovoltaic array or system.
ρ_{air}	Air density.
σ_{flat}	Standard deviation for P_{social}.
τ	Filtering time constant.

Abbreviations

DESIGEN	A simulation tool (DEcentralized system SImulation tool for optimized GENeration) developed at Helsinki University of Technology
DES	Distributed energy storage
DG	Distributed generation
DGS	Distributed generation and storage
DSM	Demand side management
ERÅD	Norwegian bottom-up load model
EWMA	Exponentially weighted moving average
IEA	International Energy Agency
MV	Medium voltage
PFR	Normalized mean power level
PITS	Power integral time scale
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme at IEA
STD	Normalized standard deviation

1. Introduction

1.1. Distributed Generation in a Broader Perspective

Distributed generation (DG) refers to electric power generation that is connected to the distribution network or on the customer side of the network [1]. In addition, it typically consists of small-sized power generation units. Photovoltaics, wind turbines, micro-turbines, fuel cells and small hydro are all examples of such generation. Although DG is a fairly new concept in general, the idea behind is not at all new. The power generation system was originally composed of small power units that supplied the nearby customers. Only later, as the advanced power transmission networks emerged, the system developed into the currently prevailing centralized generation.

To give an exact definition to DG is not a straightforward task, and several different definitions have been seen in the literature, as discussed by Pepermans *et al.* [2]. Even the terminology applied to this type of generation is not self-evident, as North American countries often use the term "dispersed generation" (see [3]), Anglo-American countries the term "embedded generation" (see [4, 5]), and the term "decentralized generation" (see [6]) is used in Europe and parts of Asia [1]. In addition, various use of the terminology exists. For example, Willis and Scott define on page 1 of their book dispersed generation as a subset of DG [7]. Additional common DG related terms are "distributed (or dispersed) resources," "distributed utility," and "micro-grid." Distributed resources refer to distributed generation and storage (DGS) [8], while distributed utility refers to a utility concept where "modular generation and storage assets along with selected demand-side management programs are used in place of the more traditional infrastructure upgrades" [9]. Micro-grid, on the other hand, refers to a network setup, where the DG and the local load form a subsystem that can separate from the distribution system or is only weakly connected to it [10, 11]. Although it is difficult to track the first use of the term "distributed generation," its use in its current context became established in 80's and 90's by articles like those by Lamarre [12] and by Racliffe [13].

In this thesis the term DG is used persistently. The scope of DG is here limited to small, under 10 MW power generation units that have been connected to the distribution network. Typical examples of DG would be a system with three micro-turbines that provides both heat and electricity for a hospital, or an array of photovoltaic (PV) panels assembled on to the roof of a single house. In Figure 1 below demonstrates some basic types of DG and their connection to grid.

Compared to the prevailing centralized power generation, DG systems could be characterized by small unit size, modularity, and local energy resource utilization. Where as centralized power generation units can take advantage of economics of scale effects, DG profits from cost reduction in the transmission or distribution network and from incremental unit sizes and related investments.

The renewed interest in DG is due to several reasons [15, 16]. On the policy-making level, the main drivers are issues like CO_2 reduction, energy efficiency, and diversification of energy sources [17]. In practice that can be seen as promotion of small-scale renewables and cogeneration. From the utility viewpoint the main drivers are issues like small unit size and modularity, easy siting, short construction time and reduction of network losses [7, 15, 16, 18, 19]. Additional benefits are available through avoided or delayed investment to the transmission and distribution system [16, 20], and the reduced investment risk to power generation units [16]. Also, while the centralized generation benefits from economies of scale resulting from large unit size and high efficiency, DG takes advantage of the new economies of mass production allowed by its modularity [12, 16].

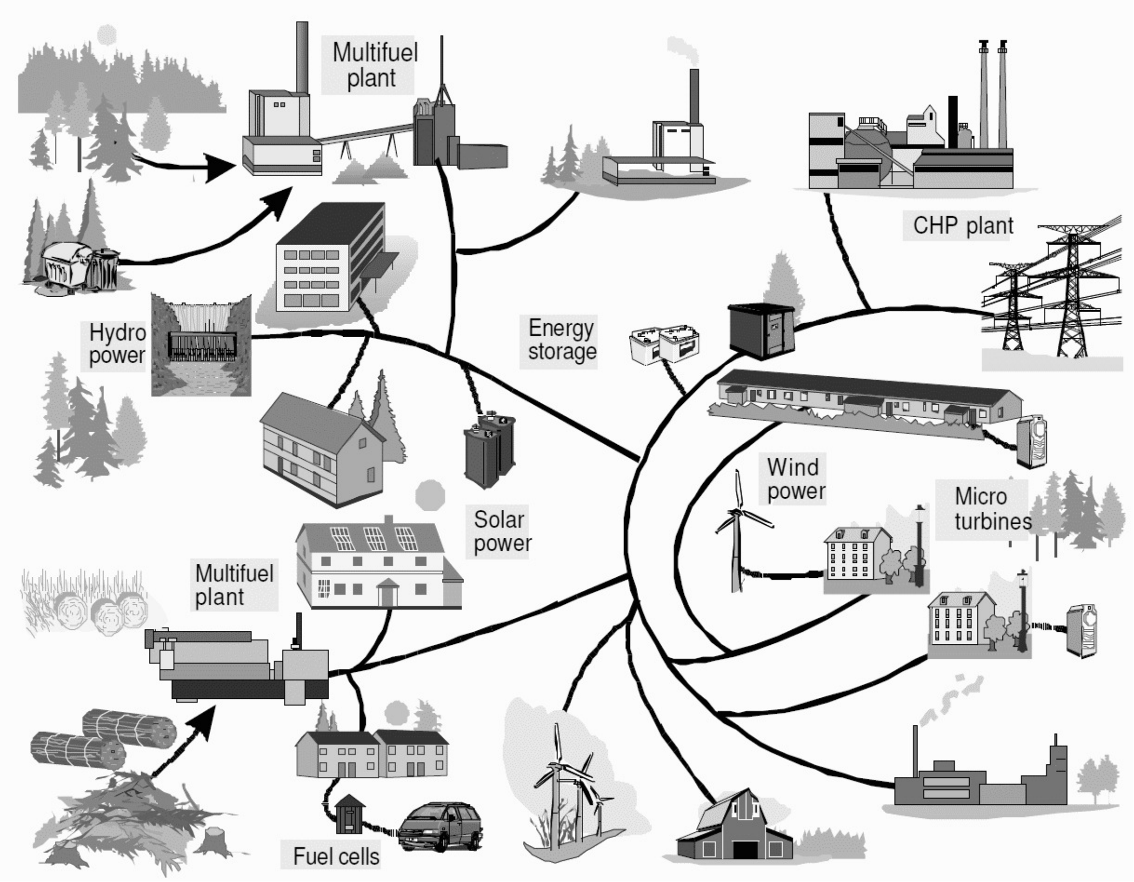

Figure 1. Implementation of distributed resources in the distribution system (adapted from [14]).

On the other hand, DG integration also involves challenges. Typically DG is connected to the distribution grid. As the amount of DG increases, several issues arise relating to system safety and quality of the delivered power. The DG type also plays a role, as synchronous and asynchronous generators as well as DG connected through power electronic converter all have slightly different impacts on the grid [21].

A DG unit can influence the grid safety in at least four different ways. The first three listed here are rather well known [3, 15, 21-24] while the fourth one is less straightforward to deal with [25]. First, the DG unit changes the fault current direction and magnitude in the grid. This becomes a concern for the correct behavior of the safety equipment in the grid. Second, a grid that has DG equivalent to its load is in danger of islanding if a fault occurs. If controlled and wanted, this can be an advantage, but accidental islanding is a severe safety risk. Reconnection to a grid that has been islanded and has drifted out of phase is a potential source of major equipment failures. Third, excess power generation can alter the direction of power flow in the distribution grid. If the grid is not properly equipped for this, equipment failure may result. Fourth, the connection of DG alters the transient stability of the distribution grid. With high levels of DG this can potentially cause the system stability to fail if not correctly addressed.

Power quality, moreover, is influenced by DG in at least four different ways [3, 15, 21-24]. First, DG can influence power quality by introducing harmonics to the grid. This is typically an issue connected to the power converter technology. Second, DG may cause voltage flicker. Such event can result from starting an engine or from rapid step change in DG power output. Third, DG integration may increase or decrease system reliability. On the one hand it can provide the grid support to ride through a problem, on the other hand failures in the DG unit or because of the DG unit can reduce the system reliability. Fourth, if the local power generation exceeds the local consumption it can potentially damage the local power quality by causing over-voltage.

When an extended time period is considered, most of these obstacles should be overcome. At that time the distributed power generation may induce wide changes in the power delivery infrastructure. Several authors have suggested future transition from the traditional top-down power delivery structure towards micro-grids, where not only the generation is distributed, but the hierarchical structure of the distribution grid will be completely altered [26-28].

The distributed power generation technologies that this work focuses on, namely photovoltaics and wind, can be classified as variable DG. Variable generation in general represents a form of power generation that is not dispatchable, but instead the power level they generate is defined by environmental factors like wind and solar irradiation. Such generation is often termed intermittent, but in this text the term variable is preferred, as it describes better the predictable nature of the fluctuation such generation may have.

Variable energy sources have become increasingly important as they typically also represent a clean and renewable energy source, such as wind and photovoltaics. In addition to them, small hydro, tidal and wave energy also belong to the category of variable energy sources. Although both wind energy and solar energy can also be utilized in centralized configuration, in this work both of these technologies are considered in applications that can be characterized as DG. Today the globally most utilized variable energy source is wind power that produces roughly 0.8% of global electricity [29]. Photovoltaics on their part have been broadly implemented in built environments in Germany and Japan with a total of 1429 MW and 1422 MW of PV capacity, correspondingly [30].

1.2. Background and Motivation for This Thesis

Variable renewable distributed power generation has been steadily growing supported by large deployment campaigns in some countries like Germany and Japan [31]. In case of photovoltaics, most of the new capacity is assigned to grid connected distributed power generation [32]. For wind power, although individual turbine installations exist [33], the tendency for new installations is towards large centralized wind farms [34]. The distributed nature of solar and wind resources naturally supports the utilization of these resources through distribute generation (DG). In addition, positive price development of solar and wind power could lead overtime to a market breakthrough in large-scale. The increasing amount of variable and distributed power generation raises new engineering challenges at the distribution grid, and in case of photovoltaics or small wind turbines, even at the level of individual households.

The typical problems caused by DG are changes in network power quality and safety, as discussed in the Chapter 1.1 above [3, 15, 21-25]. Most of the resulting power quality issues are dynamic in nature, and best handled by applying advanced power electronics. The power quality loss due to overvoltage events, however, is more a system-level planning issue. Having large amounts DG units in distribution network without appropriate system level planning easily results in overvoltage problems [15].

To systematically determine the problems that DG can cause to the power grid, simulation methods have been utilized successfully [35, 36]. While originally the system-level power grid simulations concentrated on the transmission grid level, to address DG integration the distribution grid becomes more relevant [37]. However, only limited amount of research has been done with such approach. The key elements to model for such simulation would be local consumer load, DG and distribution network.

The distribution grid simulations can be performed in a number of ways depending on their aim. Dynamic phenomena typically require analysis with small time steps and great accuracy [35]. Simultaneously the system size and analyzed time period is limited due to computational resources. Another set of phenomena, including extended overvoltage events, is reached through expanding the temporal scale of the analysis to annual level and its spatial scale to cover whole medium voltage grid branch. With such extensive problems, hourly-level simulation is commonly used to limit the amount of data points and still maintain the required accuracy for these long-term phenomena [36, 37].

1.3. The Scope and Outline of the Thesis

The scope of this thesis is on the analysis of large-scale integration of variable DG (in this case photovoltaic (PV) and wind power) in distribution networks. The aim of this thesis is on the one hand to determine how the parameters like network topology, DG penetration level, and DG siting strategy influence the effects the DG causes to the grid, and on the another hand to determine how much methods like energy storage, alternate DG siting or demand side management (DSM) can be applied to compensate such effects. As the short term dynamic phenomena, like voltage transients and frequency fluctuations, are outside the scope of this thesis the main parameters used here to evaluate the impact of DG and the compensating methods are the resulting grid voltages and network losses.

To enable effective analysis of the large scale effects typically present at the medium voltage part of the distribution network, computational methods and system-level simulation have been chosen as the main approach of this thesis. To support the analysis, various models were adapted for the corresponding system parts, like power generation technologies and storage. In addition, a detailed bottom-up consumer load model has been built for the network-level simulation tool developed in the project.

On practical level this work mainly comprises development and verification of DESIGEN simulation tool and its application to various case studies. The tool was developed at Helsinki University of Technology to estimate the effects of large-scale distributed power generation on the medium voltage (MV) distribution grid, the part of distribution grid mainly considered here. With DESIGEN it is possible to examine the effects of distribution network topology as well as to determine to what extent it is possible to reduce the adverse DG effects on the system through the use of storage and optimal DG siting strategies.

To enable simulation studies, a household electricity consumption emulation tool was developed. Its main purpose is to provide DESIGEN with large-scale consumption data (up to 10^4 households) that has been composed of consumption patterns of individual households and their appliances. The simulations as well as electricity consumption emulation in this thesis has focused on consumption households in apartment buildings. Detached houses have been excluded due to their very large consumption variability and the often dominant weather dependent electric heating loads.

The detailed knowledge of consumption also allows testing of some DSM strategies. In this thesis, even if some benefits of applying DSM have been demonstrated, extensive use of DSM or DSM with storage and related system simulations have been left outside its scope. Thus all the system-level simulations have been implemented without traditional DSM.

A number of simplifying assumptions have been used in the system level simulations. The simulation time step has been limited to hourly scale for all system level simulations to allow fast computation of up to 120 node grid branches over a time period of one year and to allow easier access to suitable weather and DG data. This choice excludes all transient phenomena related to power generation, grid interconnection and the distribution grid itself from the simulations. In addition, the simulations employ a symmetrical distribution grid that has been adapted from schematic drawings. The generation technologies have either been implemented by using a steady-state model (photovoltaics) with measured or emulated weather data or measured power generation data (wind).

Below, Chapter 2 gives a detailed view to the DG systems considered in this work. There a brief review is given on wind power, photovoltaics, and storage systems related to this work, with an additional subchapter about consumer load related issues. Chapter 3 continues further into DG research, providing a detailed review concerning the DG research related to the issues addressed in this thesis. There integration issues, storage and photovoltaics in relation to DG have been addressed. A review on electricity consumption modeling has also been included there.

Building on the reviews in Chapter 3, the methodology applied in this work is discussed in Chapter 4. First introducing the simulation model DESIGEN, the chapter reviews all the models and utilization strategies used for the DG and storage technologies. The ways the consumer load and the distribution grid have been modeled are also discussed there.

The data utilized by the models and in the simulations are presented in Chapter 5. The chapter also includes analysis and observations related to the data with special emphasis on the consumption and wind power data. This is followed by Chapter 6 where the results from the simulations are presented and discussed. There consumer data, large scale variable DG integration, and DG peak compensation are emphasized.

2. Distributed Power Generation Systems

2.1. Utility Aspects of DG

A typical reason for electric utilities to expand their power generation capacity is increase in power consumption. The choice of the right type of power generation solution is often interplay between the unit investment cost, expected development of consumption and the already existing power generation unit fleet in the system. When additional issues like local consumption and grid topology as well as local bottlenecks in the distribution grid are involved in the decision making, DG solutions may offer valuable alternatives. For electric utilities the use of DG is often motivated by avoided grid investments and relieving the load in a problematic part of the distribution network. In such case detailed knowledge of the local circumstances becomes important. This includes accurate knowledge of local consumption as well as careful studies concerning how different choices of DG sites influence the local distribution network.

From electric utility viewpoint the DG systems can be classified based on the applied technology and based on the applied mode of operation. When the distributed power generation is dispatchable like micro-turbines, piston engines or storage units there are two basic modes of operation. If the DG unit is owned by the local utility, it is natural that the utility operates the unit based on the need of the overall power delivery situation. However, when the unit is locally owned, the local consumer often operates the unit based on the needs of the consumer. From the system viewpoint this could be suboptimal, if the agreement between the utility and the local consumer is not well designed.

When variable DG like photovoltaics and wind power is considered, the ownership of the DG unit is not so much an issue. Variable unit provides power to the local consumer or grid based on natural phenomena like weather, and not based on the local needs. In this work the focus is mainly on the issues related to such variable operation.

Large amounts of variable or locally owned DG may cause problems to power distribution by generating more power than is consumed in the local distribution grid. In such case DG increases the voltage level in the distribution grid above the feeding voltage of the transformer. Such event is typically unwanted and potentially dangerous unless the distribution grid has been properly adjusted to deal with such events. Even in distribution grid where the needed adjustments have been made too high amount of DG will cause overvoltage in the grid and potentially cause damage to consumer appliances. In this work the overvoltage events are allowed to allow comparison between different grid topologies. However, the safest and most desirable situation from the utility viewpoint is always such where no overvoltage is present and no power is fed to the transmission grid from the distribution grid.

2.2. Considered DG Systems

Below, a short description is given about the basic DG technologies relevant to this study; photovoltaics, wind turbines and storage solutions. For reference, parameters for their basic technical and economical characteristics of are provided in Table 1. There, the cost of PV units is based on overall system cost for a grid connected unit, while the wind power cost is based on overall project cost for onshore wind turbines. The lead acid battery storage cost is based on the batteries that have been modified for PV use. The prices are based on the technology cost in the IEA member countries involved in the corresponding projects. Higher project prices, up to 15 €/W, were reported by IEA-PVPS in the case of PV, but the cost range used in the table below corresponds to the most widespread system prices [32].

Table 1. Basic parameters of the DG system components [32, 38-43].

	Application	Applied technology	Unit size	Power cost	Energy cost	Efficiency
PV	On-grid	Crystalline silicon	1-50 kW	5 - 8 €/W		11-16%
Wind	Onshore	Horisontal axis	1-3 MW	1.0 - 1.4 €/W		-
Storage	DS	Flywheel	1.5-250 kWh	0.1-0.3 €/W	15-80 ¢/Wh	
	DS or CS	Modified lead acid	0.01-1MWh	0.1 €/W	7 - 8 ¢/Wh	63 %
	CS	Pumped hydro	> 100 MWh	cite specific	cite specific	80 %
	CS	Redox flow cells	1-1000 MWh	0.1€/W	1 ¢/Wh	75 %

2.2.1. Wind Power

To use wind to generate electric power dates back all the way to the end of the 19th century [33, 44, 45]. The more extensive use of wind to generate electricity began during the three last decades of the 20th century. Since then, the use of wind power has become commonplace. Today, the most prevailing wind turbine technology is the three-bladed horizontal axis wind turbine, shown in Figure 2 [34, 46]. Its main parts are the base (not seen in the figure), the tower, the nacelle and the rotor.

Modern wind turbines convert the kinetic energy of wind directly to electricity with a rather high efficiency. The power developed by a vertical axis wind turbine can be given by [15, 34, 46]:

$$P_{turbine} = \tfrac{1}{2} C_p \cdot \rho_{air} \cdot V_{wind}^3 \cdot A_{rotor} . \tag{1}$$

There C_p is a turbine power coefficient that depends on the turbine design, $P_{turbine}$ is generated electric power, V_{wind} is wind velocity, A_{rotor} is the area that the rotor of the wind turbine sweeps, and ρ_{air} is the density of air. The wind turbine takes the kinetic energy of wind by slowing it down and converting it to electric power. As the Equation (1) above demonstrates, the delivered power is proportional to the cube of the wind velocity.

In practice this ideal turbine behavior is limited in the low wind speeds by the wake wind speed needed to start the rotor and in high wind speeds first by turbine maximum power and later the turbine safety breaking. The turbine limits its power generation to the maximal power by blade controls and stalling when the wind speed reaches a high enough speed. A maximal safe wind speed has typically also been defined. When reached, the rotor will be completely halted by using stalling and some breaking mechanism.

Figure 2. Three-bladed horizontal axis wind turbine with 1MW nominal power, courtesy of WinWinD.

The wind speed data typically shows two characteristic effects, namely macro-meteorological and micrometeorological fluctuations [47]. The spectral power density of wind fluctuations shown in Figure 3 clearly shows these two fluctuation types as two separate peaks. Movements of large-scale weather patterns like the diurnal cycle and the movement of low and high pressure regions cause the macro-meteorological fluctuations, while the atmospheric wind turbulence is the source of the micrometeorological fluctuations. Although the physical and electrical characteristics of the wind turbines modify these effects, similar fluctuation patterns are clearly present in the wind power data [48, 49].

The fluctuating nature of wind power influences the grid in many different ways. The effects are stronger in weak networks, for example when an individual turbine is connected at the end of a long medium voltage distribution grid branch. The macro-scale fluctuations (hourly level) in power output can cause periods of imbalance between the local generation and load, causing the local power generation to exceed local consumption. This typically results in an overvoltage event in the local grid. The short term fluctuations in wind power output, e.g. caused by turbulence, wind share over height or turbine tower shadow effect, can cause pulsation in the local grid voltage, or so-called voltage flicker. However, in modern MW-scale turbines the inertia of the rotor reduces the most short term fluctuations.

