

UNIVERSITY COLLEGE LONDON

DOCTORAL THESIS

**Optimal design and regulation of
residential distributed energy systems**

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for the degree of Doctor of Philosophy*

in the

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UCL Australia

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Declaration of Authorship

I, Carmen M.E. WOUTERS, declare that this thesis titled, '*Optimal design and regulation of residential distributed energy systems*' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Abstract

Central power systems predominantly consist of large generators that provide electricity to a broad consumer base through extensive networks. This conventional top-down supply is, however, being challenged by peak demand, energy losses, ageing infrastructure and climate change. Localised distributed energy systems (DES), consisting of clusters of small-scale technologies and various energy services and interactions at the consumer level, are increasingly presented as solutions to these challenges. However, for DES to become viable, a novel cross-disciplinary design approach is still required that encompasses multiple stakeholder interests. This thesis aims to address this need through developing a flexible multi-objective decision-making framework for DES design, from an engineering and regulatory perspective, using mathematical programming techniques. A superstructure mixed-integer linear programming approach is hereto developed to optimise residential energy system designs framed by location-specific parameters and required electricity, heating and cooling demands.

Engineering design is optimised in terms of selection, siting and sizing of energy supply alternatives and interactions from a considered pool of options. Multiple stakeholder-driven minimisation objectives are included through Pareto trade-offs, ensuring a system design that is not only competitive (total annualised energy cost) but also introduces security of supply (electrical system unavailability) and environmental benefits (annual CO₂ emissions) to the neighbourhood as compared with conventional configurations. DES, furthermore, require an adequate regulatory framework to fit in with conventional systems. Nevertheless, regulation is still lagging behind their technological development. The developed design approach is therefore extended to enable analysis of DES regulatory framework aspects by identifying quantifiable relations, such as type, scale and ownership, between engineering design, organisation and regulation.

The framework is applied to a small South Australian neighbourhood to illustrate its capability for DES design analyses and decision-making within conventional power systems generally. The developed approach ensures DES applicability within conventional power systems and their relevance to governing energy regulation.

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Nomenclature

Abbreviations

3P	Third party
AC	Absorption chiller / Alternating current
Airco	Air-conditioning unit
B	Condensing boiler
CHP	Combined heat and power unit
CL	Capacity level
Cpipe	Cold thermal pipeline
CST	Cold thermal storage
CT	Carbon tax
DC	Direct current
DER	Distributed energy resource(s)
DES	Distributed energy system(s)
DG	Distributed generation
DNO	Distribution network operator
DOC	Depth of charge of batteries
Dump	Dump load
ESCO	Energy service company
EST	Electrical battery storage
FIT	Feed-in tariff
G	Gas heater
GR	Grid connection
Hpipe	Hot thermal pipeline
HST	Hot thermal storage
IP	Integer programming
LDC	Load Duration Curve
LP	Linear programming
MG	Microgrid
MGCC	Microgrid central control unit

MILP	Mixed-integer linear programming
MINLP	Mixed-integer non-linear programming
MIP	Mixed-integer programming
NEM	National Electricity Market of Australia
NLP	Non-linear programming
OM	Operation and maintenance
PIPE	Pipeline
PPA	Power purchase agreement
PV	Photovoltaic units
SA	South Australia
SAIDI	System average interruption duration index
WT	Wind turbine

Symbols

$A(t)$	Time dependent component availability
Δt	Time interval
λ_c	Constant component failure rate
μ_c	Constant component repair rate
P_s	Probability of the system being in state s
t	Time step
$U(t)$	Time dependent component unavailability

Sets

con	Electrical system configurations
$energy$	Types of energy: electrical (<i>elec</i>) and thermal (<i>therm</i>)
h	Hours in a day
i, j	Houses in the energy system
$infDG$	Infrastructure related to MG and DES: MGCC, dump loads, pipes
k	Types of CHP units and number of microgrid-available CHP units
l	Daily solar irradiation levels
m	Months in a year
t	Piecewise linearisation sample points
$tech$	Technologies considered for the energy system, i.e AC, airco, B, CHP, CST, dump, EST, G, HST, MG, pipe, PV, WT
$techC$	Conventional cooling technologies considered for the energy system, i.e. airco
$techct$	Central DG technologies considered for the energy system, i.e. AC and CHP
$techCV$	Conventional technologies considered for the energy system, i.e. airco, B, G, grid

$techDCT$	Distributed generation units considered for the energy system, i.e. CHP (both central and decentral), PV, WT
$techDG$	Distributed generation units considered for the energy system, i.e. CHP (decentral), PV, WT
$techH$	Conventional heating technologies considered for the energy system, i.e. B and G
$techST$	Storage technologies considered for the energy system, i.e. CST, EST, HST
$techTH$	Conventional thermal technologies considered for the energy system, i.e. airco, B and G

Parameters

a_c	Component total availability [%]
A_{tech}^{com}	Component availability of technology $tech$ [%]
A_{tech}^{res}	Resource availability of technology $tech$ [%]
A_{tech}^{sup}	Power supply availability of technology $tech$ [%]
A_{tech}^{tot}	Total availability of technology $tech$ [%]
C_{tech}^C	Unit capacity investment cost [AUD kW _{inst} ⁻¹]
$C_{ELEC,i,s,h}^{LOAD}$	Average electricity demand of house i in season s in hour h [kW]
$C_{HEAT,i,s,h}^{LOAD}$	Average heat demand of house i in season s in hour h [kW]
$C_{COOL,i,s,h}^{LOAD}$	Average cooling demand of house i in season s in hour h [kW]
C_{tech}^{omf}	Unit fixed OM cost of technology $tech$ [AUD kW _{inst} ⁻¹]
C_{tech}^{omv}	Unit variable OM cost of technology $tech$ [AUD kWh ⁻¹]
CI_{elec}	Carbon intensity central electricity grid supply [kgCO ₂ kWh ⁻¹]
CI_{gas}	Carbon intensity natural gas supply [kgCO ₂ kWh ⁻¹]
COP	Cooling coefficient of performance [kW _{cool} kW _{elec} ⁻¹]
CRF	Capital recovery factor for cost annualisation
d_s	Number of days in each season s
$d_{l,s}$	Number of days of each solar irradiation level l in each season s
$DG_{tech,DG}^{UP}$	Capacity bound for maximum installed residential DG units [kW]
ECR	Electricity to cooling ratio of AC units [kW _{elec} kW _{cool} ⁻¹]
hr	Duration of time period, here one hour
HER	Heat to electricity ratio of CHP units [kW _{heat} kW _{elec} ⁻¹]
$It_{l,s,h}$	Average solar irradiation on a tilted surface for radiation level l in hour h in season s [kW m ⁻²]
$It_{s,h}$	Average solar irradiation on a tilted surface in hour h in season s [kW m ⁻²]
$l_{i,j}$	Distance between each house pair i, j [m]
L_{tech}	Lower technology capacity bound [kW or kWh]