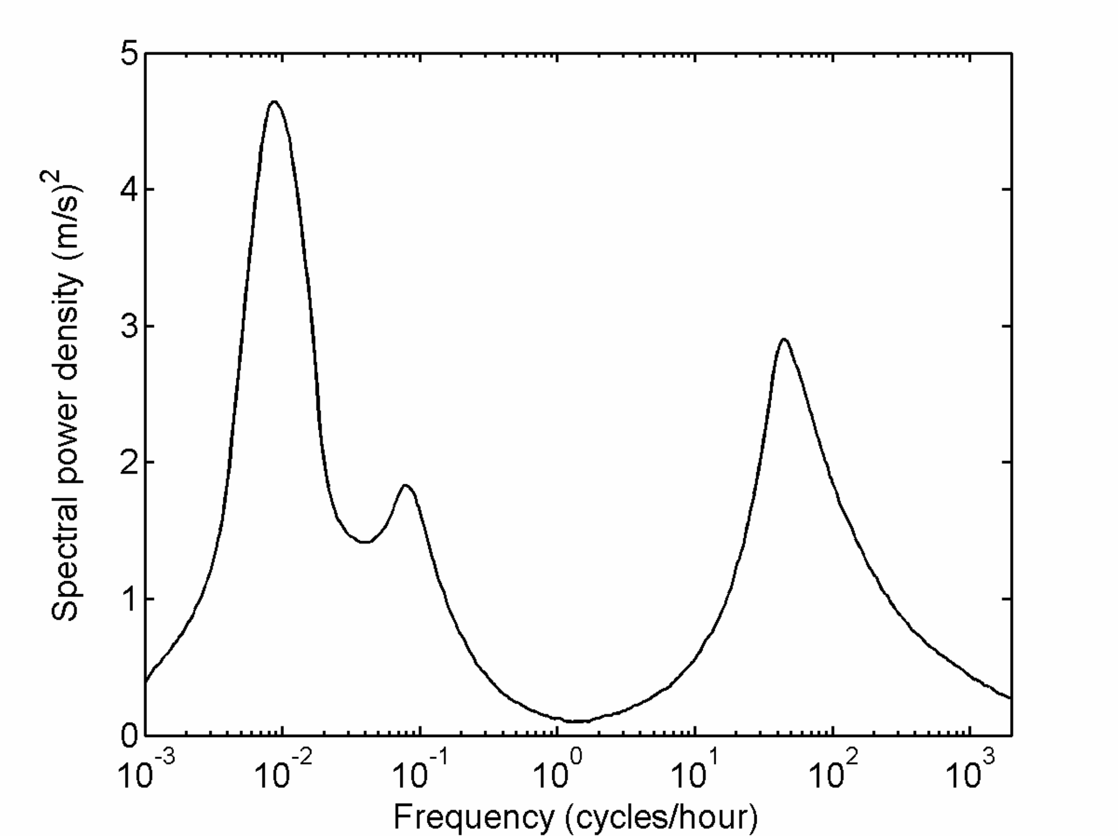

Figure 3. Spectral power density of wind speed fluctuations. The left peak corresponds to macro-meteorological fluctuations and the right peak to micrometeorological fluctuations (adopted from [47]).

The applied turbine technology also influences how it interacts with the network. The turbine can be regulated with pitch, stall or active stall and it can be based on a fixed speed turbine with a synchronous generator or a variable speed turbine with an induction generator. Some typical challenges with certain wind turbines designs are briefly presented below.

Variable speed wind turbines can emit harmonics to the grid from their converters. However, the emission of harmonics can be limited by applying suitable filters at the turbine power output. The induction generators for their part require reactive power from the grid that can cause additional voltage drop issues. On the other hand, if instead a fixed speed turbine with stall regulation is connected to the grid during startup, it can cause high current peaks to the grid due to the limitations in generator rotor controls. Fortunately this problem can be avoided by using different turbine technology: pitch-regulated and variable-speed turbines do not have this start-up problem. In high winds the pitch-regulated turbines with synchronous generators can emit strong current peaks, though, as the turbine responds very quickly to the variations of wind speed. Further details about network issues, the turbine designs and discussion about more advanced types of turbines can be found from the overview article by Ackermann and Söder [34].

However, as the current peaks, harmonics and voltage dips are fast transients in nature, they are beyond the scope of this work.

Wind power is usually installed at windy locations where the distance to an existing, at least 100 kV high voltage grid (transmission and high voltage distribution network) is not too long. In such cases, large-scale wind farms can be constructed, as a strong connection to the transmission network is not too expensive. When the distance to the transmission or high voltage distribution network is long or other constrains apply, individual turbines can be built. Even an individual turbine is better to connect to high voltage network, but when the turbine is not too massive (multiple MW scale) connection to medium voltage distribution network can also be considered.

2.2.2. Photovoltaics

Solar irradiation has always been the primary energy source for life on earth. However, it was not until the 1880's when it became possible to convert solar irradiation directly into electricity. The invention of photovoltaic (PV) cell by Charles Fritts [50] made it possible. In recent decades, the advance in PV technology has been rapid. As a result, PV technology has become a viable option for local small-scale power generation.

Without subsidies the cost of the PV technology is not yet competitive with centralized power generation [51]. On the other hand, for off-grid needs PV systems can often be cost effective solutions [52]. Detailed reviews to the state of art and prospects of PV technology have recently been given by Green [53] and van der Zwaan [54]. In addition, planning tools for evaluating PV system sizing and economy are well available [55, 56].

Several competing PV technologies and materials have developed mature enough to enter the PV market. These materials include mono-crystalline, poly-crystalline, and amorphous silicon as well as the thin film materials copper indium diselenide and cadmium telluride [52, 54]. Out of these, the traditional crystalline silicon based technologies are the ones that dominated the market with a 87% share of the PV market in 2006 [32]. They have good efficiency (typically 14-18%) and a reasonable cost range (4-7 €/W).

The typical unit size with PV technology is difficult to define, as the PV cells are small and they can be combined in PV panels in many different ways. The photovoltaic systems have the same problem, as the individual panels can be combined to form any size of PV system. In Germany, however, the average size of a domestic PV system is around 5 kWp [52], while large 60 MWp centralized PV power generation plants also exist [57].

The site requirements for PV installation are quite flexible, the most important criterion being the hours of unblocked sunlight per day. PV panels can be mounted on almost any surface, and the tilting angle of the panel is commonly chosen based on the siting latitude.

Typical application for grid connected PV would be a rooftop installation that is connected to the distribution network through an inverter. Usually such an installation has system control that is limited to the safety features provided by the controller of the interconnecting power electronics.

Power generation based on PV technology has cycles that are based on the cycles of the Sun. The diurnal cycle is very strong, as PV cells produce no energy when it is dark. Also, seasonal variation in solar irradiation is stronger in the more northern locations (in the northern hemisphere). Typically the seasonal variation changes the maximum of the daily peak power generation, as well as the frequency of bright days with abundant solar radiation.

As distributed PV generation is connected to grid, three issues typically arise. First, the diurnal PV generation peak is typically off peak for electricity consumption in domestic households. Second, the seasonal PV generation peak is also off peak for domestic households, unless significant amount of air conditioning load is present. When the PV generation peak does not match with the load peak, it can create overvoltage problems in the network. Third, the PV units are connected to the grid through power electronics, including inverters. As numerous inverters simultaneously feed power to the grid, voltage harmonics may be generated. All of these issues become topical when the amount of PV in the grid becomes very high.

2.2.3. Energy Storage

Using energy storage is a well-known solution to balance the difference between supply and demand. When power generation is considered, the typical use of storage is exactly this: to provide means to utilize power at a different time from its production. In practice, storage can be used first of all to store local power generation when there is not enough local consumption or when the available power is exceptionally cheap. Second of all it can be used to provide power to consumers when there is not enough power available or the available power is exceptionally expensive. Storage can also be used to avoid rapid changes in local power generation to ensure the power quality.

Local storage can become profitable either directly by the price difference between the electricity purchased to and sold from the storage or indirectly through avoided cost to distribution grid improvement. In the latter case storage is typically used to improve the power quality of the local grid to such an extent that grid improvement becomes unnecessary. This can mean in practice storing excess generation to a large storage unit or discharging such a unit during a local demand peak. Alternately it can mean using a smaller storage unit to smoothen the rapid fluctuations in the local power generation.

Several technologically mature electricity storage technologies exist. Most common ones are batteries, flywheels, and water reservoirs with two-directional turbines. However, there is a great difference in their performance concerning the period of storing needed. In this work the main emphasis is on technologies applicable for 1-24 hour storage. Of them, three selected technologies have been listed at Table 1 above, accompanied by flywheel that is best suited for short term use. Lead-acid battery is the cheap end of battery technologies that can be applied both to distributed and centralized storage solutions due to its modular nature. Batteries can easily be used locally with small DG units like photovoltaic system with only 1-100 kWh capacity or as a centralized storage unit up to MWh scale. On the other hand, redox flow cells are expected to become and pumped hydro storage already is economically profitable as MWh-scale centralized electricity storage units. Another potential centralized storage technology would be compressed air energy storage that, like pumped hydro storage, needs a good natural reservoir to be economical. Flywheels are typically designed for up to one hour discharge capacity, making it more suitable for smoothing fluctuations than long term storage.

Small and intermediate size storage that is sited at the distribution network is here called distributed energy storage (DES). Already in late 70's energy storage was considered as a part of grid connected DG with variable nature [58, 59]. Later on, as the amount of variable DG has rapidly increased the research has been about the applicability of DES to optimize customer benefit from DG or more broadly with the demand fluctuations in the local grid [39, 60]. For storage units the common parameters of interest are the storage capacity, power level, response time and the cost of the storage unit. Other parameters of interest may be for example efficiency, physical dimensions, life-time, and availability, but these are not considered in this thesis.

In this work, the storage applications are studied in connection with high penetration of PV or a MW size wind turbine in the local grid. When the storages are considered to be sited locally near the PV units,[2] they would typically be load-acid battery storages. When centralized schemes or storage for MW size wind turbine is considered,[3] rather large storage units need to be used. Such units could be very large battery storage assemblies or alternately small redox-battery storages or pumped storage units. When compensating short term fluctuations of wind power the storage needs to be charged and discharged almost all the time, making flywheel a suitable technology choice as long as large enough storage capacity is assembled.[4]

2.3. Load Issues

Information about local consumption patterns is crucial for designing electricity distribution networks and optimal power generation capacity. The maximum demand situations define the power delivery capacity needed for the local grid, and its timing is important for the planning ahead of power generation. The electricity consumption information at the utility level is typically aggregated from load data with limited details concerning the areal distribution of the loads. This approach is adequate when centralized power generation and delivery are utilized.

When DG is sited to distribution network, accurate knowledge of about local consumption patterns becomes important. It is needed when small-scale distributed energy technologies are optimally sized into the local network or local DSM measures are planned. The data that electric utilities typically have on domestic electricity consumption do not contain much information about its nature. The data is normally aggregated consumption of multiple households without knowledge of the events in individual households. The fluctuation of electricity consumption concerning an individual household remains unrevealed as well as the division of consumption

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[2] In Publication III with less than 5 kWh storage capacity need.

[3] In Publications III-IV with the needed storage capacity of 1-10 MWh.

[4] In Publication IV with up to 5 kWh storage capacity need.

between different types of household appliances. Nevertheless, detailed knowledge can be produced with simulation models.

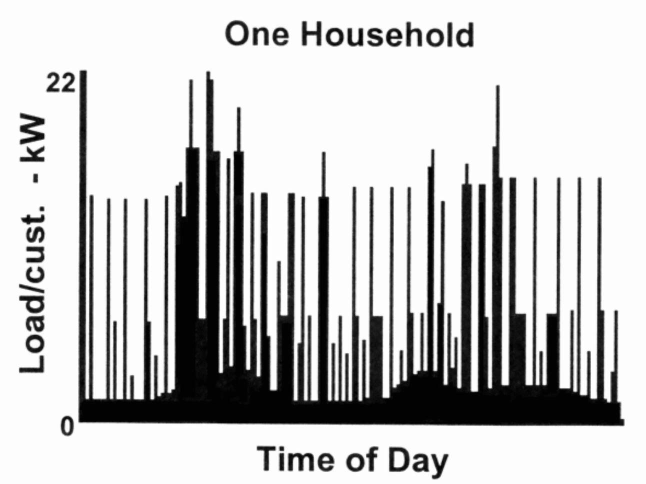

Figure 4. Typical load data for a single household [7].

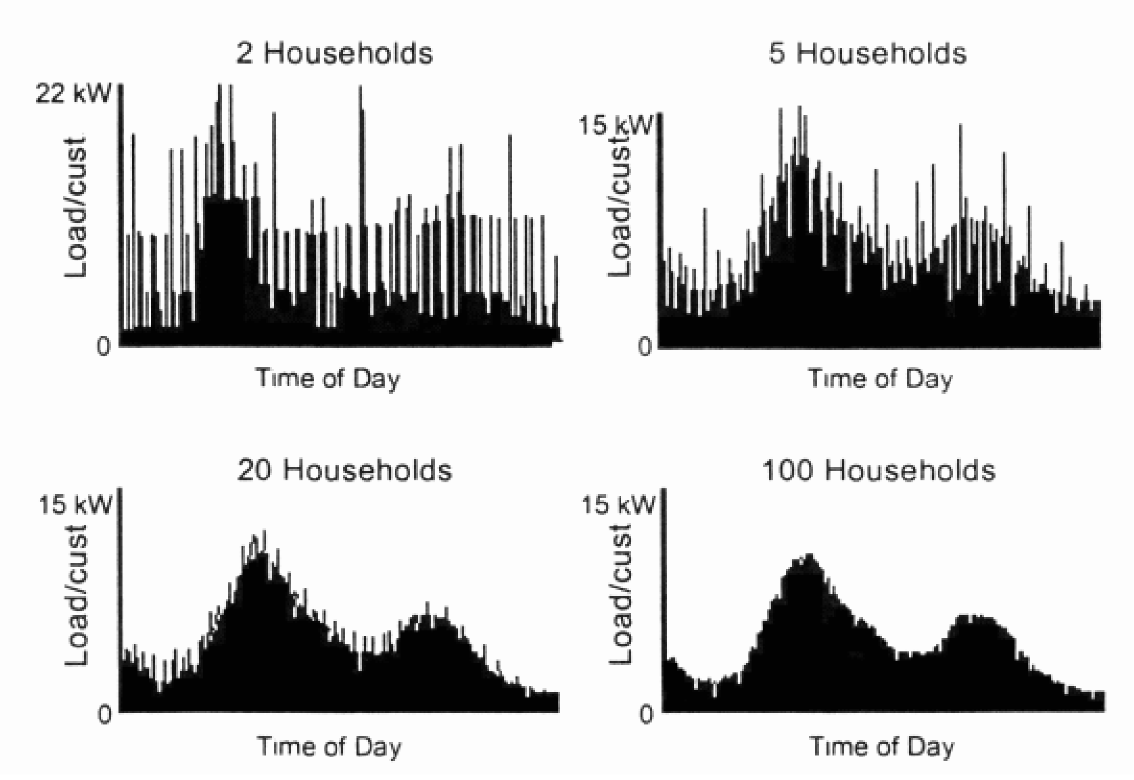

Figure 5. Smoothing due to household data aggregation [7].

The consumption data of an individual household appears quite random, as seen from Figure 4, although it does show the increased consumption at those times when people are typically awake and at home. This random-looking appearance is caused by the relatively short periods that household appliances are typically used and the lack of clearly showing consistency in their use on the individual household level. However, as the amount of aggregated households increase, clear consumption patterns emerge and the total consumption smoothens, as shown in Figure 5. This is due to coincidence in the electricity use when several households are considered. For example, it is typical for people to go to work in the morning, so most of them will make tea or coffee and prepare breakfast at some time between six and nine am. Also, if the building has electric heating and it is a cold morning, heating takes place in all of the households. This smoothing nature of the load with increasing number of households becomes very important when the local data is considered. Variations on individual household level will be large, but the pattern of the local load area should be known. Also, any model used to emulate consumer load should show similar pattern in the load behavior. That way the variations in the local power flow inside the distribution grid can be more accurately considered.

3. Research on Distributed Power Generation Systems

Issues related to integration of small power generation units, like protection and safety [61-64], reliability [58, 59], power quality [62, 65], losses [58, 66], and control [67, 68] have been discussed by the scientific community already in the end of the 1970's and the first half of the 1980's. On the other hand, the discussion concerning more widespread use of DG emerged at the beginning of the 90's [12, 13].

This was followed by a flood of research articles that explored various aspects of the potential that DG provided. The three most cited[5] articles are the one by Jenkins [4] that deals with the technical aspects of generation embedded in distribution networks, the one by Barker and De Mello [23] that discusses how to avoid power quality and safety degradation when integrating DG to radial distribution network, and the one by Ackermann *et al.* [1] that makes an appreciated attempt to define what is DG. Other much cited DG related articles[6] are those by Hadjsaid *et al.* [3], Girgis & Brahma [69], Blaajberg *et al.* [70], Dugan & McDermott [71], Joos *et al.* [72], and Pepermans *et al.* [2].

The first two books dedicated to DG were published in 2000. These were the books by Willis and Scott [7], and by Jenkins *et al.* [15]. The book by Willis and Scott approached DG from the investment point of view, concentrating mostly on DG cost analysis and other DG investment issues. The book by Jenkins provides a different, more technical viewpoint focused on the distribution network safety, disturbances, and limitations. During the following two years four more DG books appeared, two per year. The first one in 2001 discusses DG from a less technical view [73] and the second one from a United-States-centered view [74]. The first book in 2002 provided a DG market overview with policy observations and recommendations for selected OCED countries [75], while the second book gives an extensive discussion about the benefits of DG without going into technical details about the generation technologies themselves [16].

As already seen from the large variety of topics in the most cited articles above [1-4, 23, 69-72], the research on DG has developed to a very broad field of study. Therefore, only the three areas essential to this thesis will be reviewed in more detail. The integration

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[5] The popularity of the articles is based on the amount of citations listed for the articles in Google Scholar search results (http://scholar.google.com/) using one of the search word sets "distributed generation," "embedded generation," "dispersed generation," or "decentralized generation." Results not relating to distributed power generation or not on the first result page were omitted and the searched words needed to be present together in the title or the abstract. The search was done 29th Jan. 2009.

[6] The listed articles have at least 60 citations in the Google Scholar search results at 29th Jan. 2009.

issues concerning DG systems are discussed in the first subchapter below with main emphasis on hourly level over and undervoltage events. The second issue is the DGS with main emphasis on the distributed storage system and its utilization as part of the DG system. Chosen aspects of large scale use of distributed photovoltaic power generation will be discussed in the third subchapter. An additional subchapter will be dedicated to literature on electricity consumption models, with emphasis on the bottom-up models that are useful when detailed DG simulations are done.

3.1. Static DG Integration Issues

Consumption peaks are a typical challenge for power system design. The introduction of DG increases the occurrence of peaks in the sense that it generates peaks of “negative consumption” if not controlled. This can be particularly significant for the local network that is less able to withstand such fluctuations. When DG is introduced to a local distribution network branch the main static issues of concern would be the maximum voltage levels in the branch and how the new DG influences the overall losses in the system. In addition, there are several dynamic issues to consider, such as harmonics and system stability at transients discussed in Chapter 1.1 above. However, those issues are outside the scope of this work.

The basic problems related to overvoltage issues have already been discussed by Masters [22] and Barker [76]. While Masters focuses mainly on the static voltage rise issue, Barker presents a broader view including dynamic issues related to grounding and islanding. A specific engineering solution to overvoltage problems has been suggested by Choi and Kim [77], as their method helps to maintain the customer voltages within the allowed margins despite local DG or storage units and unbalanced load diversity in the network. Our approach to voltage rise issues is similar to that of Masters and Barker while the dynamic issues by Barker are outside the scope of this work.

Recently much of the research concerning DG in weak network branches has been done in connection to wind power. While Ackermann and Söder [34] have provided a nice overview of the effects when integrating wind power to the grid, their approach is more general. Integrating wind power to weak or relatively weak networks has been the main focus in the work of Sørensen *et al.* [78], Craig *et al.* [79, 80], Alejandro [81], Lundberg *et al.* [82], and Repo and Huhtala [83]. In this thesis the distributed wind power has mainly been considered in connection to hourly-scale storage applications[7], thus excluding much of the dynamic issues addressed for example by Craig and Jenkins [80].

3.2. Distributed Generation and Storage

The concept of dispersed generation and storage has already been employed in the 80’s [62, 63, 67, 84] and even before [58, 59, 66, 68]. Already then there was concern about the impacts of DGS for the distribution network. In their work Dugan, Rizy and others [62, 63, 67] addressed the issues like production of harmonics, voltage fluctuations, and system protection. The earlier contributions by Mohre [58] and Ma [59] concentrated on the additional investment options and solutions that the DGS provide for the distribution

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[7] In Publication V and part of Publication IV.

network planning, while Lee [66] was concerned about the correct economic analysis of the DGS systems. The early paper by Chowaniec [68] was focused on optimal utilization of the storage system in a grid-connected PV system with storage. Later, more detailed work has been done on grid connected storage systems, like the work on distributed storage control strategies by Barton & Infield [39], or the work on wind-hydrogen storage systems by Korpås [85].

Traditionally, the use of energy storage has been motivated by economic evaluation. For instance, economics of combining grid connected variable generation with energy storage has been reported by Bathurst & Strbac [86] and Korpaas *et al.* [87] in connection to wind power. Grid connected PV is typically installed without local storage, as the size of an individual system typically remains small and the grid can effectively act as the system storage [88]. Thus economic evaluations of grid connected PV are typically done without a storage system [89, 90]. As an exception, recent work by Hoff looks particularly into the economic benefits for customers from using storage with grid connected PV systems [60].

In this thesis the economic aspects of storage are mostly left aside, where as the effects to the system level are emphasized. That line of approach has been discussed in the work of Price *et al.* [91], where potential applications of utility scale storage use are addressed. The interaction between wind power, energy storage and the power grid has been the emphasis in the work of Abbey *et al.* [92-94]. In their work, much weight has been given to dynamic issues that are outside the scope of this thesis, but also sizing and scheduling issues relevant to this thesis have been tackled. Use of energy storage with variable generation in weak grids has been reported by Binder [95]. His implementation to use storage as a weighted moving average filter to compensate the fluctuations of distributed wind power was studied in detail as a part of this thesis[8].

In addition, there is extensive research done on DGS in connection to hybrid power generation systems [96-103]. However, such systems are outside the scope of this work.

3.3. DG with Photovoltaics

DG using photovoltaic power generation has become popular in some countries, as national programs promote PV systems for grid applications, in particular in the built environment [32]. This trend has been particularly strong in both Germany [104, 105] and Japan [106]. This has inspired a broad range of research activities that has also been reflected for example in the work of IEA Photovoltaic Power Systems Programme (PVPS) [32]. Some chosen topics of PV research are elaborated further below.