n	Component life time
$n_{chp,i}$	Total number of microgrid-available CHP units available to house i
n_h	Number of houses in the neighbourhood
n_{tech}^{elec}	Electrical efficiency of technology $tech$ [%]
n_{tech}^{th}	Thermal efficiency of technology $tech$ [%]
p^{SAL}	Percentage of equivalent installed DG capacity that can be exported
PE_{techDG}^{SALUP}	Capacity bound on export levels of residential DG units [kWh day ⁻¹]
r	Interest rate [%]
$T_{tech,i}^{av}$	Threshold capacity of technology $tech$ installed in house i in order to be considered available [kW or kWh]
$T_{MGint,energy}^{BUY}$	Internal microgrid purchase price for energy [AUD kWh ⁻¹]
$T_{techct,energy}^{BUY}$	Internal microgrid purchase price for energy from central units [AUD kWh ⁻¹]
T^{CT}	Carbon tax tariff [AUD kgCO ₂ ⁻¹]
T^{elec}	Central electricity tariff [AUD kWh ⁻¹]
T^{gas}	Central natural gas tariff [AUD kWh ⁻¹]
T_{MG}^{SAL}	Microgrid DG export feed-in tariff [AUD kWh ⁻¹]
$T_{MGint,energy}^{SAL}$	Internal microgrid selling price for energy [AUD kWh ⁻¹]
T_{techDG}^{SAL}	Feed-in tariff for residential DG electricity export [AUD kWh ⁻¹]
U_{rec}	Upper bound on power received from pipelines, MG or grid [kW]
U_{snd}	Upper bound on power send to pipeline, MG or grid [kW]
U_{tech}	Upper technology capacity bound [kW or kWh]
ua_c	Component total unavailability [%]
ua_{con}	Steady-state unavailability of electrical system configuration con
UA_{tech}^{com}	Component unavailability of technology $tech$ [%]
UA_{tech}^{res}	Resource unavailability of technology $tech$ [%]
UA_{tech}^{sup}	Power supply unavailability of technology $tech$ [%]
UA_{tech}^{tot}	Total unavailability of technology $tech$ [%]
$V_{s,h}$	Average wind speed in hour h in season s [m s ⁻¹]
β	Pipeline transfer losses [%]
$\delta\chi$	Electrical storage unit discharging losses [%]
ϵ	Electricity transfer losses [%]
ζ	Static thermal storage unit losses [%]
ζ_t	Piecewise linearisation x-axis sample point values [kW]
$f(\zeta_t)$	Piecewise linearisation y-axis sample point values [AUD]
η	Static electrical storage unit losses [%]
λ_a	Weighted-sum weighting factor for unavailability objective $\in [0; 1]$
λ_c	Weighted-sum weighting factor for cost objective $\in [0; 1]$

λ_e	Weighted-sum weighting factor for emissions objective $\in [0; 1]$
χ	Electrical storage unit charging losses [%]
ω	Ownership weighting factor $\in [0; 1]$
<hr/>	
Variables	
<hr/>	
A_i^{PV}	Installed PV capacity in house i [m ²]
a_t	Economies-of-scale relation sample points for piecewise linearisation, SOS-2 variables
$B_{con,i}$	Binary variable that decides on the installation of electrical system configuration con in house i
$B_{tech,i}$	Binary variable that decides on the installation of technology $tech$ in house i
$B_{tech,i}^{av}$	Binary variable that decides on the installation of an available technology $tech$ in house i
B^{CT}	Binary variable that determines if only central units are installed in the neighbourhood
B^{DC}	Binary variable that determines if only decentral DG and storage units are installed in the neighbourhood
B^{DCtech}	Binary variable that decides if decentral DG and storage units are installed in the neighbourhood
$C_{techct,energy}^{BUY}$	Total annualised cost of houses to purchase energy from central units [AUD y ⁻¹]
C^{CT}	Annual carbon tax imposed on the neighbourhood [AUD y ⁻¹]
C^{FUEL}	Annual fuel costs of technologies in the neighbourhood [AUD y ⁻¹]
C_{BUY}^{GRID}	Annual grid electricity import cost of the neighbourhood [AUD y ⁻¹]
C_{SAL}^{GRID}	Annual electricity export income of the neighbourhood [AUD y ⁻¹]
C^{INV}	Annualised investment cost of technologies and infrastructure in the neighbourhood [AUD y ⁻¹]
$C_{BUY,energy}^{MG}$	Total annualised cost of houses that purchase energy from other houses in the neighbourhood [AUD y ⁻¹]
$C_{SAL,energy}^{MG}$	Total annualised income of houses that sell energy to other houses in the neighbourhood [AUD y ⁻¹]
C^{OM}	Annual OM cost of neighbourhood technologies and infrastructure [AUD y ⁻¹]
C^{TOT}	Total annualised energy cost of the neighbourhood [AUD y ⁻¹]
$C^{TOT,S}$	Scaled total annualised energy cost of the neighbourhood [kAUD y ⁻¹]
$CHP_i^{A/B/C}$	Binary variables that decide on the installed capacity category of the CHP unit in house i
$DG_{tech,i}^{MAX}$	Total installed capacity of technology $tech$ in house i [kW or kWh]

EM	Annual CO ₂ emissions of the neighbourhood [kgCO ₂ y ⁻¹]
EM^S	Scaled annual CO ₂ emissions of the neighbourhood [tonCO ₂ y ⁻¹]
$ES_{i,s,h}^{STO}$	Energy stored in the battery of house i in hour h in season s [kWh]
GC_i	Binary variable that decides if house i has an available grid connection
$MGA_{i,k}$	Binary variable that decides if house i has an available microgrid connection with k microgrid available CHP units in houses j
$MGC_{i,j,s,h}$	Binary microgrid connection variable that decides if house i sends electricity to house j in hour h in season s
OH_i	Positive integer variable that indicates for each house i the visiting order in a pipeline network
$PC_{tech,i,s,h}^{Load}$	Cooling power for self use generated by technology $tech$ in house i in hour h in season s [kW]
$PC_{tech,i,s,h}^{Pipe}$	Cooling power for pipeline transfer generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PC_{tech,i,s,h}^{STO}$	Cooling power for storage unit charging generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PC_{tech,i,s,h}^{TOT}$	Total cooling power generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PE_{chpct,s,h}^{AC}$	Electrical power generated by central CHP unit to fuel the central AC unit in hour h in season s [kW]
$PE_{tech,i,s,h}^{CIRC}$	Electrical power circulated in the MG generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PE_{i,s,h}^{GRID}$	Electrical power received from the central grid by house i in hour h in season s [kW]
$PE_{chpct,i,s,h}^{LOSS}$	Electrical power MG transfer losses between the central CHP and house i in hour h of season s [kW]
$PE_{i,j,s,h}^{LOSS}$	Electrical power MG transfer losses between houses i and j in hour h of season s [kW]
$PE_{chpct,i,s,h}^{rec}$	Electrical power received by house i from the central CHP through the MG in hour h in season s [kW]
$PE_{i,j,s,h}^{rec}$	Electrical power received by house i from house j through the MG in hour h in season s [kW]
$PE_{MG,i,s,h}^{rec}$	Electrical power received from the MG by house i in hour h in season s [kW]
$PE_{chpct,s,h}^{SAL}$	Electrical power exported to the grid generated by the central CHP in hour h in season s [kW]
$PE_{tech,i,s,h}^{SAL}$	Electrical power exported to the grid generated by a DG unit $tech$ in house i in hour h in season s [kW]

$PE_{tech,i,s,h}^{SELF}$	Electrical power for self use generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PE_{chpct,i,s,h}^{snd}$	Electrical power send to house i by the central CHP in hour h in season s [kW]
$PE_{i,j,s,h}^{snd}$	Electrical power send from house i to house j through the MG in hour h in season s [kW]
$PE_{tech,i,s,h}^{STO}$	Electrical power for battery charging generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PE_{tech,i,s,h}^{TOT}$	Total electrical power generated by technology $tech$ in house i in hour h in season s [kW]
$PH_{tech,i,s,h}^{COOL}$	Heating power used for cooling purposes generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PH_{chpct,s,h}^{DIS}$	Heating power generated by central CHP unit $chpct$ and dissipated in hour h in season s [kW]
$PH_{tech,i,s,h}^{HEAT}$	Heating power used for heating purposes generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PH_{tech,i,s,h}^{Load}$	Heating power for self use generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PH_{CHP,i,s,h}^{Pipe}$	Heating power for pipeline transfer generated by CHP unit in house i in hour h in season s [kW]
$PH_{tech,i,s,h}^{Pipe}$	Heating power for pipeline transfer generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PH_{tech,i,s,h}^{STO}$	Heating power for storage unit charging generated by a DG unit $tech$ in house i in hour h in season s [kW]
$PH_{tech,i,s,h}^{TOT}$	Total heating power generated by technology $tech$ in house i in hour h in season s [kW]
$PS_{i,s,h}^{IN}$	Power inflow in the storage tank of house i in hour h in season s [kW]
$PS_{EST,i,s,h}^{IN}$	Power inflow in the battery of house i in hour h in season s [kW]
$PS_{i,s,h}^{OUT}$	Power outflow of the storage tank in house i in hour h in season s [kW]
$PS_{EST,i,s,h}^{OUT}$	Power outflow of the battery in house i in hour h in season s [kW]
$PS_{i,s,h}^{STO}$	Power stored in the storage tank of house i in hour h in season s [kW]
$QC_{acct,i,s,h}$	Cooling power transfer from central AC unit $acct$ to house i in hour h in season s [kW]
$QC_{i,j,s,h}$	Cooling power transfer from house i to house j in hour h in season s [kW]
$QC_{i,s,h}^{STO}$	Cooling power for storage in the CST of house i in hour h in season s [kW]