The work on the use of photovoltaic (PV) power generation in urban environment began already in the 80’s in the USA [107]. Later on Germany took the lead, as green energy became popular in Germany, expressed through their PV campaigns and feed-in tariffs [104, 105]. In Japan, due to the high urbanization rate, the PV use in urban environment has been the most natural application for the technology already from the beginning [106]. More recent developments in the field have been described on the one hand by IEA PVPS reports and statistics [32] and on the other hand by Green [53, 108, 109].

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[8] In Publication IV.

The overall potential for PV utilization in an urban environment has been evaluated by Scartezzini *et al.* [110]. They estimate the PV potential of a selected urban area by using building orientations, local weather data, and suitability of roofs and facades for PV use. They conclude that in their case study almost half of the roof surface is suitable for PV use (with 1,000 kWh/m^2 on annual threshold). More detailed discussion about computing the solar potential has been given by Compagnon [111]. The results form both Compagnon and Scartezzini *et al.* indicate that true potential exists for installing high penetration level of distributed PV generation to an urban environment.

Matching the distributed renewable generation with the local load is the main issue in the paper by Born *et al.* [112]. Although in their paper Born *et al.* focus on their methodology (eSmart system) to match the local consumption and generation, their choice of methods is similar to that in this work. Their main tools to avoid imbalance are both DSM and storage. These tools have also been analyzed in this work.

3.4. Electricity Consumption Models

The most typical application of electricity consumption models is the short and long term forecasting of future consumption. Various econometric and other models have been developed for this purpose, as reported by Gross and Galina [113]. More recent review on demand forecasting methods has been given by Alfares and Nazeeruddin, [114] where novel methods including fuzzy logic, genetic algorithms and neural networks [115] have been included in addition to the traditional econometric models [116]. Econometric forecasting models also form a major part of the more general kind of energy model review presented by Jebaraj and Iniyan [117]. These kind of forecasting methods are typically applied when only limited or no knowledge is available about grass root consumers and the prediction is wanted only to aggregate load [118].

An alternative for conventional demand forecasting methods is given by end-use models. These models represent a bottom-up approach to load forecasting, and these models can also be applied to generate any kind of consumption data when the needed model parameters are defined. Some electric utilities use a general level bottom-up modeling, as presented by Willis [119]. These utilities gather consumption information for different consumption classes, based for example on statistics about the number of people living in the household, or classes of appliances. However, here the individual consumer level is completely missing. Thus the model gives more overall details than traditional consumption forecasting schemes using econometric method, but less than the detailed household level bottom-up models.

More detailed bottom-up methods would ideally be based on an exact database about household appliances and their usage patterns. With an accurate model this would allow perfect emulation of the local consumption. However, typically the bottom-up models are limited to either what is here called the “social type,” like the model published by Capasso *et al.* [120], or the “engineering type,” like the Norwegian ERÅD model discussed by Larsen and Nesbakken [121]. When compared, the engineering type model focuses very much to the technical environment where the consumption takes place, while the social type model puts weight on modeling human behavior as an important model input. The engineering type model would be characterized by many technical details about the household, while the social type model would include detailed patterns about the behavior of the people with the expense of technical details. The resulting data from the engineering type model is more general than from the social type, as the usage patterns in engineering type model typically do not include sub-day patterns. In the social type model, user behavior is modeled exactly on the sub-day level.

All the types of bottom-up models presented above can be used to forecast the development of consumer load. A comparison between using the ERÅD model and their econometric model for load forecasting has been given by Larsen and Nesbakken [121]. Although the bottom-up models may not be ideal for load forecasting, they have another advantage: unlike forecasting methods, the detailed bottom-up methods can be effectively used to emulate the prevailing consumption. With a quality input database this provides new information about the details of the load.

In this work a detailed bottom-up approach has been applied. The social type model presented by Capasso was used as the foundation from where the model applied in this work was developed. Bottom-up method was chosen as it gives best support to DSM and detailed network level analysis, and the social type approach was applied because the kind of data needed for the social type model is more readily available and simpler to emulate.

4. Simulation of Grid Connected Distributed Power Generation

When grid connected DG is simulated, the three basic parts shown in Figure 6 need to be modeled: the power generation itself (located at node *i*), local power distribution grid (composed of power lines *ij*), and the local consumption (located at node *j*). Here the system is modeled using hourly time scale and any short term dynamic phenomena connected to the grid or interaction with the grid are left out of the analysis. In addition, it is assumed that the changes in the local network voltage levels do not influence the power generation and consumption. This gives the possibility to use measured data in both power generation and consumption data sets. However, the state of the power grid needs always to be solved through computational means.

The subchapter below describes the simulation tool applied in this work. The subchapters later provide details on the way DESIGEN performs the network computations and how it models the integrated power generation. A separate subchapter has also been provided for the generation of consumer load data. Discussion concerning the applied input data is included in Chapter 5.

4.1. DESIGEN Model

The simulation of power distribution networks and the connected power generation and storage units has been accomplished using DESIGEN (DEcentralized system SImulation tool for optimized GENeration) that has been developed at Helsinki University of Technology. DESIGEN first defines the local power generation and loads, followed by power flow calculations that are balancing the distribution network. The overall structure of DESIGEN is shown in Figure 7.

As DESIGEN simulation is initiated, first the program initializes the required data structures that are needed to accommodate all the input data. This part also includes the setting up of the electric grid and connecting the load and generation units to it.

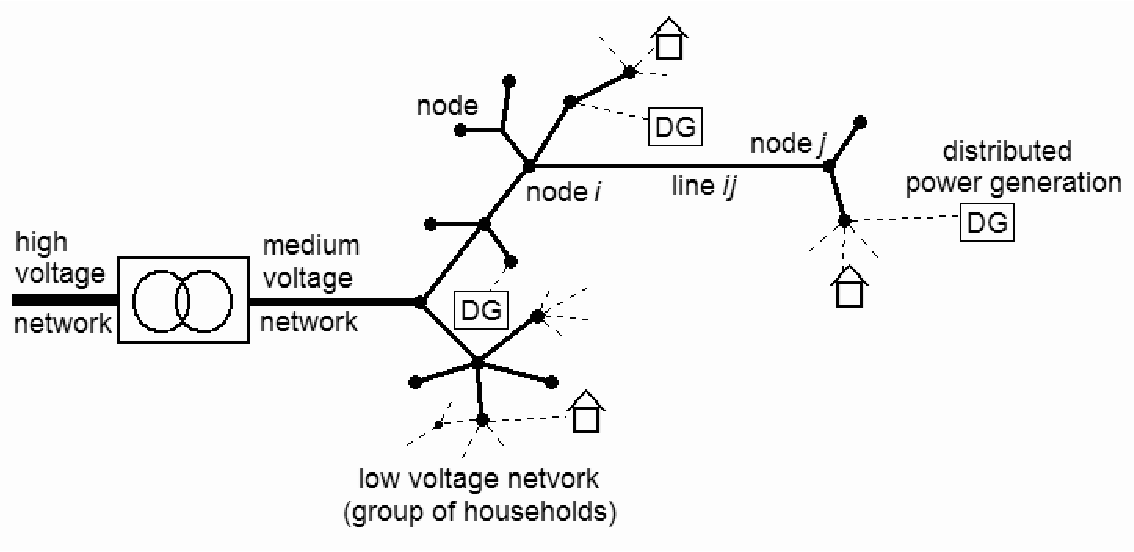

Figure 6. Schematic picture of medium voltage network with DG.

The parameter data is limited but crucial for the simulation, as it defines the actual method applied in a simulation. Number of time steps together with the length of the time step defines the total length of the simulation. Additionally, loads and power generating units can have a different time step length, as long as it is an even fraction or product of the system time step. In this work a one-hour system time step was typically applied.

When initialization is done, the program defines the power generation and loads in the grid and begins the power flow iteration. The load and power generation are defined by straight reading the values from load and generation data or emulating the power generation based on the weather data. The power flow in the grid is computed iteratively, and after the iteration reaches the accuracy criteria, the results are written to the output files. This cycle is repeated for each discrete system time step. Details about the applied network geometries and power flow calculation methods, power generation emulation models, and load data generation are discussed below.

If the simulation includes DSM, the effects to the load need to be defined before the simulation, so that the load data can be utilized as such. DESIGEN itself does not include any method for load control, so the control needs to be pre-imposed. Due to this DSM tasks can result in iterative use of DESIGEN and the load generation program.

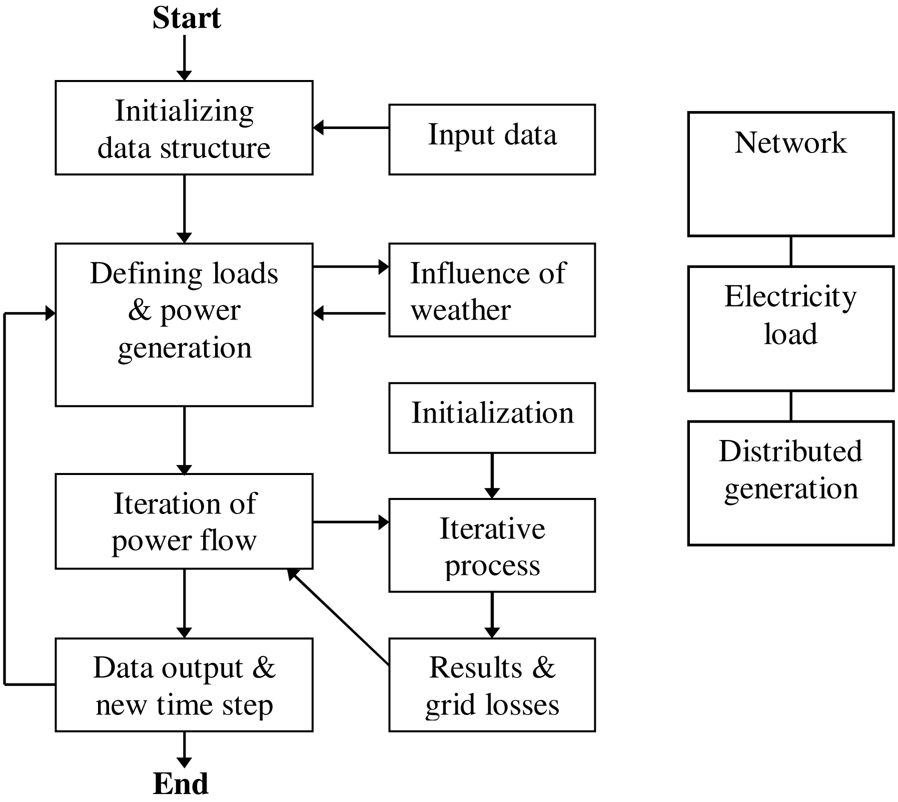

Figure 7. Basic structure of DESIGEN.

4.2. Power Distribution Network

(Publications II-III, V)

Simulation of power distribution network (the grid) can be achieved by establishing the grid with nodes and lines that are connecting the nodes to each other. In this kind of set-up the lines represent power lines or individual cables while the nodes represent their points of interconnection. The key parameters for such grid would be nodal voltages $\overline{U}_i$ as well as electric currents $\overline{I}_{ij}$ and power $\overline{S}_i = \overline{U}_i \overline{I}_{ij}^*$ flowing between the nodes. Some nodes would be importing power to the system through generation; others would be consuming it through the loads. In addition, part of the electric current would be lost due to the impedance $\overline{Z}_{ij}$ of the cables.

When an individual network branch is modeled instead of the whole network the network branch needs to have one root node that represents a connection point to the rest of the network. This node should be in a relatively strong part of the rest of the network that is left outside the model. This allows the assumption that the root node is unaffected by the events in the network branch. Thus the root node is assumed to maintain a fixed voltage level.

When simulation of power distribution network branch is initiated in DESIGEN, the root node is first defined. Next, the program begins the setting up of the rest of the network. From the input data the program gets the numbering of the nodes and the available network lines between them. As the network is set up, the program connects the loads and generators to their corresponding nodes.

When the setting up of network and time series for loads and generators has been completed, a power flow computation is executed for the network on every time step. This computation finds a static and balanced state for the network, where the feeding of power to or from the root node is defined based on the power need, losses and generation in the modeled distribution network. When the network is not looped, the power flow is computed with a five step method similar to the one published by Jenkins *et al.* [15]:

Step 1. Initial values are given to voltages of network nodes U_i^0 (typically nominal voltage, here $i = 1 \ldots n$, where n equals the number of network nodes).

Step 2. Network node currents from loads and generation are computed with $\overline{I}_i^t = \overline{P}_i^t / \overline{U}_i^t$ and then summed following Kirchoff's first law [24].

Step 3. Node voltages are computed with $U_i^{t+1} = U_j^{r+1} - Z_i I_{ij}^t$. Here j refers to the node from where node i gets its current.

Step 4. If $\left| U_i^{t+1} - U_i^{t^*} \right| > \varepsilon$, where ε is the predefined tolerance, the iteration has not converged. Then $t = t + 1$ and go to step 2.

Step 5. When the iteration has converged, the values U_i^t and I_i^t are the result.

When the network has loops DESIGEN applies the traditional polar power-mismatch version of the iterative Newton-Raphson algorithm [122, 123]. This algorithm is designed for simultaneous solving of a group of nonlinear equations. There, network flow equations form a Jacobian matrix equation:

$$\begin{bmatrix} \Delta P_t \\ \Delta Q_t \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \cdot \begin{bmatrix} \Delta \delta_t \\ \Delta U_t \end{bmatrix}. \qquad (2)$$

The equation is iteratively solved until the power values $P_{t+1} = P_t + \Delta P_t$ (real power) and $Q_{t+1} = Q_t + \Delta Q_t$ (reactive power) converge. The matrixes H, N, M and L above are Jacobian matrixes $H_{mn} = \partial P_m / \partial \delta_n$, $N_{mn} = \partial P_m / \partial U_n$, $M_{mn} = \partial Q_m / \partial \delta_n$, and $L_{mn} = \partial Q_m / \partial U_n$, correspondingly. Above $\Delta \delta_t$ is the phase angle and ΔU_t the voltage step size. Although more advanced decoupled power flow methods could also be applied [124, 125], this traditional method was applied due to its simplicity. As the voltage and phase angle values are solved from Equation (2), the Jacobian matrix needs to be inverted. This actually becomes the most time consuming step of the whole power flow computation.

Network losses mainly result from the heat generated by the movement of electric current inside the power transmission cables (Joule heating), and they are in the scope of this work. As power is transmitted through a cable between nodes i and j the change in apparent power can be expressed in terms of power lost to heating (P_{loss}) and change in reactive power (ΔQ) or as a function of impedance ($\overline{Z}_{ij}$) and current ($\overline{I}_{ij}$):

$$\Delta \overline{S}_{ij} = P_{loss}\bar{i} + \Delta Q \bar{j} = \overline{Z}_{ij} I_{ij}^2 . \quad (3)$$

Above $I_{ij}^2 = \overline{I}_{ij} \cdot \overline{I}_{ij}^*$, P_{loss} is the active part, and ΔQ is the reactive part of the overall change in the transmitted power[9]. Unit vectors $\bar{i}$ and $\bar{j}$ are orthogonal with $\bar{i}$ parallel to active power component and $\bar{j}$ parallel to reactive power component. While the reactive part influences the power factor of the transmitted power, the active part is the power lost to heating. When written separately, it becomes:

$$P_{loss} = R_{ij} I_{ij}^2 . \quad (4)$$

4.3. Power Generation and Storage

4.3.1. Modeling of DG

Distributed power generation and storage models can roughly be divided into two categories, dynamic models and steady-state models. Here "dynamic" refers to a model, where very short term phenomena are modeled, while "steady-state" refers to a model, where the system is considered to have reached a steady state. While dynamic models are often rather complex and they might include groups of differential equations, the steady-state models can often be reduced to a rather simple functional form. When the modeling is done with an hourly time scale, a steady-state kind of performance averaging is typically adequate.

The local power generation can be applied to DESIGEN in two ways. If measured power generation data is available, particularly for variable sources, the data can be directly imported to DESIGEN. This was the case for wind power, as all wind power analysis in this thesis is based on measured wind power generation data. When such data is unavailable, a steady-state model for power generation needs to be applied. For dispatchable power generation, like combustion engines, the steady-state model is simply following the control strategy applied in the simulation. In contrast, for variable generation their model needs to define the system output based on the weather parameter values. Although several power generation models have been integrated into DESIGEN, the models for photovoltaic power generation and energy storage have mainly been applied in this thesis.

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[9] Here * refers to complex conjugate. Multiplying a complex number by its conjugate squares its magnitude and makes its angle 0.

4.3.2. Photovoltaic Power Systems Model

(Publications II-III)

In DESIGEN a temperature-dependent PV model has been utilized as the module temperature may affect quite much the performance of PV panels. The model assumes that the panel conversion efficiency is a function of ambient temperature. Thus the power output from a photovoltaic array P_{PV} can be obtained with:

$$P_{PV} = A_{array} \cdot I_{solar} \cdot \eta_{syst}(T_a). \tag{5}$$

Above A_{array} is total array area, I_{solar} is incident solar irradiance, and $\eta_{syst}(T_a)$ is temperature dependent conversion efficiency of the photovoltaic system. The irradiance I_{solar} on the PV module is a sum of beam and diffuse components. The beam part of the irradiance is calculated with an hourly time step applying the standard incidence angle formulas [126]. The diffuse part of the irradiance is calculated correspondingly using Klucher's model [127]}. The conversion efficiency is expressed as a function of ambient temperature T_a as applied in the ALLSOL© system simulation tool [128]:

$$\eta_{syst} = \eta_{PV} \cdot \left[1 - 0.0042 \cdot \left(\frac{I}{18} + T_a - 20\right)\right] \cdot \eta_{inv}. \tag{6}$$

Above η_{PV} is the efficiency of the solar module and η_{inv} is the DC to AC conversion efficiency including cabling losses. Typically η_{inv}=0.85 and η_{PV}=0.15 for polycrystalline silicon PV. As a result, increase in ambient temperature typically reduces the conversion efficiency by about 0.4-0.5% per C°.

4.3.3. Storage Model

(Publications III-V)

The performance of grid-connected storage systems are modeled in DESIGEN through a steady-state storage model and the control strategy chosen for the applied storage. These control algorithms define when and how the storages are charged and discharged. In addition to that, the loss mechanisms are modeled, including storage self-discharge and losses in the charge-discharge cycle. Thus the energy in the storage at time t+1 is defined as:

$$W_{t+1} = W_t + P_{sto,t} \cdot \Delta t + \Delta P_{sd,t} \cdot \Delta t. \tag{7}$$

Here $P_{sto,t}$ is the power used to charge (positive) or discharge (negative) the storage, while $P_{sd,t}$ is the power lost through the self-discharge of the storage. The term Δt refers to the length of the computational time step. The power lost through self discharge is defined as:

$$P_{sd,t} = W_t \cdot d_W. \tag{8}$$

Here d_W is the storage self-discharge factor. When the self-discharge phenomena are omitted from the model d_W is set to zero.

The basic storage model in DESIGEN applies either an ideal storage model with no losses in charging and discharging cycles or a storage with constant or linear efficiency for charging and discharging. The capacity change from charging/discharging of such storage at time t can be written in generalized form as:

$$P_{sto,t} = P_t \cdot \eta_{sto}(P_t)^{\frac{P_t}{|P_t|}}. \tag{9}$$

Here P_t is the charging (pos.) or discharging (neg.) power at time t while η_{sto} is the corresponding efficiency. The exponent term simply defines the use of the efficiency term, as the power is multiplied by the efficiency when charging, and divided by it when discharging. The efficiency itself has been defined as:

$$\eta_{sto}(P_t) = \eta_{sto,0} + |P_t| \cdot \eta_{sto,P}. \tag{10}$$

Here $\eta_{sto,0}$ is the constant part of the (dis)charging efficiency, while $\eta_{sto,P}$ expresses the (typically negative) slope for the efficiency. For ideal storage, $\eta_{sto,0} = 1$ and $\eta_{sto,P} = 0$. It should also be noted that separate values for $\eta_{sto,0}$ and $\eta_{sto,P}$ have been used for charging and discharging, correspondingly.

In addition to the storage model, the storage control strategy defines how the storage interacts with the rest of the system. Typically the storage control depends on the consumption or power generation patterns in the local power system. In our first control strategy, the charging and discharging of the storage was defined by three external parameters: local consumption, local power generation and time of day. In addition, there are storage parameters that influence the storage behavior pattern. Those are the maximum charging and discharging rates as well as the total storage capacity.

Three kinds of operational patterns for storage can be found: the charging period, discharging period and several stand still periods. During the standstill periods the storage remains inactive, and the stored electricity capacity only gradually self-discharges during that time. During charging period, at time t, the amount of power available for storing is defined as a difference between local reference power generation $P_{ref,t}$ and local reference load $L_{ref,t}$:

$$P_t = P_{ref,t} - L_{ref,t}. \tag{11}$$

During discharging period the power would be evenly discharged from the storage:

$$P_t = -\frac{W_t}{t_{disch}}. \tag{12}$$

Here t_{disch} is the total length in time of the discharging period and W_t is the energy stored in the storage at time t.

In the second storage control strategy, an exponentially weighted moving average filter is applied. When the reference power generation $P_{ref,t}$ is the filter input signal and the filter output signal is $P_{ref,t}$ plus the storage power P_t, we have:

$$\left(P_{ref,t} + P_t\right) = \alpha \cdot \left(P_{ref,t-1} + P_{t-1}\right) + \left(1-\alpha\right) \cdot P_{ref,t}, \ \alpha = \frac{\tau}{\tau + \Delta t}. \qquad (13)$$

Here τ is the filtering time constant and Δt is the time step applied in the computation. When solving the equation for P_t, we get:

$$P_t = \alpha \cdot \left(P_{t-1} + P_{ref,t-1} - P_{ref,t}\right) = \alpha \cdot \left(P_{t-1} - \Delta P_{ref,t}\right). \qquad (14)$$

It should be noticed that at startup ($t = 1$) the initial value $P_0 + P_{ref,0}$ needs to be defined. Also, in both of the control strategies above, when the (dis)charging exceeds the remaining storage capacity, the magnitude of (dis)charging is defined by the available (dis)chargeable capacity.

In the third control strategy the storage is used to reduce the fluctuations in the local production using four different regions for storage control. These regions were defined using three different parameters. In the first region the local power generation $P_{ref,t}$ exceeds the upper power threshold value P_{up}, while in the second one $P_{ref,t}$ is between P_{up} and the expected power value P_{ex}. In the third region $P_{ref,t}$ is between the lower power threshold value P_{down} and P_{ex}, while in the fourth region $P_{ref,t}$ is below P_{down}. When in first region, the storage is charged with the excess power $P_{ref,t} - P_{up}$ if the necessary storage capacity is available. In the second region the storage is charged only if the remaining storage capacity is under the expected capacity value Q_{ex}. In the third region the storage will be discharged to make $P_{ref,t}$ plus the storage discharging power P_{sto} equal to P_{ex} as long as the storage capacity is above the expected capacity value Q_{ex}. In the fourth region the storage will always be discharged to make the total power equal to P_{down} until the storage capacity is depleted. Below, the control logic of the third storage control strategy is presented as a simplified procedure:

```
IF $P_{ref,t} > P_{up}$ THEN [region 1]
    IF $Q_{ref,t} < Q_{max}$ THEN $P_{sto} = -(P_{ref,t} - P_{up})$
    ELSE $P_{sto} = 0$
ELSE IF $P_{ex} < P_{ref,t} < P_{up}$ THEN [region 2]
    IF $Q_{ref,t} < Q_{ex}$ THEN $P_{sto} = -(P_{ref,t} - P_{ex})$
    ELSE $P_{sto} = 0$
ELSE IF $P_{down} < P_{ref,t} < P_{ex}$ THEN [region 3]
    IF $Q_{ref,t} > Q_{ex}$ THEN $P_{sto} = (P_{ex} - P_{ref,t})$
    ELSE $P_{sto} = 0$
ELSE [region 4]
    IF $Q_{ref,t} > 0$ THEN $P_{sto} = (P_{down} - P_{ref,t})$
    ELSE $P_{sto} = 0$
END
```

4.4. Consumer Load Model

(Publication I)

The consumer load patterns for the DESIGEN simulations have been generated by applying a bottom-up load model similar to that by Capasso *et al.* [120]. In both of the models the household appliances of each individual household are separately simulated. Then these load patterns are summed up, first at individual household level, then to form more sizeable load groups.

The difference between the models is the way the appliances of the household are used. The "Capasso model" uses occupant availability statistics as the basis to define what appliances they could possibly use in the household. In the model applied here, the household appliance usage is defined based on daily usage probabilities. The advantage of this approach is that such information is much more readily available than the occupant availability statistics. On the other hand, some correlations between appliance uses are lost with this approach.

The random fluctuations in the appliance load patterns are generated by using stochastic processes and probability distribution functions as the consumption is generated. In practice, the model simulates the temporal electricity consumption profile of each individual appliance in each household separately. The electricity consumption of an appliance is based on its consumption cycle that is initiated based on its starting probability. The starting probability is defined by the probability function p_{start}:

$$\begin{aligned} &p_{start}(A, w, \Delta t_{comp}, \sigma_{flat}, h, d) = \\ &p_{season}(A, w) \cdot p_{hour}(A, h, d) \cdot f(A, d) \cdot p_{step}(\Delta t_{comp}) \cdot p_{social}(\sigma_{flat}), \end{aligned} \tag{15}$$

where

p_{season} = seasonal probability factor, models the seasonal changes,
p_{hour} = hourly probability factor, models the activity levels during the day,
p_{step} = step size scaling factor, scales the probabilities according to Δt_{comp},
p_{social} = social random factor, models the weather and social factors influencing the communal behavior,
f = mean daily starting frequency, models the mean frequency of use for an appliance [1/day],
A = appliance or group of appliances,
h = hour of the day,
d = day of the week,
w = week of the year,
Δt_{comp} = computational time step [s or min], and
σ_{flat} = standard deviation for P_{social}.

The probability function is defined for each time step and it has a value between 0 and 1. The appliance starts when p_{start} is larger than a random number between 0 and 1. As the appliance starts, its consumption cycle will be added to the total load curve of the corresponding household and the appliance will be available for restarting after the cycle has been completed. For cumulative appliances, like lighting, where many small appliances are modeled as one appliance, new starting of the appliance can occur even during the earlier consumption cycle.

The parameters needed by the model can be divided into two groups. First, the probability factors, as the p_{season}, p_{hour}, and p_{social} in the Equation (15) above, and second, the appliance consumption data, like standby consumption and typical appliance consumption cycle data. The weekly and social seasonal probability factors p_{season} and p_{social} are easiest to define from a measured data sample, while the hourly probability factor p_{hour} can be determined based on existing data, like that by Sidler [129, 130]. The appliance consumption data is achieved by combining data from a variety of sources, like that by Sidler, Mansouri, and Meier [129-132], as no comprehensive data has been published. Some calibration of parameters may be needed to achieve a good model performance, which is a typical issue for bottom-up models [121].

The consumption data for individual households is generated using a procedural method, where the parameters and equations discussed above are implemented. In practice the main structure of the procedure is shown in Figure 8. In the first part of the procedure (I) the needed input data is loaded and set up followed by the generation of daily fluctuations in the social random factor p_{social}. Then, entering the main loop, the set of appliances in the emulated household is determined. The second part (II) in the main loop emulates separately the use of each appliance and constructs step by step the appliance load curve for each of the appliances using Equation (15). After all appliances for that household have been treated, their total consumption curve is calculated to complete the main loop. As all the household data has been generated, the procedure exits after data output and verification.

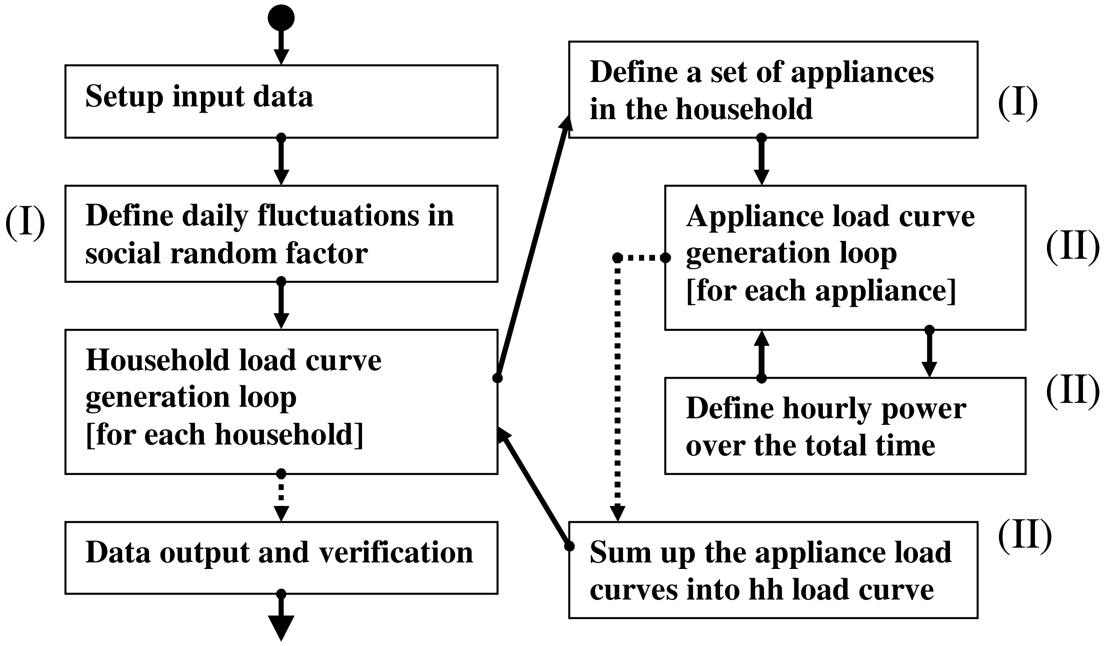

Figure 8. Household load data generation procedure.

When the individual household-level load data has been created for a number of households, they can be summed up to bigger amounts of households. Therefore, load profiles from individual households to whole cities can be created. However, if different types of housing (like apartment buildings, detached houses, offices, etc.) are to be combined, they typically have significant differences in their appliance and usage profiles and thus such loads should be generated separately and added up only later. An example of some generated household data is given in Figure 9 below. Frame a) shows hourly load curve for 2 households, frame b) for 15 households, and frame c) for 110 households, demonstrating how the load data smoothens up as the number of households increase.

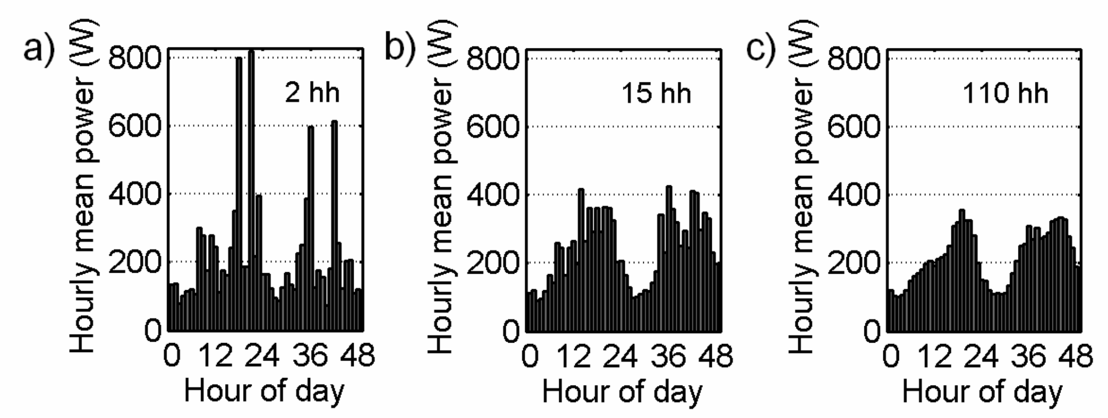

Figure 9. Example of generated household data with mean load curves for apartment building households in Helsinki with a) 2 households, b) 15 households, and c) 110 households.

5. Input Data and Analysis

This chapter discusses issues connected to the input data applied in the simulations made by DESIGEN. This data can be roughly divided into three main parts: the base data, the load data and the power generation data. The base data and its application will be discussed in Chapter 5.1 below, while the detailed discussion concerning load and power generation data follow in their separate chapters, correspondingly.

Special emphasis has been given to the analysis of the load data and wind power data. The characteristics of load data have a significant importance for the simulation runs, and thus it will be discussed in detail in Chapter 5.2. The discussion about power generation data in Chapter 5.3 has been limited to wind power data, as no other measured power generation data was applied in this work. With the wind power data, emphasis is given to determining the different types of fluctuation patterns present in the data.

5.1. Input Data for DESIGEN

(Publications II-III, V)

The simulations made by DESIGEN require an extensive set of base input data that can be divided into to four different categories. There is the parameter data, as discussed in Chapter 4.1 above, technical data, externalities data, and the siting and control data. The technical data is used to defining the details of the system to be modeled, like technical details of an applied storage unit. The externalities data defines the external phenomena influencing the system, such as ambient temperature. The siting and control data defines the location of power generation, storage and load in the grid as well as the corresponding control strategy information when needed. In addition, special parameters may be needed by particular appliance models applied by DESIGEN, like for example the storage model discussed in Chapter 4.3.3. Such data is also provided for the program together with the siting and control data.

The technical data defines technical and modeling parameters for the DGS units as well as network. For generation units it includes details like maximum output power, type of grid connection, linear approximation of the unit efficiency at varying power levels, etc. For storage units the corresponding data includes storage capacity, maximum charging, and discharging power and efficiency, type of grid connection, rate of self-discharge, etc. The corresponding network data comprises information about the cables used in the grid, including resistance, reactance, and maximum power transfer capacity. All the technical data has been obtained from external sources or, at times, based on a linear estimation of the behavior of the corresponding appliance.

The externalities data defines the external influences to the simulation. Typically this would include weather data with direct and indirect solar irradiation, ambient temperature, and wind speed for every hour of the simulated time period.

The location of the loads, generation and storage in the grid are defined by the siting and control data. Each load and all the generation and storage units are connected to a single node in the modeled distribution network. The type of connection has been specified with the technical data of the storage and generation units. The control strategy related data is used to refer to the control strategy routines inside DESIGEN.

5.2. Observations and Hypotheses Concerning Residential Consumption Data

(Publication I)

To generate a realistic and well-balanced consumption data set, a detailed analysis was performed first to a real domestic data set gathered from Finnish apartment buildings. The analysis was made with the goal to determine the key parameters and characteristics of the data. In practice, several statistic methods were applied to characterize the data.

The data used in this project consists of two data sets from whole apartment buildings. The first set (data set 1) consisted of hourly data from a total of 702 households during the 365 days of the year 2002. The second set (data set 2) consists of hourly data from a total of 1,082 households during 143 days from September 2002 through January 2003, including also the households in the first data set during that period. Most of the analysis was done based on data set 1, while set 2 was only applied to analyze the aggregated behavior of the data. The buildings where the data was measured consist of between 27 and 74 apartments. The load itself is composed mainly of lighting and general household appliances, while heavy loads like sauna, water boilers, space heating, and air conditioning were absent.

As a result, three basic forms of periodicity were found from the data, one on the annual level, one on the weekly level and one on the daily level. This was found to be consistent with findings from other projects concerning domestic consumption [129, 130, 133]. The data was also found to have similar behavior to that shown in Figure 4 and Figure 5. When aggregated, the total load data became smoother and it converged towards an averaged load curve, as expected.

The annual level variation of the consumption is connected to the seasonal changes. The variation is caused by the indirect connection between electricity consumption and effects like natural lighting conditions, ambient temperature and precipitation. In Finland, all of these effects have a clear connection to the seasonal changes. As a result, a sinusoidal connection between the consumer load and the annual cycle of days has been identified. Such connection is typical to the Finnish conditions [134, 135]. It is caused by the lack of summer time cooling loads, significant seasonal variation in lighting needs and the increase in the use of domestic appliances in the cold season [134]. This sinusoidal nature of the variation is shown in Figure 10a, where the annual variation of the first data set is presented.

The weekly level variation observed in this work has been simplified to that between weekdays and weekend days, i.e Saturday and Sunday, the term being used henceforth in this work for its precision and accuracy. Although a more complex approach could easily be motivated, these two classes of days were found sufficient enough to give a realistic picture of the overall situation. The overall consumption during the weekend days was found to be slightly higher than that during the weekdays. However, more significant variation was present in the daily level variation during these two types of days.

The variation in consumption on daily level was observed on an hourly basis. Whereas during weekdays there was a significant consumption peak in the evening, during the weekend days the evening peak was slightly lower while the daytime consumption was considerably higher. This is characteristic to Finnish load curves for apartment buildings [136]. A detailed picture about the hourly mean distribution of the consumption is shown in Figure 10b. There the weekend day consumption curve is on the right and the weekday consumption curve on the left.

The consumption on individual household level varies greatly, whereas adding more households to the total load curve should make the load smoother. This phenomenon has already been discussed in Chapter 2.3 and shown in Figure 5. However, it was necessary to measure how this smoothing effect manifests itself in the real household data, in particular in the data set 2. An absolute error sum $\sum\left|\overline{P}_t - \overline{P}_{ave,t}\right|$ was chosen as the measure to determine the smoothing of the hourly consumption data. The sum $\overline{P}_t$ is hourly consumption per household and $\overline{P}_{ave,t}$ is mean hourly consumption per household for all the households in the sample while t is index for the hours. When the error sum is shown on a log-log scale for the data set 2, the result in Figure 10c is achieved. The error sum is computed over a period of 143 days and the mean data $\overline{P}_{ave,t}$ was computed using the total load of the whole set of 1,082 households. Figure 10c clearly shows that the relation between the error sum and the number of households is almost linear on the log-log scale. For 27 households the $\log_{10}$ of the error sum is 1.59 and it decreases almost linearly till 272 households, where the $\log_{10}$ of the error sum is 1.02. There the slope seems to slightly change, as adding till 684 households is done, although this is more due to the random differences in the error sums of the households. To look into this phenomenon some testing with the data was done. When the order of adding the households is altered, the smoothness of the left side of the error curve varies significantly. This is caused by the large differences in the errors causing the fluctuations in the consumption on the level of apartment buildings the data is available. This variation is strong in the low number of apartments, while the overall linear trend still prevails. The curve in Figure 10c was chosen to demonstrate the behaviour of the error sum as it shows the underlying trend quite clearly. This phenomenon is not expected to be very strong in the emulated data, as there the data is available on individual household level, and not as whole apartment buildings.

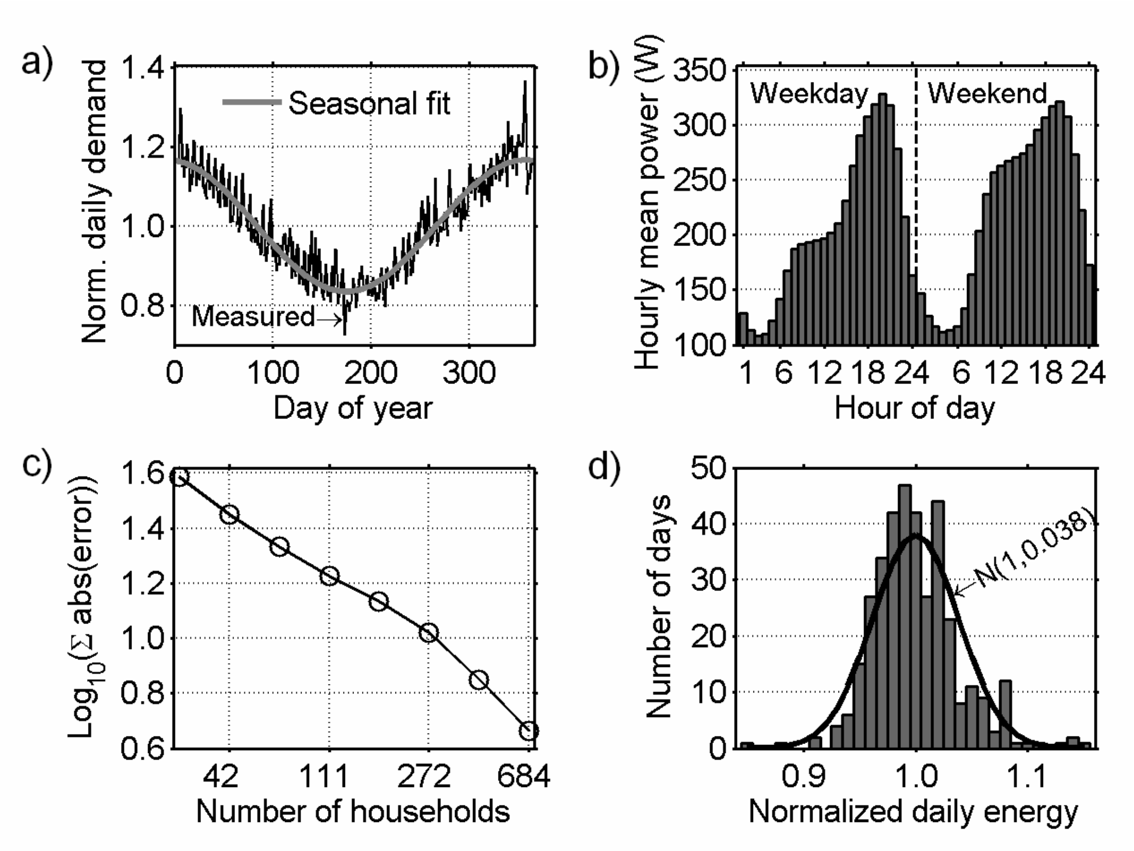

Figure 10. a) Daily electricity consumption of measured data set 1. The mean curve is presented by the grey line. b) Mean hourly consumption curve of a household for weekdays and weekend days for the data set 1. c) Effect of the number of households in the load data for data set 2. The deviation is measured as absolute deviation from the normalized mean load. d) Distribution of the measured mean daily electricity consumption for the first data set after seasonal and weekday compensation.

Regardless of the amount of households summed up the mean load per household has some variation. After seasonal and weekly differences have been compensated for, a part of the variation still remains. This is caused by the influence of environmental and social factors that the load correlates with. For example, outside temperature has a direct correlation with heating or cooling loads [137]. Nevertheless, as such loads are absent in the applied data, other reasons like correlated social phenomena connected to power consumption are expected to be responsible for the variation. For example, television programs and commercial breaks in them may cause variations observed in the national power grid [138]. Such phenomena exceed the level of details considered in the load analysis, and so they are not separately identified.

When all the seasonal and weekday variations are compensated for in the data, the fluctuation remaining in the data will be caused by correlated social behaviour and loads weakly correlated to sporadic weather phenomena. For example, the changes in mean temperature have been compensated in the annual level consumption pattern, while the daily variation in the temperature has not been compensated. Weather, as well as many social phenomena will influence a large amount of households simultaneously, thus causing effects to the total load level.

The distribution of the compensated mean daily electricity consumption of the data set 1 is shown in Figure 10d. It shows the distribution when all mean seasonal and weekday effects have been compensated from the data. The distribution of the data follows roughly that of the normal distribution.

5.3. Wind Speed and Turbine Data

(Publication IV)

To evaluate the influence of energy storage to the output of wind power turbine, wind turbines are modeled using real or emulated wind turbine power generation data. Wind turbine power data from different locations around Europe has been applied, as shown in Table 2. The table includes the site and sample names, location and the data sampling interval. Both synchronous and asynchronous turbines are included, also one older wind turbine model with passive stalling.