$QH_{chpct,i,s,h}$	Heating power transfer from central CHP unit $chpct$ to house i in hour h in season s [kW]
$QH_{i,j,s,h}$	Heating power transfer from house i to house j in hour h in season s [kW]
$QH_{i,s,h}^{LOAD}$	Heating power received by house i from pipeline transfer of houses j in hour h in season s [kW]
$QH_{chpct,i,s,h}^{LOSS}$	Heating power losses from transfer from central CHP unit $chpct$ to house i in hour h in season s [kW]
$QH_{i,s,h}^{LOSS}$	Heating power losses from transfer from houses j to house i in hour h in season s [kW]
$QH_{i,s,h}^{STO}$	Heating power for storage in the HST of house i in hour h in season s [kW]
UA_i	Electrical system unavailability of house i
$UA^{TOT,S}$	Scaled average house electrical system unavailability [\log_{10}]
$X_{i,s,h}^{rec}$	Binary variable that decides if house i receives electricity from the central grid in hour h of season s
$X_{chpct,s,h}^{snd}$	Binary variable that decides if the central CHP exports electricity to the central grid in hour h of season s
$X_{i,s,h}^{snd}$	Binary variable that decides if house i exports electricity to the central grid in hour h of season s
$Y_{i,k}^{chp}$	Binary variable that decides whether a number of CHP units (k) in the neighbourhood is microgrid-available to house i
$YC_{i,s,h}^{rec}$	Binary variable that decides if house i receives cooling from a pipeline in hour h of season s
$YC_{i,s,h}^{snd}$	Binary variable that decides if house i sends cooling to a pipeline in hour h of season s
$YH_{i,s,h}^{rec}$	Binary variable that decides if house i receives heat from a pipeline in hour h of season s
$YH_{i,s,h}^{snd}$	Binary variable that decides if house i sends heat to a pipeline in hour h of season s
$YP_{techct,i}$	Binary variable that decides on the installation of a uni-directional pipeline from central unit $techct$ to house i
$YP_{i,j}$	Binary variable that decides on the installation of a uni-directional pipeline from house i to house j
Z	Binary variable that decides on the installation of microgrid electrical sharing infrastructure in the neighbourhood

Chapter 1

Introduction and background

Central power systems still predominantly consist of large generators that provide electricity to a broad consumer base through extensive networks. This conventional top-down supply is being challenged by peak demand, energy losses, ageing infrastructure and climate change. Localised distributed energy systems (DES), consisting of various small-scale technologies, energy services and interactions at the consumer level, are increasingly presented as solutions to these challenges. However, for DES to become viable, a novel cross-disciplinary design approach is still required that encompasses multiple stakeholder interests. This thesis aims to address this need through developing a flexible multi-objective decision-making framework for DES design, from an engineering and regulatory perspective, using mathematical programming techniques. This first Chapter frames the modern DES concept and demonstrates the need for a new design approach by looking at the evolution of power systems over time (Section 1.1). Section 1.2 defines the current research and development status of DES. The researched problem, aims, solution approach and scope are detailed in Sections 1.3 to 1.5. Section 1.6, finally, presents an overview of the thesis.

1.1 Setting the stage for distributed energy systems

The development of electric power systems and their conventional structure, policy framework and challenges are detailed below. A new power system paradigm is subsequently introduced to alleviate conventional power system challenges.

1.1.1 Historical development of power systems

Electricity is an indispensable good for the industrial development of a country [1]. Nevertheless, the development of regional and national electricity systems in industrialised countries only dates back to the turn of the 20th century. Electricity (power) systems have here developed from small direct current (DC) grids, serving a local consumer base, to large centralised alternating current (AC) networks serving a wide region [1, 2].

Thomas Edison developed the first small lighting DC networks around 1900, where a small steam turbine generator served a limited local consumer base [1, 3]. About 500 of these isolated ‘micro-grids’ were installed, predominantly in the United States, Chile and Australia [1, 2]. Electricity subsequently gained increasing interest and applicability aiding industrialisation [1, 2]. The invention of the transformer in the late 19th century allowed to increase voltages, enabling long-distance AC electricity transport at reduced losses [1, 4, 5]. Growing demands of cities facilitated the upscaling of small isolated ‘micro-grids’. Additionally, system centralisation occurred, based on large central fossil fuel based power plants that moved away from cities [1, 5]. Locally managed ‘micro-grids’ were no longer applicable in these centralised – often national or regional – networks. The first central electricity systems were typically vertically integrated. One central party, often government, owned, operated and managed all four system activities of generation, transmission, distribution and retail [1, 2, 5], see Figure 1.1. The 20th century thus marked the transition from privately owned and operated ‘micro-grids’, established by competitive utilities¹, to large government controlled monopolies [1, 5]. This change in ownership and control accelerated the trend towards network centralisation, upscaling and the use of fossil fuels, such as oil, coal and gas, for electricity generation.

The fossil fuel crisis of the 1970s resulted in rising fuel prices and the realisation of the finiteness of fossil fuels. As a result, new energy generation technologies based on alternative energy resources, such as sun, wind and electricity-heat co-generation, started to appear to increase self-sufficiency and security of supply [1–3]. These new technologies were, however, still integrated within conventional network topologies (see

¹A *utility* is a company that provides a service, such as electricity, water or gas, to consumers. A utility can be publicly (government) or privately (commercial company) owned and can be set up as a monopoly or a competitive service. A *monopoly service* is a service, which is provided by a single utility without direct competitors that provide a similar service to consumers. A *competitive utility* is a service, which is provided by a utility with direct competitors that provide similar services to consumers. See for more information [1, 6].

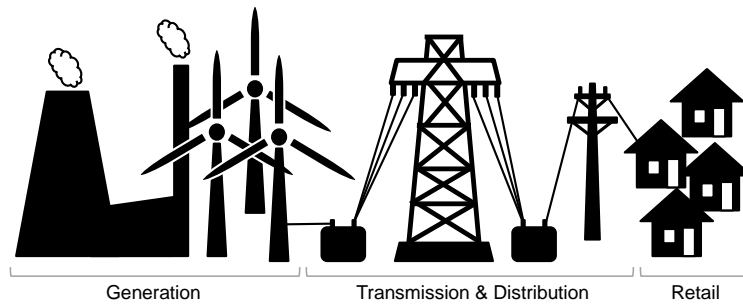


FIGURE 1.1: Schematic of conventional power system activities.

Section 1.1.2). Small independent power producers emerged throughout the United States and Europe, providing alternative energy supply at a smaller localised scale [1].

In the early 1980s, Chile initiated a global wave of liberalisation of vertically integrated monopoly power systems, based on a strong belief in market mechanisms to address the energy crisis [1, 7–9]. Markets namely allow many competitors to provide similar services to reduce prices of goods, increase system efficiency and attract new investment [1, 7–9]. Power system activities were here no longer vertically integrated but became structurally and legally unbundled separate entities governed by regulatory oversight and/or competition.² Energy policy in the first liberalised power systems was therefore mainly based around competition, security of supply and affordability (see Section 1.1.3).

In 1987, ‘*Our common future*’ – known as the Brundtland Report – was published by the World Commission on Environment and Development to address growing concerns about the climate and availability of fossil fuel based resources [10]. This report initiated the concept of sustainable development with regard to the environment, the economy and society. Sustainable development was herein defined as ‘*a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*’ [10]. The international Kyoto agreements of 1997 introduced an environmentally measured sustainability aspect to energy policy through binding emission reduction targets [11]. The most recent Paris climate conference (December 2015) bound its adopters to a global agreement to limit global warming to ‘well below 2°C’ [12]. Conventional liberalised power system energy policy therefore started to include environmental focusses, complementing competition and security of supply aspects.

²*Liberalisation* refers to the introduction of competition in power system activities. *Unbundling* is an aspect of liberalisation and refers to the legal and structural separation of the four power system activities that were previously vertically integrated. *Privatisation* refers to the transition from governmental to privately owned and operated system activities. See for further information [1, 7–9].

1.1.2 Conventional power systems

Conventional centralised electric power systems refer to top-down uni-directional electricity supply from large central generators down to a broad consumer base, see Figure 1.1. Electricity generation is herein still primarily based on fossil fuels, such as coal, gas and oil. Alternative energy resources, such as nuclear and renewables, are, however, increasingly being adopted [1, 13, 14]. Conventional fossil fuel based generators attain maximal primary energy conversion efficiencies of about 40% [1, 15]. Generated electricity is transformed to high voltages and transported over a central meshed long-distance high voltage (e.g. in the order of 500-220 kV and 132-66 kV) AC transmission network and local radial middle (e.g. 22-11 kV) and low (e.g. 230-240 V) voltage AC distribution networks to passive consumers who are served under retail contracts [13, 15]. Competition is typically introduced at the generation and retail level, while networks are established as natural monopolies since their duplication is not economically viable [1]. Thermal heating and cooling, in contrast, is conventionally generated at consumer premises through, for example, gas heaters, air-conditioning systems or central heating fuelled by, amongst others, natural gas, oil or electricity [16].

1.1.3 Energy system objectives

Power systems are governed by an energy policy. Energy policy is a strategy adopted by a governing body to develop its energy system [17, 18]. The adopted policy can be translated into, for example, national laws, international agreements, incentives and guidelines. Within liberalised power systems, currently, three interrelated objectives must be balanced to integrate and address the challenges these systems experience: competition, security of supply and sustainability [1, 18], see Figure 1.2. These three objectives are also defined by the World Energy Council ‘Energy Trilemma’ as energy equity, energy security and environmental sustainability, respectively [19]. Energy policies should simultaneously take into account these aspects in addressing power system challenges [19]. The three objectives are thus interconnected [19, 20]. Environmental targets and new technological developments can, for example, only be implemented if they are competitive with conventional supply. Competition is here key to opening up the market to new entrants and driving down prices. Furthermore, more market players,

affordable energy supply and resource diversification – resulting from environmental and competitive focusses – could also increase security of supply [20]. The European Union energy policy, for example, explicitly addresses these three aspects [17, 21, 22]. The three ‘policy pillars’ or energy system objectives can each be measured through indices.

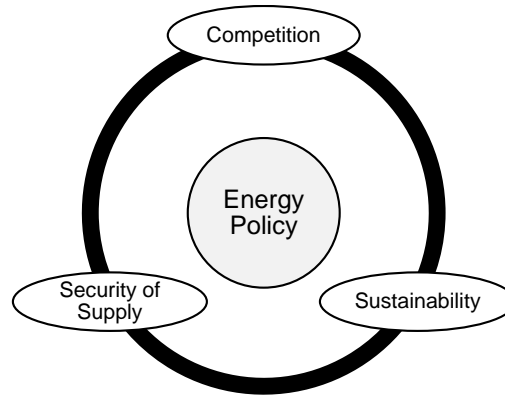


FIGURE 1.2: Energy policy pillars in liberalised power systems.

Competition refers to the strong belief that market mechanisms facilitate more innovative and attractive products and services to consumers, often leading to reduced prices (affordable), improved product quality and a levelled playing field for emerging technologies. Competition with respect to power systems refers to economic efficiency and affordability [1, 17–19]. Competitiveness can thus be measured through, amongst others, price signals, energy costs to consumers and economic viability of technologies.

Security of energy supply refers, amongst others, to dependability [1]. A dependable system allows trusting the services it is supposed to deliver without disruptions now and in the future [23, 24]. Security of power system supply can hence be determined through probabilistic or deterministic indices related to system up and down times [24, 25]. Additionally, security of supply can be measured through diversification of generation and primary energy resources portfolios, component redundancy and self-sufficiency.

Sustainability applies to the environmental impact of power systems. The European Union internal energy market initiated an explicit sustainability objective within its power system development with the *2020* targets [11, 26]. Sustainability relates here to and can be measured through, for example, a reduction in greenhouse gas emissions, an increase in renewable energy resources, an increase in primary energy efficiency or a reduction in fossil fuel dependency [10, 11, 17]. The *2020* targets established percentage reductions in each of these areas [11, 26].

1.1.4 New power system paradigm

Currently, power systems are designed to meet the demand of their designated consumer base. Residential consumers are here typically still passive receivers of electricity. Conventional systems, however, face multiple challenges related to cost effectiveness, sustainability and security of supply [27, 28];

First, central power system infrastructure is dimensioned based on peak consumer demand. Total system infrastructure cost contributes to retail electricity tariffs. In the National Electricity Market (NEM) of Australia, for example, about 20 to 30 % of the network capacity is used less than 90 hours per year [13, 29].³ Residential households in the NEM, furthermore, are responsible for about one third of the total yearly electricity consumption but for about two thirds of the peak demand, due to increased air-conditioning use on extreme hot days [13]. The need for generation capacity and network upgrades to facilitate peak demand events, combined with a stagnating average demand, is leading to increasing electricity tariffs and *costs* to consumers [13].