All wind turbine sites in Finland were based on real measured turbine data. Data with one second time interval was obtained through VTT.[10] Access was given to data from 1 MW wind turbine with an asynchronous turbine at Pori, a 1 MW turbine with synchronous turbine at Oulu, and an already disassembled asynchronous turbine with passive stalling of 220 kW at Pyhätunturi. While the turbines at Pori and Oulu are on seashore, the Pyhätunturi turbine was inland on top of a fell. The data from Pyhätunturi turbine was quite different when compared to the two onshore sites.

In addition to the 1 second data, hourly level data was obtained from three additional Finnish wind turbine sites. The data for the turbines at Föglö and Vårdö was obtained from Ålands Vindenergi Andelslag, while the data for Riutunkari turbine was obtained from Oulun Seudun Sähkö. The turbines at Föglö and Vårdö are both synchronous and

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[10] VTT is the Technical Research Centre of Finland.

their rated powers are 600 kW and 500 kW, correspondingly, while the Riutunkari turbine is asynchronous and it is rated at 1.3 MW.

Table 2. Applied wind turbine data.

Site	Country	Wind turbine *	Location	Sample Name	Sample interval, Δt
Pori	Finland	1000 AA	61°22'N 21°18'E	Pori	1 s
Oulu	Finland	1000 SA	65°02'N 25°01'E	Oulu	1 s
Pyhätunturi	Finland	220 AP	68°15'N 23°22'E	Pyhä	1 s
Föglö	Finland	600 SA	60°00'N 20°19'E	Fögl	1 h
Vårdö	Finland	500 SA	60°14'N 20°24'E	Vård	1 h
Riutunkari	Finland	1300 AA	65°00'N 25°12'E	Riut	1 h
Trapani	Italy	1300 AAS	37°55'N 12°30'E	Trap	1 h
Lerwick	Great Britain	1300 AAS	60°08'N 01°11'W	Lerw	1 h
Copenhagen	Denmark	1300 AAS	55°48'N 12°30'E	Cope	1 h
Paris	France	1300 AAS	48°46'N 02°00'E	Pari	1 h

* AA = Asyncronous turbine, Active stalling
SA = Syncronous turbine, Active stalling
AP = Asyncronous turbine, Passive stalling
AAS = Asyncronous turbine, Active stalling, Simulated

The emulated hourly wind power data applied here was made by using the power curve from the Riutukari wind turbine [139] to convert wind speed data from European sites to wind power data. The utilized hourly wind speed data was adapted from European test reference years TRY [140]. A total of four different European locations were emulated. In Table 2 these sites are marked having a “simulated” wind turbine type (AAS). Three of these locations are on the coast while Paris represents an inland site.

To compare the different data sets, qualitative differences in wind power data series have been identified. Wind data is typically classified by integral time scale and length scale, as well as turbulence intensity using 10 minute wind data samples [141]. Here the autocorrelation of the wind power time series is applied in a similar way to define integral time scale for the wind turbine power fluctuation. The sample autocorrelation function r for a given lag m is defined as [116]:

$$r_m = \frac{\sum_{i=1}^{n-m} (p_i - \bar{p})(p_{i+m} - \bar{p})}{\sum_{i=1}^{n} (p_i - \bar{p})^2} \quad \text{for } m = 1,2,3,\dots,n/4, \tag{16}$$

where $\bar{p} = \frac{1}{n}\sum_{i=1}^{n} p_i$, n being the number of the sample data points. Next the power integral time scale (PITS) that corresponds to the integral length scale for the wind is defined for the wind turbine power time series as:

$$PITS = \int_{m=1}^{m_{r=0}} r_m dt = \sum_{m=1}^{m_{r=0}} r_m \Delta t. \tag{17}$$

Above Δt is the sampling interval for the data set and $m_{r=0}$ is the point where r_m for the first time equals zero or becomes negative. The normalized mean power level (PFR) is defined as:

$$PFR = \frac{\overline{p}}{P_{nom}}. \tag{18}$$

Here P_{nom} is the nominal power of the wind turbine.

Next the applied wind turbine power data time series are classified based on their PITS and PFR values. Two kinds of data sets have been applied, one with a short (Δt = 1 s) and one with a long time scale (Δt = 1 h). This choice was motivated by the way Rohatgi and Nelson [47] divide the fluctuations in horizontal wind speed. They apply two distinct wind-speed regions, macro-meteorological and micro-meteorological. The micro-scale fluctuations typically result from atmospheric turbulence, while the macro-scale fluctuations result from the movement of large-scale air masses in connection to cyclones and anticyclones. Figure 3 shows that the macro-scale fluctuations have a time scale from 12 to 100 hours, while the micro scale fluctuations are in the scale of one minute.

For the data set with the short time scale, 10-minute windows (600 data points) are used for defining PITS. The overall PITS value is defined as an average from all the 10 minute PITS values, as this allows comparison between data samples of different length.

In addition, normalized standard deviation (STD) of the wind power data was applied to measure the relative deviation in the data. It is defined as:

$$STD = \frac{1}{P_{nom}} \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (p_i - \overline{p})^2}. \tag{19}$$

Here P_{nom} is the nominal power of the wind turbine.

The samples of the short time scale data set are presented in Table 3. Only samples with power levels up to 80% of nominal turbine power have been included there, as they present the data with most power fluctuations. Classification of the data has been done in Figure 11. Most of the data have high PITS and low PFR as in category A or low PITS and high PFR as in category D. More statistical values for the data series are provided in Table 3.

The long time scale data set comprises two subsets of data. The first subset is measured wind turbine data from Finland that has been averaged over one hour intervals. The second part contains simulated wind turbine output that has been calculated using height corrected mean hourly wind data together with wind turbine power curves. In practice, the simulated data was generated applying European wind data [140] together with the power curve [139] and turbine tower height (65 meters) of the actual turbine located at the site Riutukari in Finland. The logarithmic wind profile is used to estimate the wind speed at the tower height [141]. The long time scale data samples are one year long except for the measured data from two smaller wind turbines that covers only 202 days.

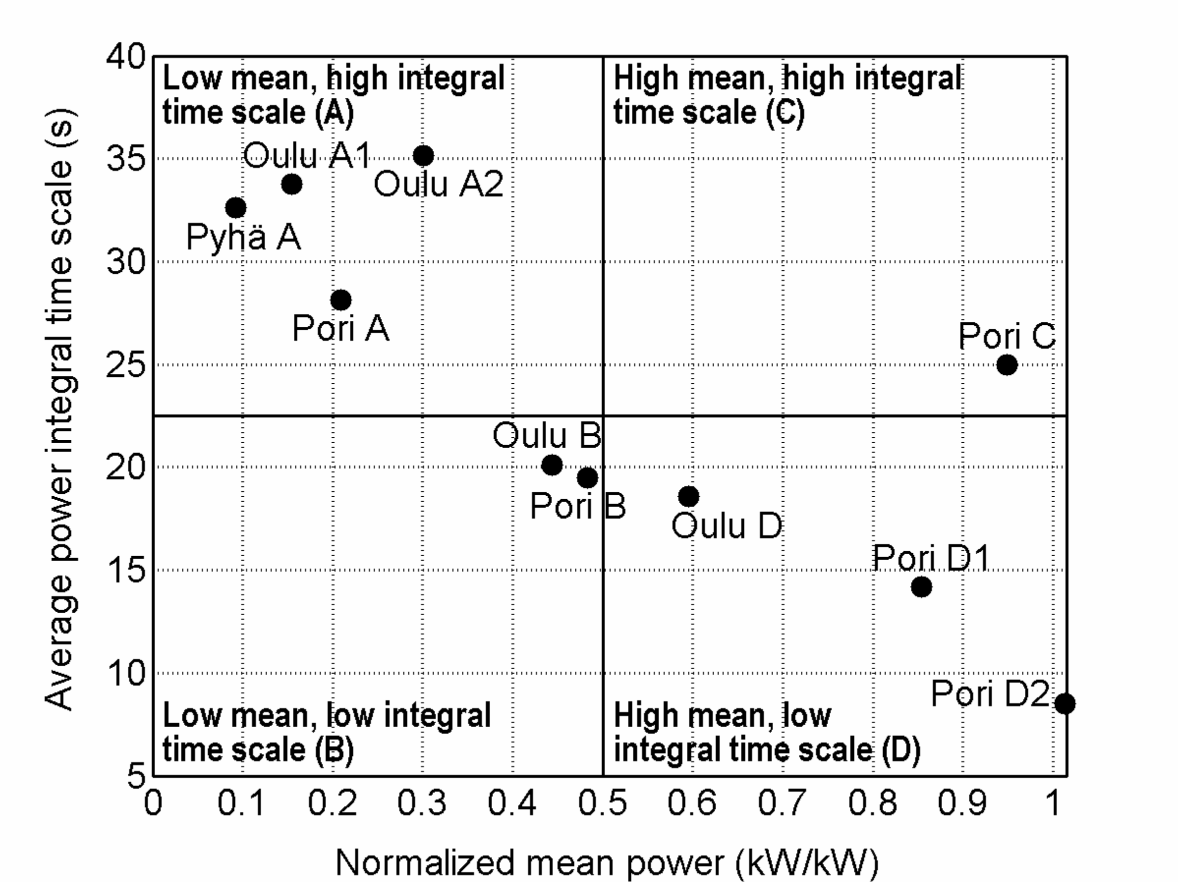

Figure 11. Classification of wind power fluctuations in power data with 1 s time step.

Table 3. Wind turbine parameters and statistical values of the turbine power generation for power data with 1 s time step.

	Units	Oulu A1	Oulu A2	Pori A	Pyhä A	Oulu B	Pori B	Pori C	Oulu D	Pori D1	Pori D2
Nominal Power	kW	1000	1000	1000	220	1000	1000	1000	1000	1000	1000
Mean Power	kW	155	300	209	92	444	483	949	595	854	1014
Power SD*	kW	42.9	97.7	43.1	20.3	79.4	101	107	124	177	153
Normalized Mean Power	-	0.155	0.300	0.209	0.417	0.444	0.483	0.949	0.595	0.854	1.01
Normalized Power SD*	-	0.043	0.098	0.043	0.092	0.079	0.101	0.107	0.124	0.177	0.153
Mean PITS*	s	33.8	35.2	28.1	32.6	20.1	19.5	25.0	18.6	14.2	8.51
PITS SD*	s	20.2	14.3	16.4	18.1	13.3	15.1	16.4	11.9	7.65	4.98

* SD = Standard deviation
PITS = Power Integral Time Scale

For the hourly data only limited statistical analysis was applied, as the averaging process applied as the data was composed has removed much of the statistical information from the data. Statistical details on the applied long time scale data are given in Table 4.

Table 4. Wind turbine parameters and statistical values of the turbine power generation for power data with 1 h time step.

	Units	Pari	Cope	Trap	Lerv	Fögl	Vård	Riut
Nominal Power	**kW**	1300	1300	1300	1300	600	500	1300
Mean Power	**kW**	232	370	343	469	165	94.1	338
Power SD*	**kW**	314	417	435	465	168	107	366
Normalized Mean Power	**-**	0.179	0.285	0.264	0.361	0.274	0.188	0.260
Normalized Power SD*	**-**	1.35	1.13	1.27	0.99	1.02	1.13	1.08

* SD = Standard deviation

6. Results

6.1. Statistical Characteristics of Modeled Consumer Data

(Publication I)

Using the bottom-up load model described in Chapter 4.4 a full year domestic load data set was generated for 10,000 households in apartment buildings, representing a total electricity consumption of 18.6 GWh. This was compared to the statistical patterns of two genuine Finnish data comprising 1,082 and 702 apartments in apartment buildings. In the process of generating household data, patterns similar to those observed in the generic data were introduced to the generated data. This was achieved by defining such input for parameters p_{season} and p_{hour} in Equation (15) that periodicity corresponding to the authentic data was generated. The random fluctuation in daily consumption levels was achieved by using a normally distributed random number as p_{social}.

The statistical characteristics of the generated data can be seen in Figure 12, while the corresponding genuine data is in Figure 10. Frame a) shows the annual consumption curve of the load. It can be seen, that the generated data follows closely the general characteristics of the authentic data. However, distinctive socially originating phenomena, like the Christmas cooking peak at the end of December and the Midsummer holiday minimum at the end of June are not reproduced, as they have been interpreted as part of the random fluctuation of the genuine load. Frame b) in Figure 10 and Figure 12 show the hourly mean consumption during weekdays and weekend days. Here the patterns of genuine and generated data are very similar, with no distinct differences.

The most significant difference in the comparison of data statistical characteristics is shown in Figure 10c and Figure 12c. The figures show the total absolute deviations that the load data has from its average. Thus the figures demonstrate how the increasing number of households is reducing the corresponding error value, thus demonstrating the coincidental nature of the load data, as discussed by Willis [119]. There a clear difference between the error values of the genuine and generated data can be seen. However, part of this effect is caused by the choice of the reference curve that in the measured data included 1,082 households and in the simulated data 10,000 households. If the values on the horizontal axis would be relative to the total number of households used in the samples, the data could be more comparable and the right end of the curves would be positioned on top of each other with some difference in the slope of the error sum. This error in the slope may be due to such occupant behavior that is not captured by the model, such as socially correlated activity.

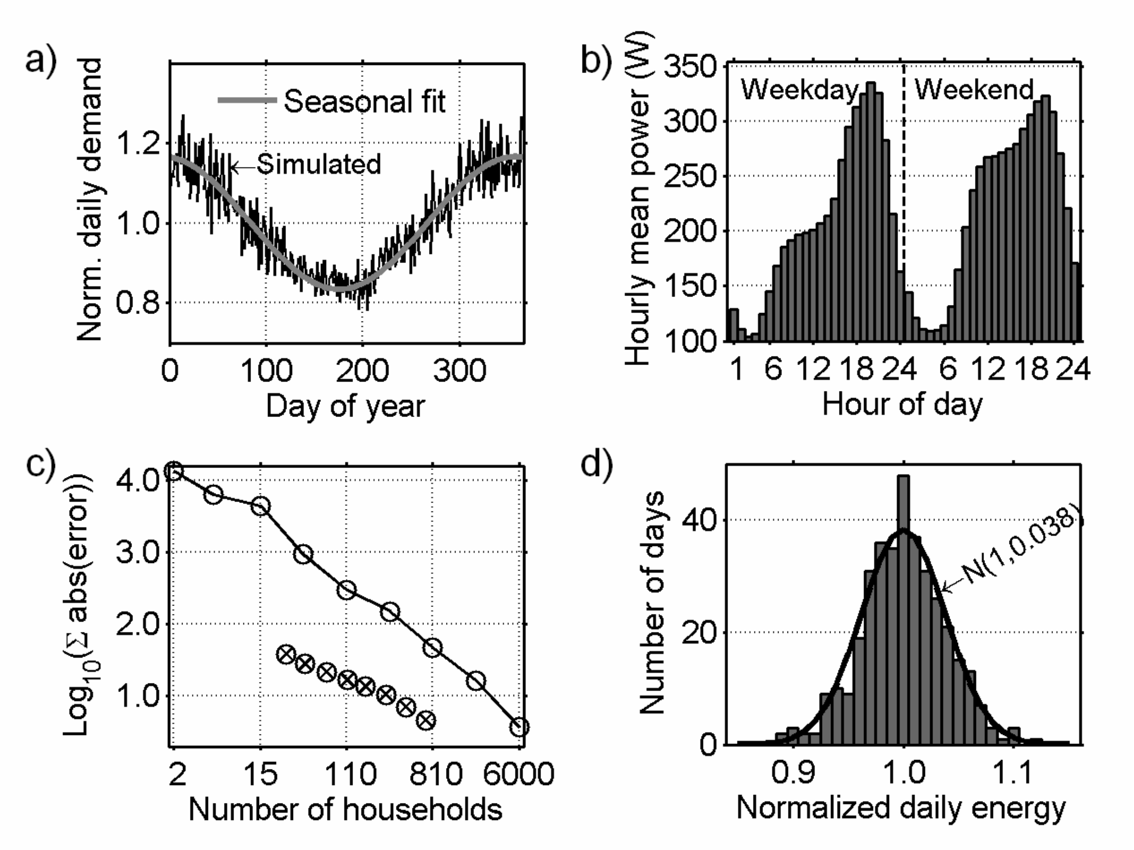

Figure 12. a) Daily electricity consumption for generated data set. The mean curve from Figure 10 is presented with thick grey line. b) Mean hourly consumption curve of a household for weekdays and weekend days for the generated data set. c) Coincidental behaviour for generated data set. The corresponding data from Figure 10c is shown with the symbol ⊗. d) Distribution of the compensated mean daily electricity consumption days for generated data set. The corresponding normally distributed curve is presented with thick dark line.

Frame d) in Figure 10 and Figure 12 characterizes the distribution of daily energy values in the data after the seasonal variation has been compensated. Normally distributed density function has been fitted to the data. As Figure 10d shows, the normal distribution applies only approximately for the genuine data. A more in-depth analysis might reveal something that would better explain the large deviations from normal distributions, like several overlapping density functions. The normally distributed approximation was applied to the generated data, and it seems to follow very well the distribution, except for the average value, where some error source might be present. For 10^4 households a more flat distribution is expected.

Although in general the generated data corresponds well to the behaviour of the measured data, there are possible indications from the differences when the data is applied with DESIGEN. The most significant difference can be seen in the distribution of the normalized daily energy, after the seasonal and weekly phenomena have been eliminated. The distribution of the generated data in Figure 12d indicates that the data generation procedure might be biased to give a higher appearance rate for the energies close to average daily consumption. On the other hand, the distribution of the measured data in Figure 10d might not be normal at all, but instead a sum of several distributions. However, as the deviations from the normal distribution are relatively small, no major bias should be caused to the simulations by DESIGEN due to the origin of the applied data.

Another issue is the missing of the special culturally related consumption peaks from the generated data. Christmas consumption peak and mid-summer decline in consumption in Finland are just examples of such phenomena. Their absence does influence the simulation results, as such systematic extremes in the consumption do not exist. However, as such issues are very much culture related and vary from country to country it is not very meaningful to try to implement them to the load model. Therefore, such issues have been omitted and the limitations they pose for the analysis have been accepted.

6.2. Effects of Large-Scale Integration of Variable DG

(Publications II-III, V)

Applying the DESIGEN simulation tool, power distribution network was modeled to study the effects of large-scale integration of variable distributed power generation. The scope of the modeled system has been limited to medium voltage distribution network, more accurately to a single 20 kV network main branch or loop, which may have multiple sub-branches. Concerning the variable generation, photovoltaic technology has been chosen for the study.

Using the hourly level analysis, the effect of DG has been evaluated based on network voltage levels and transmission losses. The rise in local voltage levels is strongest at times when the PV-generation is high and the local consumption particularly low. The effect is most visible in the part of the network that is most distant from the strong network nodes. In medium voltage distribution grid the simulations allow 2.5% deviations above and below the nominal 20 kV voltage level. If the grid experiences over 2.5% voltage deviation it causes overvoltage (e.g. with high DG power peak) or undervoltage (e.g. with high consumption peak). The more serious the overvoltage or undervoltage is the less desirable the simulation result is for the grid operation. In such case some compensation may still be achievable with the low voltage transformer but such specialties are not considered here. Also other security and safety concerns as well as the more short-scale phenomena are excluded here.

In addition, effects from several different parameters have been assessed. The key parameters include climate and consumption patterns, network topology, PV siting and orientation, and total PV generation level. To address the climate difference, measured weather data and consumption data generated by the load model described in Chapter 4.4 have been used based on Helsinki, Finland, and Lisbon, Portugal. For Lisbon, two kinds of consumption data were applied, one close to the current consumption patterns and one with an assumed significant increase in the air conditioning load. The annual curves for these loads can be seen in Figure 13. The corresponding weather data with direct and indirect solar irradiation for the PV power generation has been composed in two different ways. The Helsinki irradiation data is a time-of-year based average from 10 consecutive years of measurements by Finnish Meteorological Institute at Helsinki-Vantaa Airport while the Lisbon data has been constructed based on monthly irradiation measurements. Both of these irradiation data sets have been used in earlier research and solar energy planning assignments by ALLSOL© system simulation tool [128].

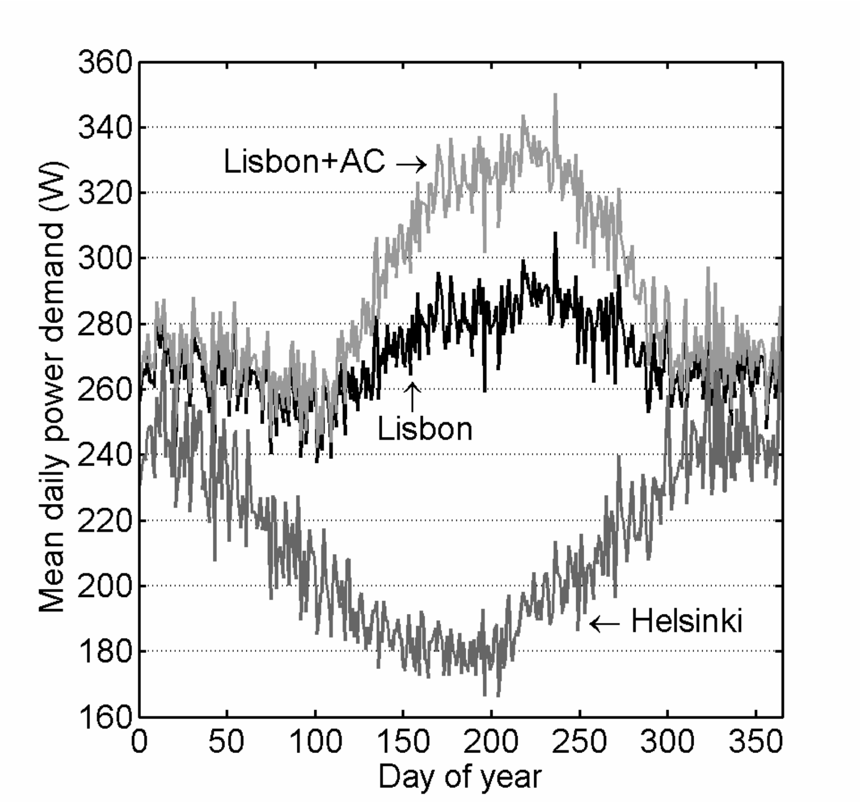

Figure 13. Annual load curves in Lisbon and Helsinki. The curve Lisbon+AC is a speculative load pattern, where increased air conditioning is assumed in addition to the current consumption levels.