Second, central network infrastructure is ageing, requiring expensive upgrades to keep up with the increasing peak demand strain on the system [1, 13]. Additionally, low voltage distribution networks are currently responsible for over 90 % of end-consumer interruptions [30]. These both introduce *security of supply* issues to consumers.

Last, although continuing efforts are being made to reduce emissions in conventional systems through, amongst others, large scale wind power plants, generation is still predominantly fossil fuel based (need for dispatchable sources) resulting in greenhouse gas emissions [1, 15, 29]. Additionally, electricity transmission and distribution network losses amount to about 8% of transmitted energy [15]. Emissions and reduced energy efficiency are thus compromising *environmental sustainability* of power systems.

Residential consumers in the system are globally responsible for 30-40% of energy consumption in developed countries and contribute significantly to system peak demand [13, 27]. Furthermore, as passive agents, residential consumers are largely insensitive to price or demand signals [13, 29]. Incorporating new technologies into residential areas is thus often seen as a way to address the governing system challenges [28, 31, 32].

³Furthermore, in the State New South Wales, peak demand events occur less than 40 hours per year but are responsible for about 25 % of retail electricity bills [13, 29].

This, however, requires a redesign of conventional power system infrastructure and regulation [15]. Small-scale technologies located close to or at the premises of end-consumers in the grid (so called distributed energy resources (DER)) are one example of developments in the residential sector. DER comprise small-scale electrical and thermal energy generation and storage technologies (so-called distributed generation (DG) and storage units), local energy sharing, electric vehicles as well as novel demand side practices⁴, located at the consumer-side of meters rather than at a central level. Additionally, DER are able to exploit locally available renewable energy resources and increase energy system efficiency [31–36]. DER consequently enable active consumers that can engage in energy generation and sharing, becoming so-called ‘prosumers’ [28, 36–39]. DER are ideally combined into highly efficient energy integrated *microgrid* – or, more generally – *distributed energy system* (DES) environments that are tailored to location specific needs and local requirements. Adequate DES design is therefore required.

1.2 Distributed energy systems (DES)

Distributed energy systems (DES) and their key components (DER) are defined in Section 1.2.1. Additionally, an overview of current DES research and development is provided in Section 1.2.2 to shape the research problem.

1.2.1 DES as key concepts of future energy supply

The modern DES concept is not new in that it consists of local balancing of energy supply and demand, relating back to the initial ‘micro-grid’ development stage of conventional power systems (see Section 1.1.1) [2, 5]. Modern DES are, however, not always solely local providers of electricity, i.e. electrical DES/microgrids, but are also smart and flexible systems that provide additional services, such as heating, cooling and local energy sharing, to their consumers [28, 40–42]. No single definition exists, but modern microgrids, i.e. purely electrical DES, can be defined based on characteristics of the Consortium of Electric and Reliability Technology Solutions (CERTS) in 1998 as ‘*a cluster of micro-generators and storage with the ability to separate and isolate itself from the*

⁴Australian Government - Productivity Commission [13]: ‘*Demand side management involves using price and non-price measures to curtail customers’ use of electricity during peak demand periods, including shifting electricity usage to non-peak times.*’

utility seamlessly with little or no disruption of loads [40, 43]. Based on this definition, a microgrid is typically considered to be installed within a localised cluster of consumers with (i) locally controlled sources (generators), sinks (demands) and possibly storage, and (ii) either has a bi-directional connection with the central grid or is disconnected (i.e. in island) [5, 16, 28, 40–42, 44]. Other services are also increasingly integrated, introducing the broader concept of DES [15, 28, 40, 41]. In this work, the term ‘DES’ is used to refer to small-scale localised energy systems of a cluster of consumers that include various central and decentral DER, multiple energy services, local energy sharing and local balancing of demands through a control unit, see Figure 1.3 [15, 45]. The term ‘microgrid’ is sparingly used when referring to purely electricity based DES. DES are typically installed at the conventional distribution level, close to or at premises of consumers, and present themselves as single entities to the central grid through a point of common coupling [15, 28, 40, 41].

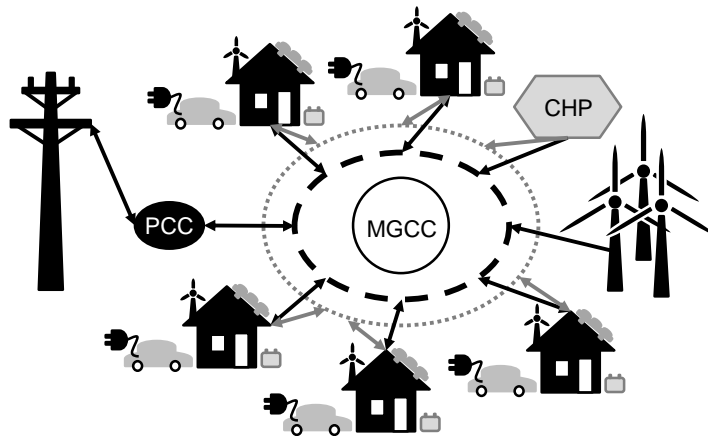


FIGURE 1.3: Schematic of a distributed energy system architecture. Several consumers with DER, a centralised wind farm and co-generation (CHP) unit are interconnected. The microgrid central control unit (MGCC) manages the local balancing and sharing of electricity (black arrows and dashed line), heating and cooling (grey arrows and dotted line). A grid connection occurs through a single point of common coupling (PCC).

Local energy generation in DES is provided through distributed generation units (DG) [5]. DG are small, modular and on-site dispatchable (based on a controllable primary energy resource) or intermittent (based on an uncontrollable primary energy resource) units [15, 31, 33, 35, 46]. They are generally limited in size, ranging from several kW to about 50 MW in installed capacity. Several DG capacity classifications exist that determine their registration requirement as central electricity market participants. The

NEM of Australia, for example, classifies DG units as in Table 1.1 [47]. In a residential setting, DG units typically range from 1 to 10 kW (micro/mini) [15, 28, 31].