6.2.1. Effect of Photovoltaic Panel Orientation

Several PV panel orientation schemes were applied to determine the most optimal one for both climates. The difference between the most extreme cases, the sharply at noon producing all-south case and the flattened 50% east and 50% west case, is shown for both climates in Figure 14. It should be noted that the angles of inclination for the panels are very different in Lisbon (30°) and Helsinki (45°), and that explains why the effect of the east-west orientation is so much more significant in Helsinki. The Figure 14 also shows the local voltage response to extensive PV generation at the end of a weak network line when the corresponding load curve is also concerned.

In the Helsinki data (Figure 14b) the East-West orientations of the panels make a significant reduction to the midday generation peak and also some addition to the hours that provide PV electricity. However, the total reduction in annual power generated in Helsinki is significant when compared to the directly South oriented panels.

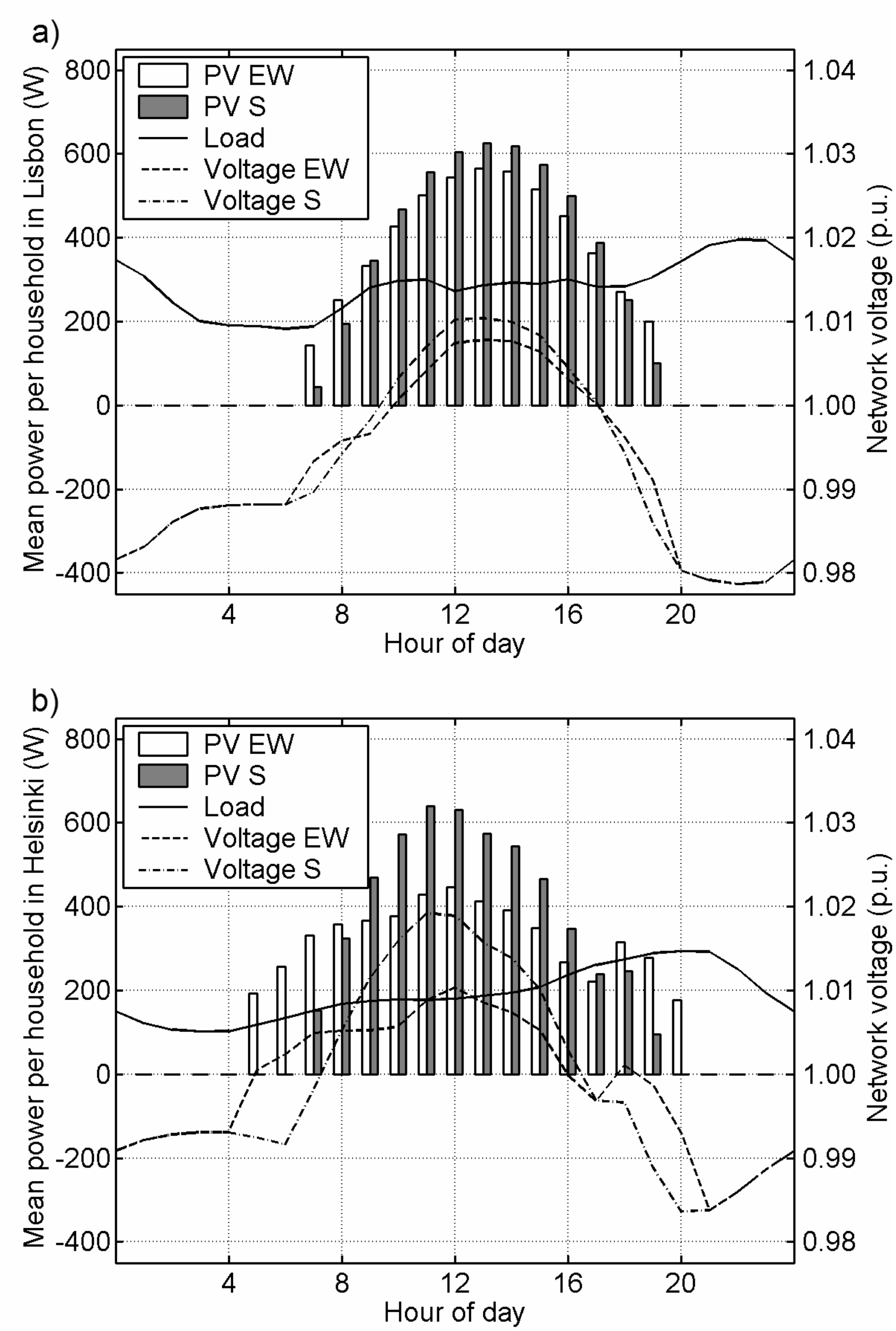

Figure 14. The effects of PV-panel orientations a) in Lisbon and b) in Helsinki. PV EW refers to panel orientation 50% east, 50% west, while PV S refers to all-south orientation.

Figure 14a suggests, that panel orientation at latitudes relatively close to equator is not such a significant issue, as only minor adjustments are achieved with East-West orientation of the panels. However, if the panel inclination would be much more than the optimal 30° for Lisbon, the difference between the orientations in Figure 14a would surely be more like that of Helsinki in Figure 14b.

6.2.2. Effect of Siting and Topology

A schematic picture of the distribution network topologies considered here are shown in Figure 15. There the comb-type has the main cable with very large transmission capacity while the main cables in both tree- and loop-type distribution networks can be of lesser capacity. The simulation results demonstrate that the tree-type network has most difficulties to incorporate large PV penetration levels, while the comb-type network with strong main cable performed very well. A loop in the network eased significantly the effects from the PV generation when compared to the case where the loop was left open.

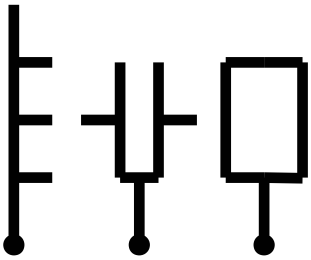

Figure 15. Schematic structure of the applied network topologies, from left to right: comb-, tree-, and loop-type setups.

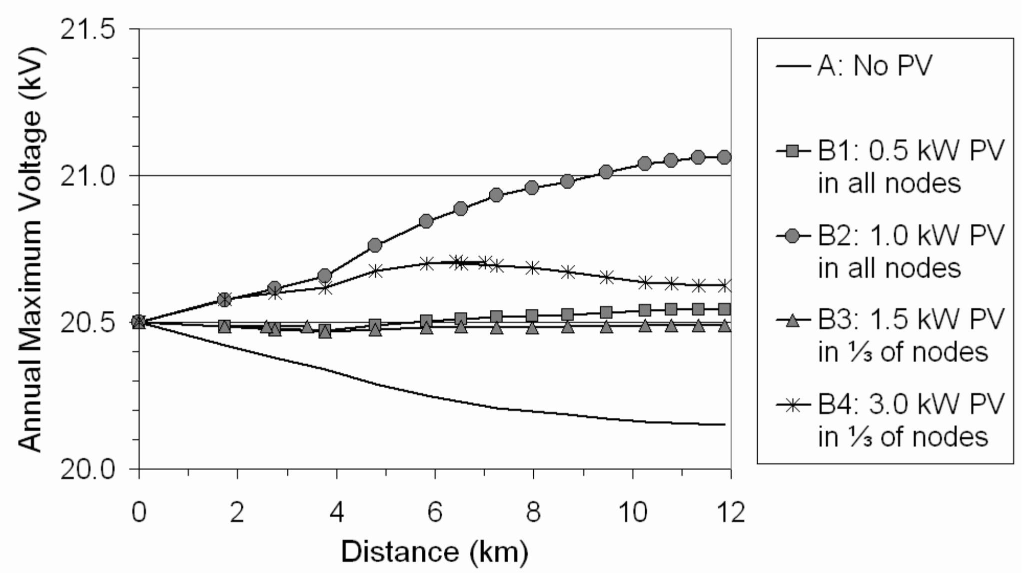

Figure 16. Effects of siting the distributed PV generation. The siting to ⅓ of the nodes is assumed optimal.

The effects of PV siting and penetration levels are shown in Figure 16. There, even a rather low evenly distributed PV generation is causing overvoltage events on the annual level, while a smarter siting to only 33% of the nodes can lead to significant reductions and even removal of the overvoltage events. On the other hand, increase in total PV capacity has a tendency to introduce or increase the severity of the annual overvoltage events, unless some compensating means like storage are applied.

When the effects of panel orientation, siting, penetration level and siting are all considered together, a multi-dimensional view is achieved to the PV-grid interaction. All these parameters play an important role on the effect of large-scale PV generation to the network. However, the most dominant parameters are the total PV penetration level and the local load pattern and its coincidence with the generated PV power. If high penetration level is applied despite the lack of coincidence, the tuning of other parameters will not solve the induced overvoltage events, although some reduction may be possible. More rigorous methods to compensate such problems are discussed in the Chapter 6.3 below, where storage methods and DSM will be discussed.

6.3. Compensating Local Peaks in Consumption or Variable DG

(Publications I, III-V)

In this part, the effects from the consumption peaks due to consumer behavior and generation peaks due to variable DG to the local electricity distribution network have been addressed by applying two complementary methods, DES and DSM. Both DES and DSM provide an opportunity to shift some consumption from the consumption peak to off-peak time. Alternately some generation can be shifted from peak generation time to off-peak time. Such shifts are often desirable as the domestic consumption peak typically does not coincide with the generation peak of variable generation.

With DES, load shifting is achieved by charging the storage during the off-peak consumption and the possible generation peak and discharging it during the consumption peak. on the other hand, the DSM typically postpones some of the peak consumption to a later off-peak time by delaying or prohibiting the use of some appliances, like a washing machine. To smooth the generation peaks by variable generation, DSM could be applied to activate loads that can store the benefit from the use to an off-peak generation time. The increased local load would lessen possible adverse effects from the generation peak. Cold appliances and water heaters could be considered to provide such DSM services. Storage, on the other hand, can simply store the excess generation and discharge itself during the peak consumption period, providing help to both generation and consumption peaks.

In this work, DES has been applied as a solution to system level problems. The opportunities provided by DSM have been discussed and demonstrated[11] but no system level applications have been demonstrated. The opportunities provided by combining both DSM and storage should clearly exceed those by storage alone, but system level analysis of such cases has been left outside the scope of this work.

Three basic control strategies have been applied in this work to utilize the DES systems. In the first strategy the storage utilization is controlled systematically by the time of day. In the second strategy the storage acts as an exponentially weighted moving average (EWMA) filter. In the third model fluctuations of local production are reduced using four fixed storage regions that have been defined by local production level and the

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[11] In Publication I.

available storage discharge capacity. These regions can simply be described as “always charge,” “conditional charge,” “conditional discharge” and “always discharge.”

The time controlled storage systems have been applied with large-scale photovoltaic (PV) power generation schemes to examine the topological and size issues connected to the storage systems. On the other hand, the EWMA storage system has been applied to compensate for power fluctuations of single megawatt-scale variable generation units, in this case wind turbines. The third method has also been applied with megawatt-scale wind turbines; not to dampen the local fluctuations as such, but to minimize the unwanted effects to the local distribution grid.

6.3.1. Leveling Photovoltaic Generation Peak with Storage

On a sunny day photovoltaic (PV) power generation provides a symmetric and well-predictable power output. The peak power occurs at solar noon and the generation on a sunny day also provides a rough estimate of the maximal hourly power generation[12]. Due to this symmetry the PV generation peaks can be tackled quite effectively with a simple time and power generation level based storage control strategy.

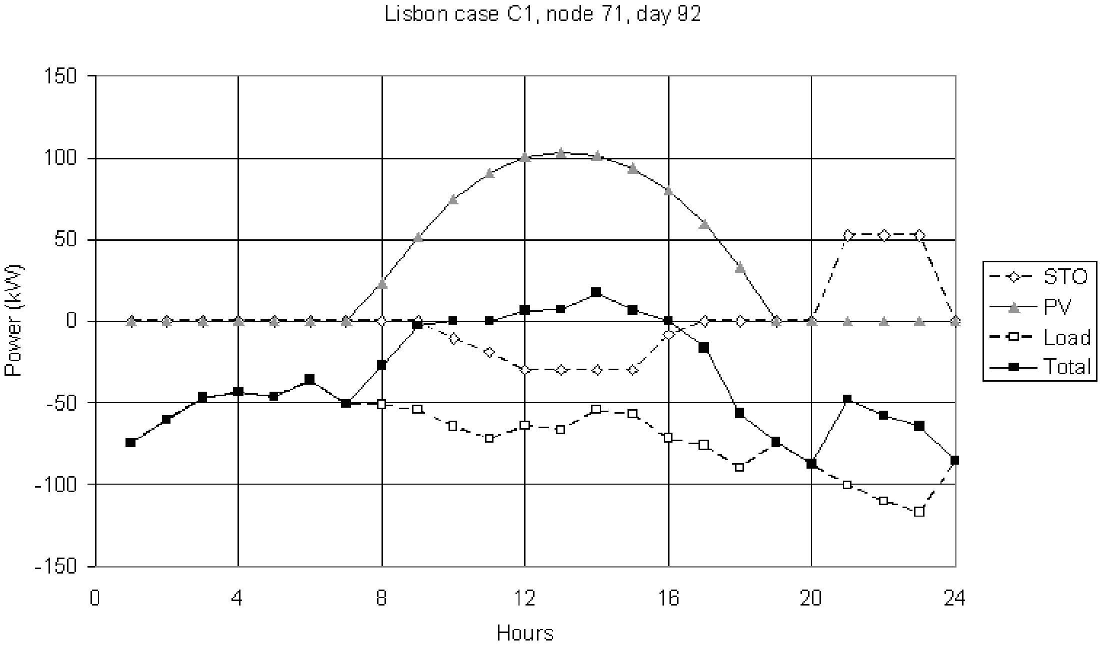

Figure 17. Typical daily cycle for a PV node with a storage unit.

The method applied here stores the excess energy during the daytime generation peak, while the early morning and late afternoon generation, and a part of the day time generation are utilized directly. As a result, the day time generation is reduced as much as the storage capacity allows and the evening consumption peak is smoothed by discharging the storage at peak consumption hours. A typical cycle for such storage is shown in Figure 17. There, the local load and PV generation curves are shown with response from the storage. In this case the storage begins charging at hour 10 and ends it

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[12] PV power generation can make peaks that are higher than the maximum generation during a sunny day due to reflections from clouds etc. [142]

at hour 16. Three evening hours (21-23) are used for discharging the storage. The case in Figure 17 shows a total reduction of the surplus mid-day PV generation peak of about 30 kW (60%) and the reduction of evening consumption peak of also about 30 kW (25%).

With such smoothing of the PV generation daytime peak and the evening consumption peak, the effects from integrating large amounts of PV generation can significantly be reduced. Results from case studies using such smoothing on a system level have been demonstrated in Figure 18 and Figure 19 for both Finnish and Portuguese climates, correspondingly. The effects of spread-out PV generation and PV generation with local storage are shown in the figures by cases B1 and C1. In these cases the annual maximum overvoltage was reduced by 65% in the Helsinki case and in the Lisbon case it was completely removed.

The effect of storage siting has also been tackled in Figure 18 and Figure 19. The results demonstrate that the storage size as well as centralization with optimal locating is an important factor in countering the unfavorable effects from local PV generation. The difference between the dispersed and centralized storage in a grid branch with much PV generation shows more clearly in Figure 18 due to the overvoltage situation in case C5. This shows that optimally placed central storage or few large storage units can actually serve the network better than multiple small storage units at various generation sites. In this case the overvoltage reduction is improved up to 80%.

However, yet another type of solution can also be reached by placing for example three times larger PV and storage units to optimal locations in the one third of the PV sites used in cases B1 and C1. In Figure 18 and Figure 19 this is demonstrated by cases B3 and C3. In Helsinki the relocating of the PV generation in case B3 reduces overvoltage by 59% while in Lisbon it is again completely removed. In Helsinki the case C3 that additionally uses local storage reduces the overvoltage further by a total of 70%. This indicates that if placing large amounts of PV generation and storage to a distribution grid is done in a centrally coordinated and well-planned manner, the grid can tolerate significant amounts of PV generation without adverse effects.

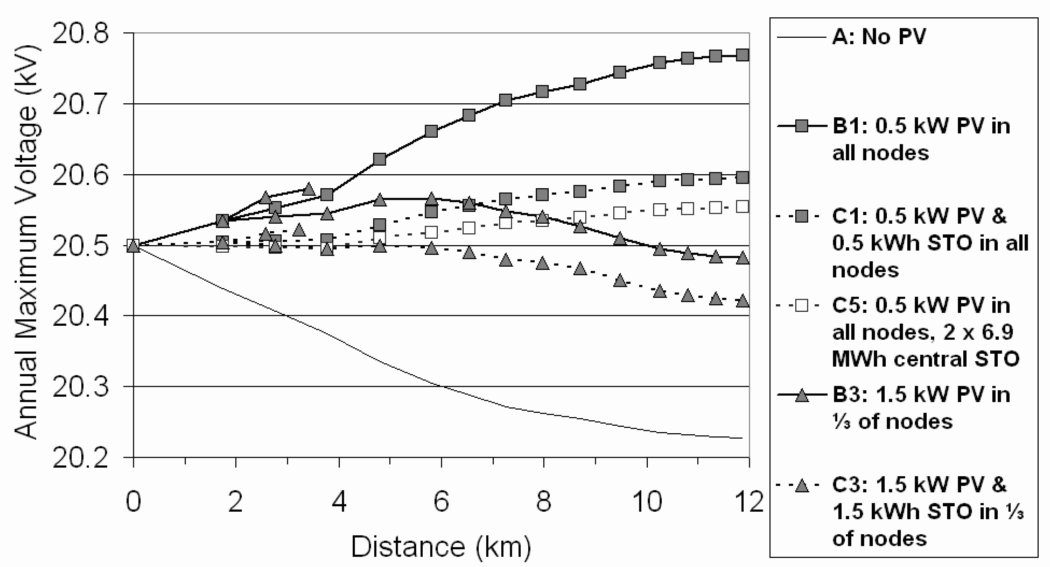

Figure 18. Effect of storage (STO) to large-scale photovoltaic (PV) power generation in Helsinki.

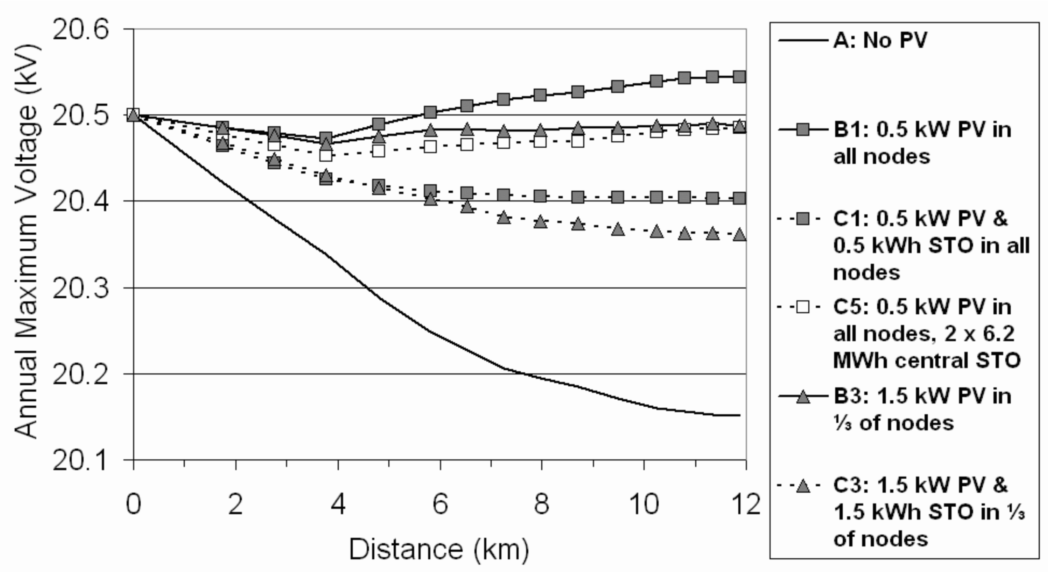

Figure 19. Effect of storage (STO) to large-scale photovoltaic (PV) power generation in Lisbon.

6.3.2. Smoothing Wind Power Fluctuations with Storage

To assess the possibilities of using a relatively small storage unit to smoothen the output curve of an individual megawatt-scale wind turbine, several different types of wind turbine data were categorized in the data analysis of Chapter 5.3. Here the data has been analyzed by applying the smoothing storage control strategy, namely exponentially weighted moving average (EWMA) filtering. An example about using storage for such smoothing with several τ is given in Figure 20, where the measured power output data from a 1 MW turbine is being smoothened.

When storage is used as an EWMA filter, the filtering time constant τ is proportional to the needed storage capacity as well as the level of smoothing. Through applying such a filter it was possible to analyze how τ influences the normalized power standard deviation (STD) and the power integral time scale (PITS) of the wind power data samples. As the corresponding storage capacity need was also measured, a direct relationship between STD and storage capacity could be established. This relationship was expected to differ between different types of data samples, depending on the prevailing wind conditions.

In addition, two different analyses were done with two different kinds of data. In the short term data with measurements every one second the STD was calculated from 3-7 hours long data samples. In the long-term data with hourly measurements, the STD was calculated over a period of one year, except for some data that was available only for 202 days.

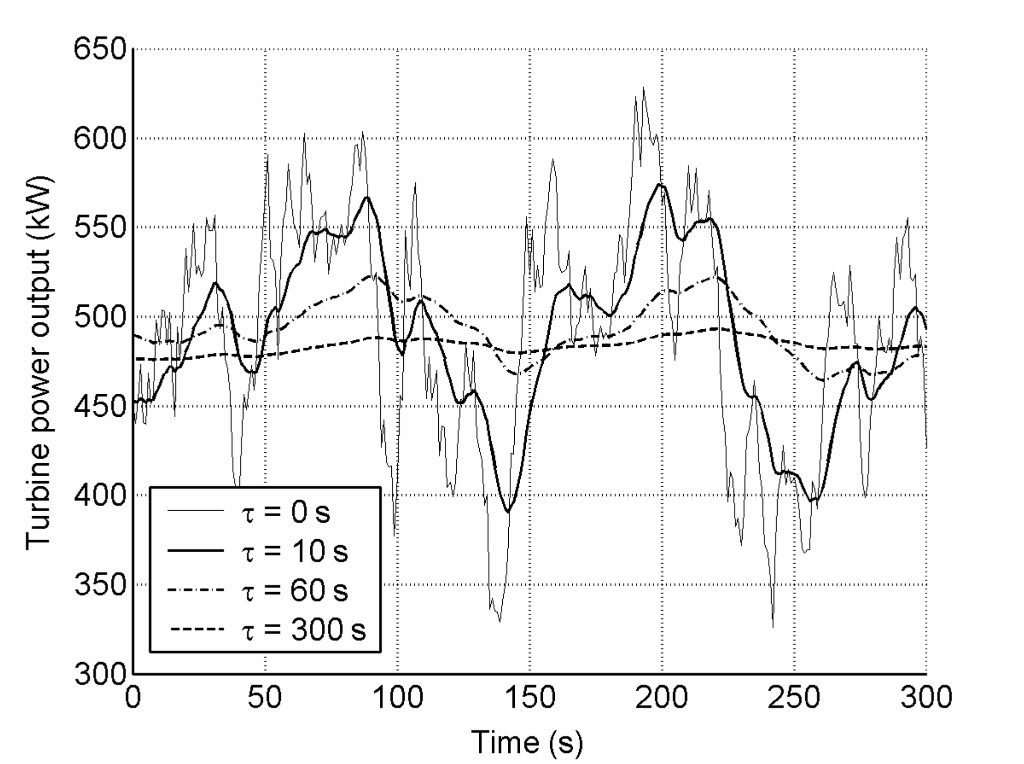

Figure 20. Smoothing the wind turbine power output with a storage using exponentially weighted moving average filter using several different values for the time constant τ.

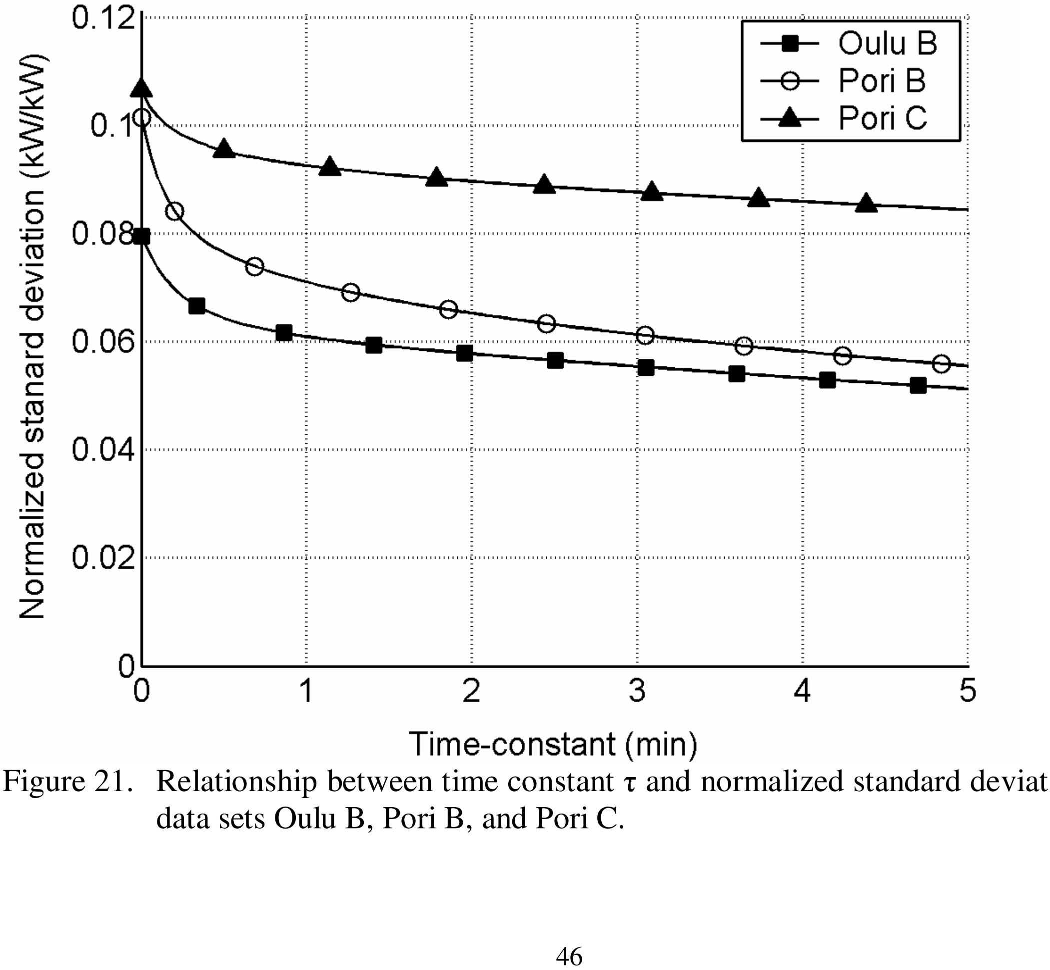

Figure 21. Relationship between time constant τ and normalized standard deviation for data sets Oulu B, Pori B, and Pori C.

The relationship between the time constant τ and STD of some of the short-term data samples is demonstrated in Figure 21. With τ =5 minutes (or 300 seconds) all data sets (also the ones not shown in the figure) but one (Pori C) have their STD below 0.06. For the data sets defined in Figure 11 the sets Pori A and Pyhä A have the relatively lowest influence from the storage filtering due to their already low STD value. However, the data set Pori C represents the most difficult type of wind power generation to smoothen up among the short time scale data. In addition to the small ripple-type fluctuations, the data has rather substantial fluctuations that have a time scale of minutes. To significantly smooth such a generation profile, storage with very high time constant (and storage capacity) is required.

To consider the practical implementation of a storage system, the correlation between the reduction of standard deviation of the wind power output and needed storage capacity has been considered. For the short term fluctuations, Figure 21 shows the relation between storage capacity need and reduction of the standard deviation in the wind power data.

As the correlation between capacity need and STD is observed, the result becomes that seen in Figure 22. There, the class C data (Pori C) shows the same problematic behavior as was seen in Figure 21. Only about 8-10% reduction in the standard deviation of the data is achieved with 2 kWh/MW energy storage capacity for class C and most of class A data, while for the rest of the data the reduction is double of that.

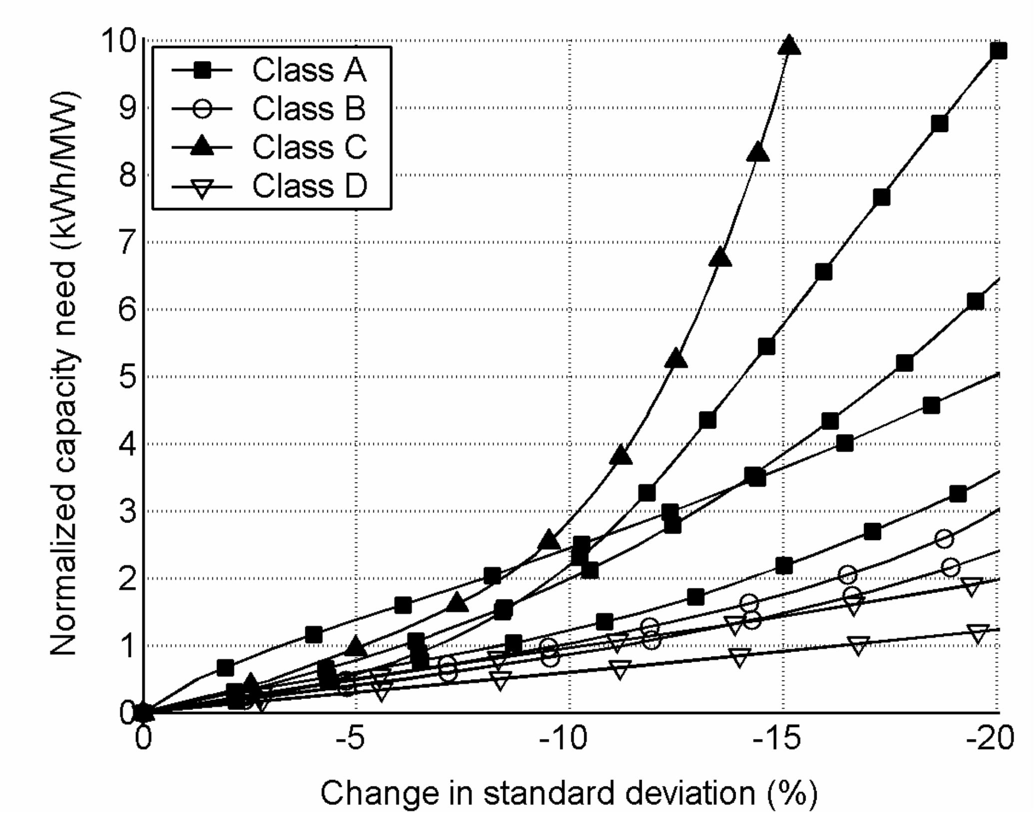

Figure 22. Relation of short-term energy storage capacity and relative standard deviation of the wind turbine power output. Turbine data with Δt = 1 s and power fluctuation classes A-D form Figure 11 have been applied.

The hourly wind power data was analyzed in similar ways like the short-term data. As a result, a correlation between STD and storage capacity was computed. The results of such an exercise are shown in Figure 23. Although significant deviations were present in the short term data, the long term data demonstrates a notably coherent behavior. Corresponding to storage size of 10 MWh/MW the data standard deviation is reduced 22-29%. From the hourly data, the data sets Riut II and Lerv II are the most difficult to smoothen.

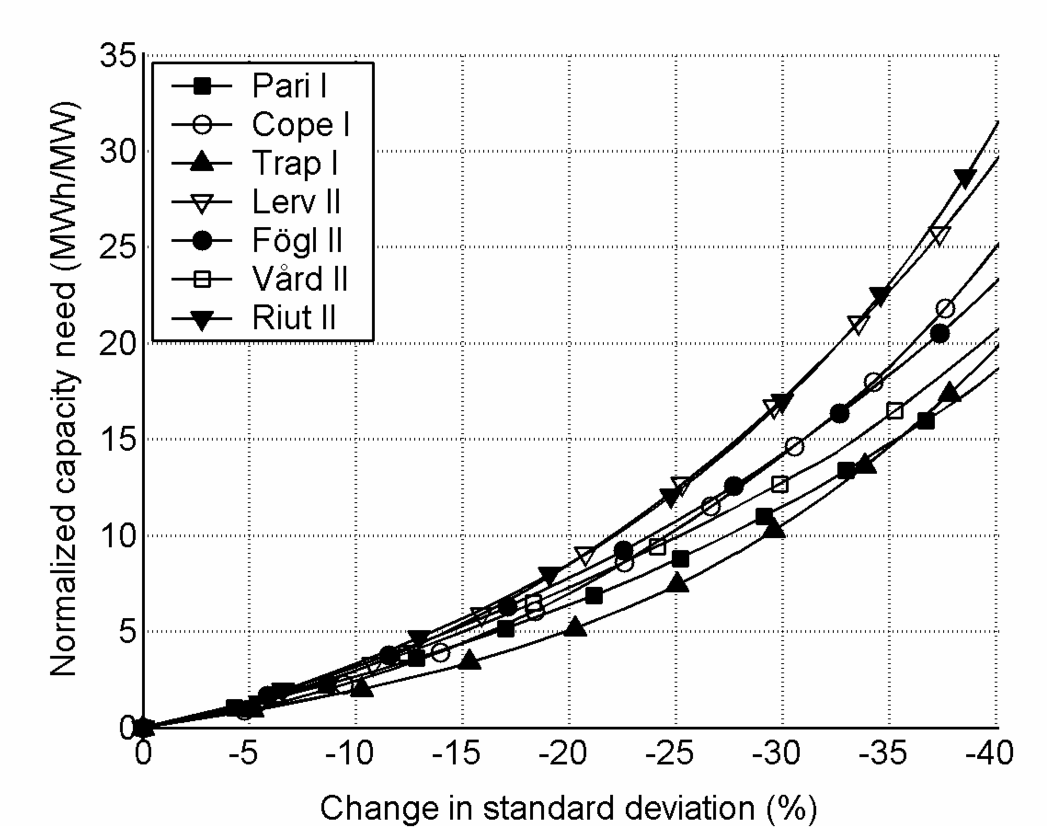

Figure 23. Relation of long-term energy storage capacity need and reducing standard deviation of the wind turbine power output. Turbine data set with $\Delta t = 1$ h.

In conclusion, it seems clear that the short term wind power fluctuation can be dominated by either very short or intermediate fluctuations. This causes large differences in the results when the fluctuations are smoothened using storage. These fluctuations can be either typical to the wind pattern during the measurement of the applied data or partly to the interference caused by the local surroundings.

On the hourly level, however, the main fluctuations on the annual scale result from cyclones and anticyclones, which make fluctuations in wind strength very similar between different sites. Therefore, the differences in the impact from storage resemble each other closely. Only with very large reductions of STD differences begin to show themselves. The only exception is the Mediterranean data Trap I that shows quite an early deviation that later disappears.

6.3.3. Compensating Local Wind Power Over-Production with Storage

To estimate the practical use of energy storage to compensate fluctuations caused by a large individual wind turbine in the distribution grid, simulations with two network topologies were done. While the previous chapter focused on smoothing the fluctuations in the wind power generation, here the voltage deviations experienced in the local grid are the main concern. Using one-year long grid simulations with emulated household consumption data and production data from a real 1.3MW wind turbine the worst hours of the year were analyzed and compared.

Effects in a comb-like grid branch (see Figure 15) were analyzed using a 70 km long 20 kV line. The cable used in the analysis has a 402 mm^2 cross-section and the grid branch has 31 nodes each with consumption by 40 households. While four 1.3 MW wind turbines were located in the half way of the distribution branch (L=1), the electricity storage unit was placed to different grid nodes from close to mains (L=0.05) to far behind the wind turbine (L=1.5). The storage used in these simulations has the capacity of 5,670 kWh, or roughly 1 MWh per MW of wind.

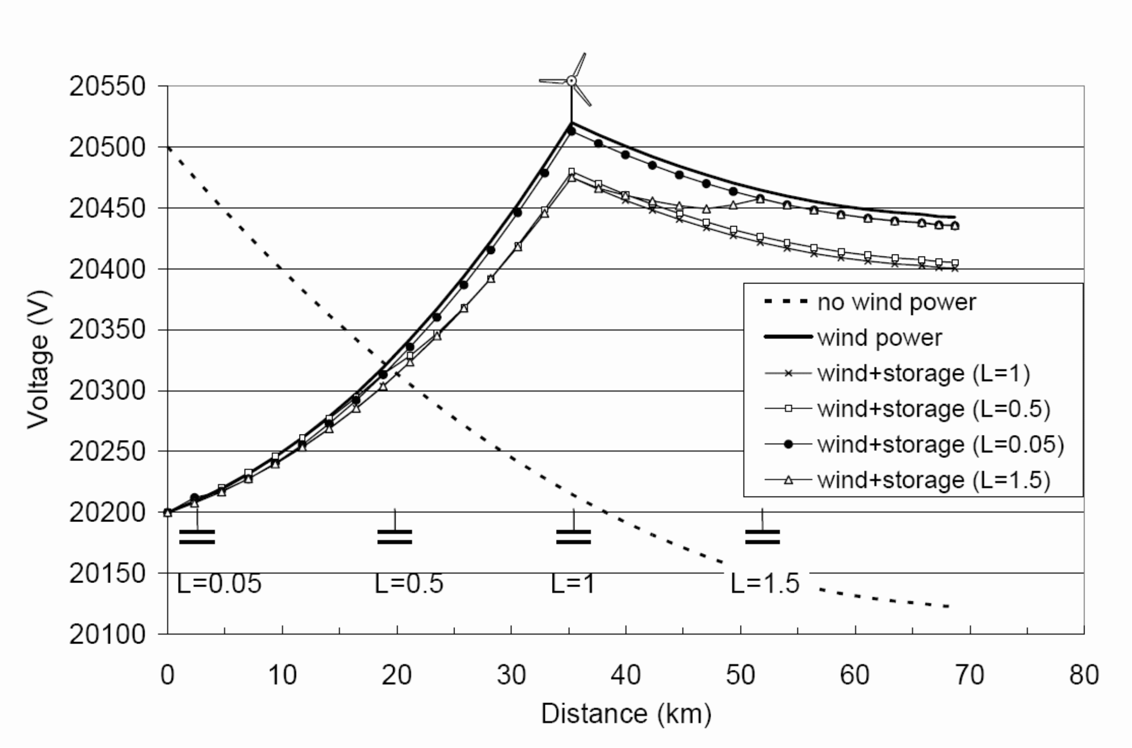

Figure 24. Maximum voltage along the comb-type distribution line.

Results from simulating the wind turbine and storage in a linear grid are shown in Figure 24. While the storage reduces the voltage peaks well as long as it is not too far from the wind turbine site, the best overall performance is achieved by siting the storage next to the wind turbine. About 10% reduction in the maximum overvoltage was achieved using the storage when compared to a grid with wind power but no storage at all. The figure also shows that the feeding voltage of the grid branch could be reduced to 20.2 kV. This was due to the comb-like grid topology and the good coincidence with the local wind generation and the annual peak consumption. In a tree-like grid topology benefit from such coincidence can not be so fully utilized. There, even if the grid branch with wind turbine would experience the power coincidence fully the other branches would get the power indirectly through the connection point to the wind power branch resulting as lesser benefit and higher voltage drop in those lines.

When the effects in a more sophisticated network were simulated, a 78 node 20 kV distribution grid branch was used. This branch has a tree-like topology (see Figure 15) and three different cable types with 33.8-201 mm^2 cross-sections depending on their expected loads. The cables near the mains connection are with most cross-section area while the cables at the far end have the least.

The results from simulating a tree-type network branch are shown in Figure 25. There, two different sites with 1-3 wind turbines and corresponding storage (1.26 MWh/MW) were modeled. A single turbine in the beginning of a weak grid branch (Node 6) shows clear benefit from the storage that gives almost 50% reduction to the worst overvoltage event during the year. Two to three turbines were simulated at the end of the strong cable string (node 4). Despite the rather strong grid location, the wind power generation during worst hours of the year exceeds the compensating capabilities of the storage. While the two turbines perform rather well, three units cause overvoltages to almost all over the grid branch. From another viewpoint the results show clearly that when MW-scale distributed power generation unit is considered choosing the unit site in relation to local grid topology makes a huge difference in the induced grid anomalies. While the nodes 4 and 6 are only 6.8 km apart in a 39.6 km long tree-like grid branch, node 4 can accommodate double the wind power than node 6 with lesser overvoltage problems. In Figure 25 the minimum voltage curve indicates the voltage levels in the grid during maximum consumption peak. The peak occurs when no wind power in the grid is produced.

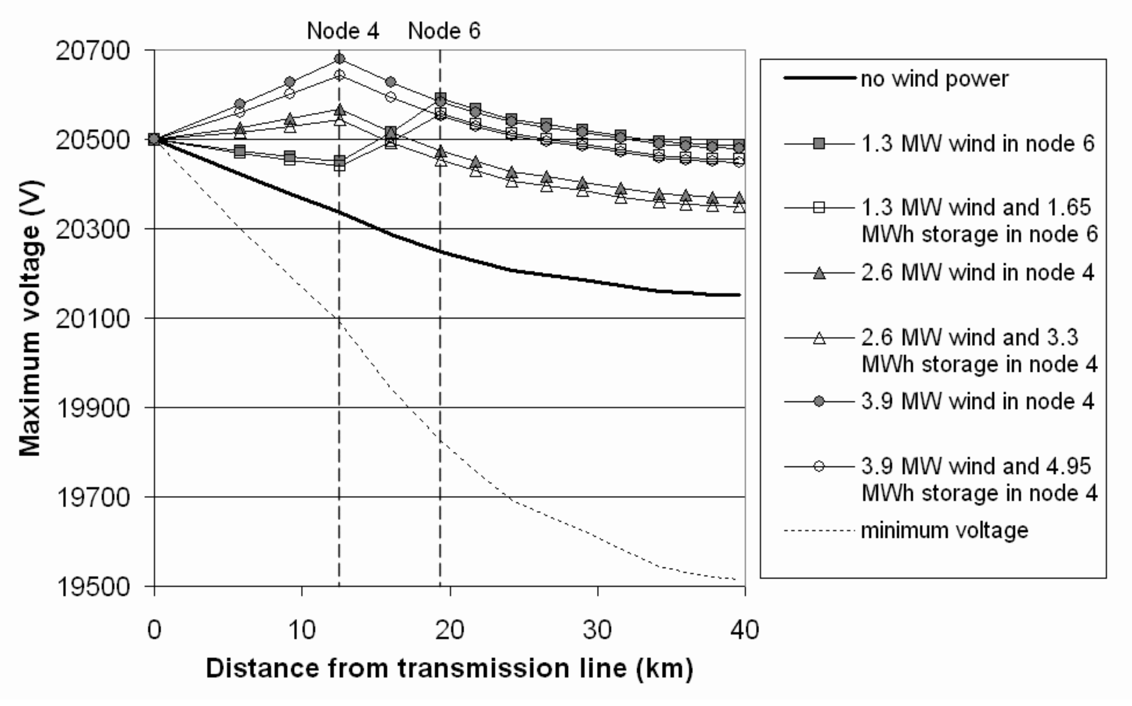

Figure 25. Maximum voltage along a chosen string of the tree-type distribution network branch.