TABLE 1.1: Classification of DG units in the National Electricity Market of Australia, adapted from the Australian Energy Market Operator [47]. ϕ =power phases.

Classification	Technical definition	Typical installation
Micro	≤ 2 kW and connect to LV network	Roof top solar PV
Mini	2 - 10 kW (1ϕ) or 30 kW (3ϕ)	Fuel cells; combined heat and power systems
Small	10 kW (1ϕ) or 30 kW (3ϕ) to 1 MW	Biomass, small hydro
Medium	1 - 5 MW	Biomass, hydro, local wind generating units
Large	≥ 5 MW	Co-generation, hydro, solar thermal, wind

DES are designed to exploit full distributed energy resource (DER) potential [45]. DES are, however, highly location specific in terms of design and operational characteristics since they are framed by climate, economical conditions and governing regulatory environment [48]. Integrating DES in conventional distribution networks therefore leads to potential advantages and disadvantages [5, 31–33, 35, 49, 50].

Technical benefits mostly relate to security of energy supply. DES can be highly dependable through energy resource diversification, active redundancy, parallel grid operation, and through providing uninterrupted power supply and various reliability level services to consumers [16, 40–42, 45].⁵ Furthermore, if authorised to do so, DES can operate in electrical island mode, i.e. disconnected from the central network in case of central system outages [45]. Additionally, DES could provide electrical ancillary services⁶ to the central system, such as black start capability [5, 15, 31–33, 35, 37, 50].

Economic benefits relate to the competitiveness of DES with respect to conventional power systems. DES can decrease electrical network losses due to smaller scales and the absence of long-distance transmission networks [5, 15, 31–33, 35, 50]. Furthermore, fuel costs can be reduced due to increased energy generation efficiency through, for example, electricity-heat co-generation [5, 15, 31–33, 35, 50]. Additionally, DES are tailored to local requirements. This reduces the need for peak power plants in the central system

⁵*Diversification* refers to increasing the variety of primary energy resources used for energy generation rather than relying on a single source like, for example, natural gas. *Redundancy* refers to implementing components that are on stand-by to supplement units that fail in order to maintain energy supply to consumers. Components can be in hot (active) or cold redundancy. The latter need a start-up period once required to step in to maintain generation. The former are ready to operate when required. See for more information [23, 25, 51–56].

⁶*Ancillary services* are defined by, for example, the US Federal Energy Regulatory Commission as: ‘services necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system’ [57]. *Black start capability* helps restarting the central power system after an outage.

and allows for appropriate selection, sizing and siting of DER to balance and coordinate local demand and supply [44, 58]. Moreover, central electricity network upgrades can be deferred through smaller infrastructural scale DES installations to accommodate for increasing demand [5, 15, 32, 39, 45, 59]. Especially in end-of-line (remote) communities this could lead to significant cost savings.

Environmental benefits relate to sustainability. DES are tailored to location specific requirements and can thus exploit locally available renewable energy resources, such as sun and wind, reducing greenhouse gas emissions [5, 32, 59]. Co-generation DES have an energy integrated design where local electricity generation is complemented by the use of waste heat from the electricity generation process for local heating and cooling purposes [5, 16, 34, 40–42, 45, 49, 60]. This increases overall generation efficiency from about 40 % for large central generators to about 90 % for co-generation [5, 34, 49].

Social benefits to consumers arise from increased choice of energy supply alternatives and increased self-sufficiency through reducing dependency on the central system [5, 32, 59]. Additionally, DES provide more *flexibility* in terms of generation portfolio and fuel mix, balancing of energy demands, introducing new technologies, adapting to changing consumer needs and optimising the local balance of supply and demand [5, 31–33, 35].

Introducing DER within distribution networks is, however, not what conventional top-down networks are designed for [15, 45]. DER introduce bi-directional power flows by not only importing from but, additionally, exporting to the central grid. This may lead to operational safety challenges, power quality issues and local energy sharing problems, requiring appropriate connection and operational standards [15, 45]. Additionally, DER move generation from central to urban levels, which might increase local pollution and noise levels in urban areas. This could require changing operational, emission and design standards for DER as well as hinder the willingness to adopt DER by consumers.

1.2.2 DES research and development

DES are starting to become technically and economically feasible but research on several levels is still required to enable their widespread implementation as detailed below.

1.2.2.1 DES globally

In contrast with DER, such as solar photovoltaic (PV) units, DES have not yet emerged on a large scale [61]. Their global uptake is, however, expected to follow a similar upward trend [62]. Currently, established DES are mainly electricity based (i.e. microgrids) and used as off-grid systems, rural electrification programs, high reliability systems, military or university campus systems, or, trial-systems [48, 61, 63–65]. On-grid electrical DES with seamless islanding capabilities still experience challenges regarding protection systems, islanding procedures, authorisation and regulation [61]. Most conventional power systems, namely, restrict bi-directional interactions and do not authorise islanding but require disconnection in case of central system outages.