In conclusion, significant reductions in unwanted effects from even megawatt-scale variable DG are possible with MWh-scale storage. Some differences were detected between the comb and tree type network geometries, although the basic events remained the same. When the simple four-region strategy is applied to reducing the fluctuations of a megawatt-scale wind turbine, it gives only limited benefit to the grid. A more sophisticated storage control strategy would allow additional compensation of local consumption peaks that would reduce the total voltage variation range in the grid. This should be an effective way to allow accommodation of even more wind power.

6.3.4. Smoothing Fluctuations with DSM

In addition to controlling the use of DGS, smoothing options exist on the demand side. By managing the demand by temporarily either delaying or denying the consumption, significant modification to the consumption patterns can be achieved. In this work, only the basic opportunities provided by DSM are presented, whereas a more detailed and integrated study in combination with DG and storage is beyond the scope of this work.

In order to demonstrate the opportunities provided by DSM, the results from two case studies will be presented below. These case studies were performed using domestic consumption data generated for a total of 10,000 households. In these cases, DSM measures influence simultaneously all the households according to the management rules applied. Table 5 summarizes how the total household load is divided between its major uses.

Table 5. Share of consumption in an average household applied in cases 1 and 2.

Share of consumption	%
Cold appliances	24.6
Clothes-washer	7.0
Dishwasher	8.8
Cooking	15.8
Entertainment	17.5
Lightning & misc.	26.3
Total	100.0

These cases utilize two kinds of DSM strategies: delaying the use of an appliance group to a later time, or denying its use for a certain time period. The kind of DSM applied to an appliance group depends on the kind of end use it represents. The appliance groups are also given different priorities to represent the level of inconvenience their management causes to the end user.

The kinds of control strategies applied to the various groups of appliances are presented in Table 6. The strategy to delay the use has been utilized with appliances where the delaying can reasonably be coped with by the appliance itself or its user. In practice, cold appliances have a delay of one hour (with one full hour recovery time after) and clothes and dish washing activities six hours, correspondingly. The other appliances are managed with simply denying their use completely for the period of management.

Table 6. DSM strategies applied for various household appliances in cases 1 and 2.

Appliances & groups	Priority	Control	Limits
Stove & oven	1	cut	–
Microwave oven	1	cut	–
Coffee maker	1	cut	–
Refrigerator	0	post. 1 h	1 h
Freezer	0	post. 1 h	1 h
Second freezer	0	post. 1 h	1 h
Dishwasher	3	post. 6 h	–
Washing machine	2	post. 6 h	–
Tumble dryer	2	post. 6 h	–
Television	4	cut	–
Second television	4	cut	–
Video recorder	4	cut	–
Radio/player	4	cut	–
Personal computer	4	cut	–
Printer	4	cut	–
Lighting	5	cut	50%
Other occasional loads	5	cut	50%

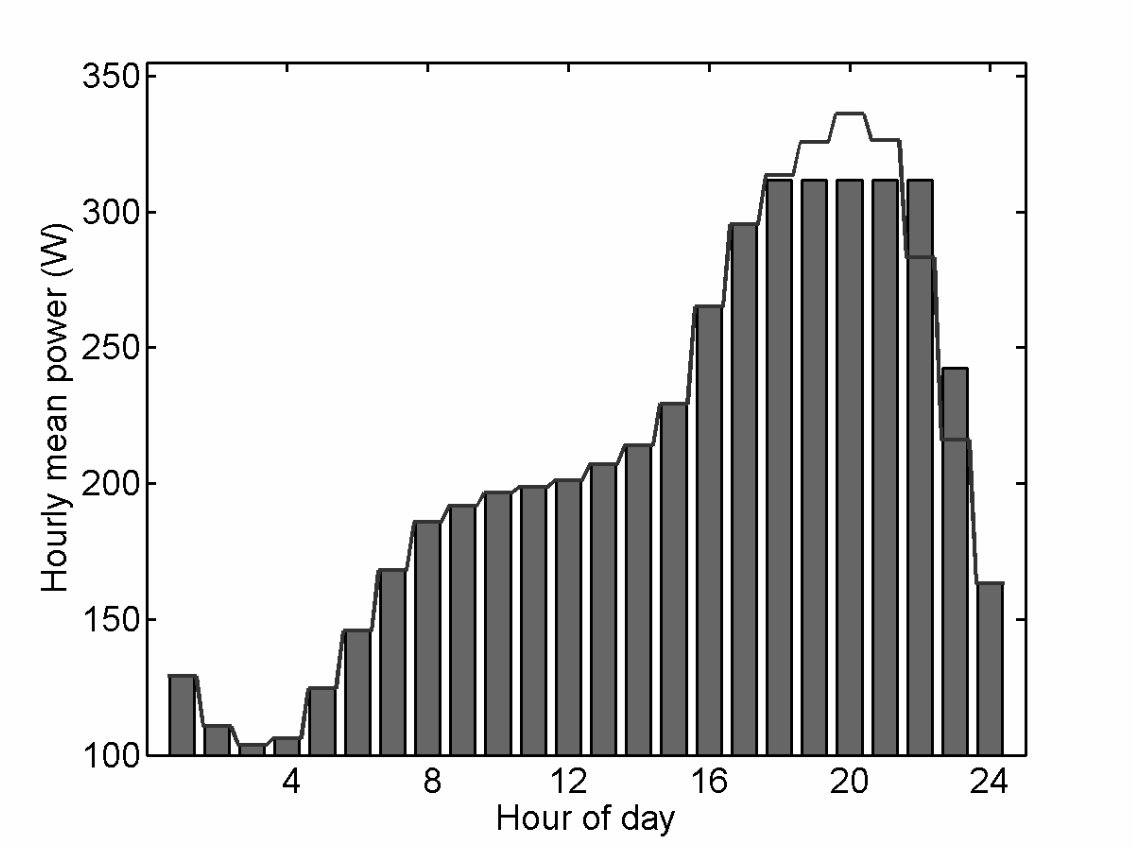

Figure 26. The hourly consumption in an average household before and after the DSM in case 1.

In case 1 a mild DSM has been applied to reduce the peak load during weekdays throughout the year. There, by managing the use of cold loads (priority 0 loads in Table 6) during the peak consumption the total consumption peak has been reduced. In the second case an intense DSM has been applied to reduce the peak during the peak consumption day of the year to avoid a temporal blackout. This case corresponds to a situation where an unexpected partial loss of power generation capacity needs to be dealt with by managing the consumer loads according to their assigned priorities. As a result, some compromises in the customer comfort have been made.

In case 1 a maximal peak reduction (7.2%) has been achieved by using optimal DSM strategy with the use of cold appliances. It is a DSM case where the heat capacity of cold appliances is utilized to provide a temporal reduction in electricity use. The reduction is achieved during weekdays without any noticeable inconvenience to the consumers. The resulting load curve of an average weekday is demonstrated in Figure 26. There, a comparison between the original load curve and the DSM load curve can be seen. As the managed peak extends over several evening hours, the overall reduction of the load is much smaller than the total capacity of the cold appliances. In practice, the management in Figure 26 is achieved by delaying the use of 0.1%, 27.6%, 52.9%, 47.1%, and 25.5% of the total cold load capacity, and it is managed during the corresponding hours between 18 and 23. Such distribution is necessary to extend the reduction to all the peak consumption hours.

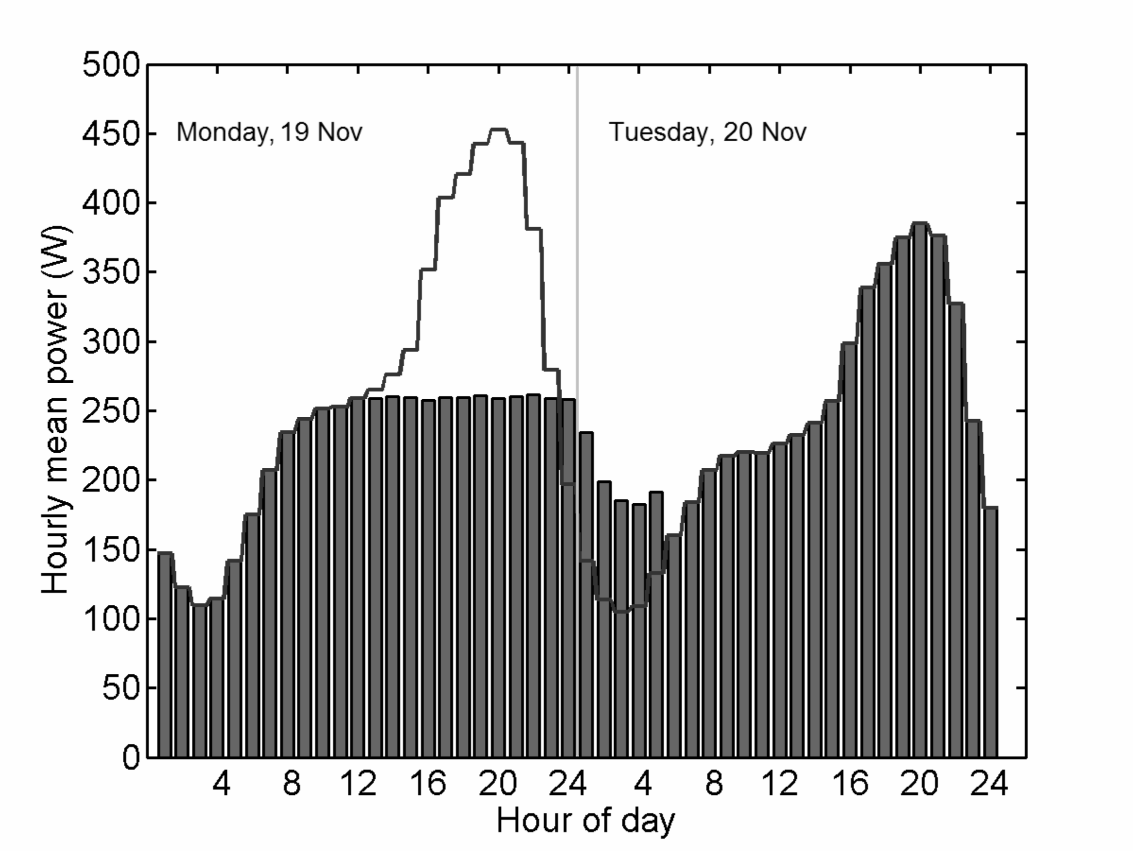

Figure 27. Peak reduction and partial delay of the evening consumption in case 2.

In case 2, all the domestic appliances with priorities from 0 to 5 are controlled in the corresponding order. The result of such management is shown in Figure 27, where the evening consumption peak has been completely removed. To achieve such a 42% demand peak reduction, consumer comfort was violated: during the hours from 14 through 23, most of the washing loads were postponed 6 hours and between 17 and 23, most of the entertainment loads were cut off, and the lighting was reduced by 50% in 75% of the households during one hour of the evening. It can also be seen that the postponed loads caused a significant increase of consumption between 23 and 05 off-peak hours, yet the increased night-time consumption still remains within acceptable boundaries.

The inconveniences due to DSM in case 2 can still be seen as a minor compromise in comparison to a 6-hour total blackout during the evening consumption peak. Overall, both of the two case studies have demonstrated that the DSM offers a significant additional potential when dealing with the consumption peaks or alternatively the power generation peaks of the local DG.

Although an integrated study of the total effects of DG, storage, DSM, and network topology are beyond the scope of this work, such a work would most likely provide even deeper insights into the management of local power generation. It should be noted, however, that the 7.2% maximum consumption peak reduction achieved in case 1 gives a significant release for a fully loaded distribution grid branch.

7. Concluding Remarks

This thesis has been done as a computational research focusing in three areas of distributed power generation. These areas are storage use in connection to DG, the ability and limits of medium voltage (MV) power distribution grid with domestic load to accommodate DG, and the potential impact of selected methods and circumstances (like network topology, storage use and site etc.) to reduce the unwanted effects of high levels of DG. Moreover, a multi-use bottom-up domestic consumption modeling tool was developed and verified as part of the thesis. The model was used to generate consumption data for the grid simulations.

The use of storage has been evaluated in connection to two variable power generation technologies, wind turbines and photovoltaics. With wind turbines the short term power fluctuations (from second through minute scale) can be compensated with relatively small storage capacity. Already with a 3 kWh storage capacity per MW of wind power over 10% reduction in the standard deviation of the power output can be reached. However, the long term fluctuations are difficult to compensate without extensive storage capacity due to the over 24 hour long cycles present in these fluctuations. With photovoltaic power generation the use of storage is more straightforward, as PV power has a very predictable diurnal basic cycle. The storage needs to carry the energy from the noon generation peak to the evening consumption peak to achieve a significant smoothing of the local power production profile. Use of one kWh storage capacity per kW of PV results in at least 36% reduction of local overvoltage and up to 0.6% reduction in the voltage drop during the consumption peak[13]. However, compensating the seasonal fluctuation in PV power generation would be difficult using energy storage.

This thesis is limited to addressing only the steady-state voltage levels and transmission losses concerning the large-scale integration of DG to medium voltage (MV) distribution network. When DG is evenly deployed to the distribution network, up to 34% reduction in network losses is observed[14]. However, if the generation is

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[13] In Publication III.

[14] In Publication II, tree-type grid in Lisbon case with 0.5 kW per household PV penetration level.

concentrated to limited part of the grid or much of the generation is fed to the main grid, the MV network losses may also increase.

When compared to the transmission losses the changes in MV network voltage levels proved to be a more crucial issue for the integration. If the total simultaneous generation by DG exceeds the local load with more than the local network losses[15] the direction of power flow in the MV distribution network is changed and the nodes generating power end up with higher voltage levels than the node at the MV transformer. If the maximum consumption in the grid does not cause the grid branch to use the whole allowed voltage range the overvoltage can be handled by lowering the feeding voltage at the MV transformer[16]. However, if that is not possible, other methods are needed to reduce the amount of power fed to the grid.

Concerning the integration of PV generation, three different approaches were tested to reduce the voltage rise in the distribution grid both in North-European (Finnish) and South-European (Portuguese) climates. First, changing the orientation of the south-facing PV panels enabled the generation peak to be flattened up to 30% and the overvoltage to reduce up to 46%, but it also causes up to 23% loss in the total power generated[17]. This approach was enough to avoid overvoltage in some border cases but typically the change is too minor to act as the only solution. Second, altering the way how the generation was distributed in the grid can influence the grid voltage profiles significantly. Placing generation to more central and strong grid nodes reduces the caused overvoltage by about ⅔. Third, using distributed or centralized storage improved significantly the voltage profiles of the grid. Here, a centralized storage would typically provide a better solution than an evenly distributed storage, although extensive research on the issue was not pursued. However, our research does show that a 30-100% overvoltage reduction may be achieved with relatively small storages, i.e. one kWh per kW of PV. Combination of any of the three approaches would result in further reduction in voltage rise as their effects are not interdependent in nature.

Concerning wind power, integration of a large, megawatt-size turbine to a MV network was modeled and use of a single storage unit was tested as a way of improving local voltage profiles. Here placing the storage near the wind power unit proved to be the most effective approach.

In connection to the work with consumption load profiles and their modeling use of DSM was evaluated. The preliminary results show that use of DSM may significantly reduce the consumption peaks thus reducing the voltage range needed by the distribution grid branch. By controlling just cold appliances a 7.2% maximum load reduction can be achieved with practically no inconvenience to the consumers.

The significance of this thesis is based on two main issues. First, a multi-use bottom-up load modeling method has been introduced and its applicability verified. This method allows straightforward yet accurate emulation of domestic household consumption based on easily accessible consumption and appliance ownership data, enabling detailed

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[15] Losses are typically under 1% in medium voltage distribution network.

[16] For 20 kV grid branch with ±2.5% allowed voltage variation the allowed range would be 19.5-20.5 kV. If the minimum voltage at maximum load would be 19.8 kV, the feeder voltage at the transformer can safely be brought down to 20.2 kV from 20.5 kV.

[17] In Publication II, during a sunny summer day in Helsinki.

analysis of the local effects of DG, DSM, and other load-related issues that benefit from detailed information about the composition and local behavior of the consumption. This method is expected to see a lot of interest in the scientific community and active future use.

Second, general tendencies and critical issues have been identified concerning broad scale integration of DG in the distribution grid. Overvoltage problems will inevitably ensue when enough DG is integrated. However, when storage and other methods are applied, the amount of DG that can be integrated without issues can be significantly increased. Although this thesis does not thoroughly explore all such options, it has been demonstrated that through computation simulations these options can be assessed and evaluated in detail.

There are several issues to be considered further to reach a more complete picture concerning the interplay between local electricity consumption and large scale integration of variable distributed power generation. Main areas of further work seen here are load modeling, grid management methods, and further verification of the results.

Although a statistically sufficient bottom-up load emulation method has been developed, some further work on the model details is recommended. The current model does not include a way to model special holidays and events, although they are significant while predicting anomalies in the electricity consumption. Furthermore, the load model does not include the seasonal changes in the timing of consumption peaks although that has been suggested by the measured data. The challenge with both of the suggested improvements is to find or gather data that would provide enough detailed knowledge of these phenomena to model them correctly. When such data is accessible, these features should be introduced to the model. Moreover, even the current load model could be employed to emulate new types of loads like commercial and industrial buildings. For offices the needed consumption data should be easily accessible, while in industrial use the gathering of input data might require more effort, as the consumption of industrial equipment is less standard.

While several methods to accommodate DG to the distribution grid were applied, further extensions on these studies are recommended. For example, integrated use of both DSM and storage was left outside the scope of this thesis, although it provides an interesting addition to the methods employed here. When this is combined with developing an effective overall storage and load management strategy they should improve significantly the amount of DG that can be accommodated in the local MV grid. Further improvements could be reached by active adjustment of the power factor of DG and storage. If the locally generated power is utilized smartly to compensate reactive load and so to reduce the local voltage drop, the control over voltage variation in the distribution grid should improve even further.

Concerning a more methodology based issue; the optimal size of applied time step to be used in this kind of simulations could be analyzed. In this work, an hourly time step has been applied mainly due to available consumption data. However, it would be valuable to determine if shortening the data and simulation time steps would reveal some new information about the phenomena seen in the results.

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Abstracts of Publications[18]

I. A model for generating electricity load profiles

Electricity consumption data profiles that include details on the consumption can be generated with a bottom-up load models. In these models the load is constructed from elementary load components that can be households or even their individual appliances. In this work a simplified bottom-up model is presented. The model can be used to generate realistic domestic electricity consumption data on an hourly basis from a few up to thousands of households. The model uses input data that is available in public reports and statistics. Two measured data sets from block houses are also applied for statistical analysis, model training, and verification. Our analysis shows that the generated load profiles correlate well with real data. Furthermore, three case studies with generated load data demonstrate some opportunities for appliance level demand side management (DSM). With a mild DSM scheme using cold loads, the daily peak loads can be reduced 7.2% in average. With more severe DSM schemes the peak load at the yearly peak day can be completely leveled with 42% peak reduction and sudden 3 h loss of supply can be compensated with 61% mean load reduction.

II. Effects of large-scale photovoltaic power integration on electricity distribution networks

The public support in photovoltaic (PV) technologies and increasing markets have resulted in extensive applications of grid-connected PV, in particular in the consumer side and electricity distribution grid. In this paper, the effects of a high level of grid connected PV in the middle voltage distribution network have been analyzed. The emphasis is put on static phenomena, including voltage drop, network losses and grid benefits. A multi-purpose modeling tool is used for PV analysis in Lisbon and Helsinki climates. All network types studied can handle PV without problems with an amount of PV equaling at least up to the load (1kWp/household). The comb-type network showed the best performance. The PV is unable to shave the domestic load peak in the early evening hours but through orientating the PV panels both to east and west, the noon peak from PV can be reduced by 30%. PV integration reduces network losses positively up to a 1kWp/hh (100% of annual domestic load) level. For 2kWp/hh all but the comb-type networks demonstrate clear over-voltage situations and the annual network losses are much higher than without PV.

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[18] Few minor errors in the abstracts have been corrected in comparison to the original texts published in the articles.

III. Impacts of energy storage in distribution grids with high penetration of photovoltaic power

This paper investigates the influence of energy storage on the network impacts from large-scale PV schemes applying a dynamic computational method. A total of 11 case studies were computed applying a simulation tool that combines powerflow calculations with distributed generation and storage models. Different storage schemes, PV sizing and climatic zones have also been considered. The study indicates that using a storage of 1kWh per 1kWp PV may reduce the PV induced over-voltage by 30-100% depending on the case. The benefits were more distinctive in a southern climate than in northern latitudes where the mismatch between solar output and load is more severe at the seasonal scale. With careful siting of the PV units in the grid, significant benefits can be achieved even without storage. These benefits are achieved by placing PV systems in strong grid locations and avoiding the weak ones.

IV. Effect of energy storage on variations in wind power

Irregularities in power output are characteristic of intermittent energy, sources such as wind energy, affecting both the power quality and planning of the energy system. In this work the effects of energy storage to reduce wind power fluctuations are investigated. Integration of the energy storage with wind power is modeled using a filter approach in which a time constant corresponds to the energy storage capacity. The analyses show that already a relatively small energy storage capacity of 3 kWh (storage) per MW wind would reduce the short-term power fluctuations of an individual wind turbine by 10%. Smoothing out the power fluctuation of the wind turbine on a yearly level would necessitate large storage, e.g. a 10% reduction requires 2–3 MWh per MW wind.

V. Energy storage options for improving wind power quality

The intermittency of wind may in some cases limit the applicability of wind power when integrated directly into the distribution network. Energy storage technologies can provide a local solution either through peak shaving or increasing temporal stability of the power generation. In this work the needs and options for peak shaving storage are investigated with practical implementations through case studies. It is demonstrated, that roughly 1 MWh storage per MW of wind power is enough to reduce at least 10% of the local voltage rice in weak networks. The weaker the network is, the more the storage influences the local network voltages.

ISBN 978-952-248-124-5
ISBN 978-952-248-125-2 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)