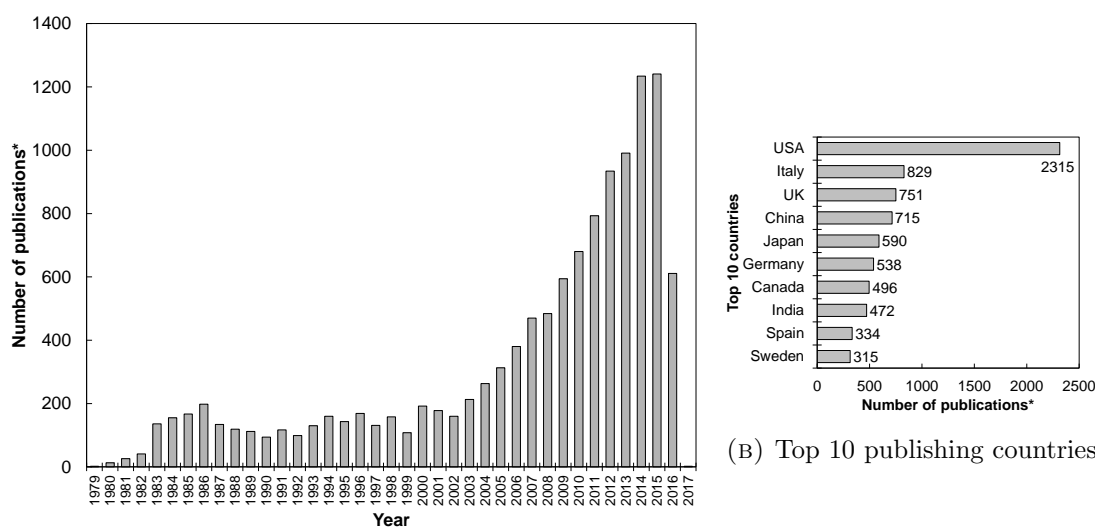
In 2012, the total global installed electrical DES capacity was estimated to 3.2 MW, of which the majority (66%) was located in the United States, followed by Europe (12%) and Asia Pacific (8%) [62, 63]. Major developments have been made within North America, Asia, the European Union and Australia [48, 63–65]. The IMAGINE Consortium of the Lawrence Berkeley National Laboratory produces regular reports regarding global DES development [16, 48].

Electrical DES development in the European Union was initiated in 1998 with the ‘More Microgrid’ project led by the National University of Athens in Greece with a pilot project on Kythnos Island [66]. Japan, furthermore, shows a great interest in co-generation to increase energy supply dependability due to earth quake risk and to increase energy efficiency [67].⁷ North America has various military and campus based electrical DES, as well as the CERTS microgrid test facility [16, 48]. In Australia, remote communities necessitate the need for (end-of-line) electrical DES to complement or substitute central network connections [13]. Moreover, interest in seasonal tri-generation DES is increasing to employ waste heat for both heating and cooling requirements in community energy projects [47, 69]. DES are thus increasingly being considered but still require research on various levels.

⁷The Sendai microgrid, for example, has a power supply with different levels of reliability for on-site consumers and proved its islanding capability in the wake of the Fukushima Daiichi nuclear disaster in March 2011 [68].

1.2.2.2 DES research

DES have been researched since the 1980s but specifically within the last five to ten years, as shown in Figure 1.4.⁸ The work of Lasseter, published in 2002, forms the basis of electrical DES research with the formulation of the CERTS microgrid concept [40]. DES research is predominantly being conducted in three (partially overlapping) research areas: technology, economics and regulation, see Figure 1.5, with a main technological and economic focus [5, 34, 38, 49, 65].



(A) DES research in Scopus

(B) Top 10 publishing countries

FIGURE 1.4: Number of publications* per year in the Scopus search engine with the search term combination as in Appendix A on 14 July 2016 (left). Number of publications per country (top 10) (right). *Note that publications refer to English publications.

Technological research looks at the development, adequacy and feasibility of DER technologies and their integration within DES or central power systems [5, 34, 38, 40, 49, 65]. DES design on various levels is here an important topic;

(i) Detailed electrical DES design encompasses the interactions that arise from installing DER within conventional networks, such as bi-directional active and reactive power flows, protection systems, optimal component placement, losses, power quality, islanding procedures, and voltage and frequency control [70–73]. This has led to the development

⁸Number of publications per year in the Scopus search engine with the search term combination as in Appendix A on 14 July 2016. Note that publications refer to peer-reviewed English journal/conference articles/reviews (in press).

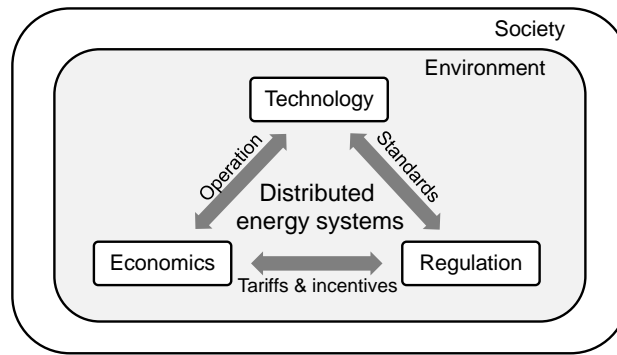


FIGURE 1.5: Distributed energy systems research areas.

of standardised test systems, and implementation and operational schemes.⁹ Electrical design also involves smart grid design, including communication technologies for energy management and operational optimisation [15, 75, 76].

(ii) When waste heat is employed for heating and cooling purposes, detailed thermodynamic design of district thermal networks is required, including pipeline transfers, mass balances, losses, temperatures, pressure drops and pumping requirements [77–79].

(iii) Superstructure DES design, in contrast, looks at components as black boxes, characterised by parameters [34, 80–82]. Components can here interact with each other through power or energy flows rather than detailed electrical and thermodynamic interactions.

Real-time energy management and control schemes that ensure safe system operation (both on- and off-grid) are also important aspects of technological research [83–85]. Here adequate communication, controller and metering technologies are researched. Operational decisions and local energy management schemes relate to *economic research* aspects [34, 38, 44, 49, 50, 86–88]. Internal DES interactions and operation, as well as interactions with the central infrastructure, can be analysed based on game-theoretic models and bidding strategies. Cost effective DES design is another area of research based on the selection, siting, sizing and interactions of DER. Cost-benefit analyses have also been conducted to determine the cost and benefits to utilities and consumers from the integration of DER into the central system. Economic research, in summary, aims to level the playing field for DES within conventional power systems.

⁹The Roy Billinton Test System is such a standardised test system. The fundamental microgrid standard is IEEE Std P1547.4 Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems [64, 65, 74]. In contrast with earlier distributed energy resource standards (eg. 1547.1), 1547.4 accommodates islanding of microgrids and distributed generation units. IEEE also formulates standards regarding *inter alia* smart metering.

Regulatory research regards the development of a regulatory framework for DES [15, 39, 40, 42, 44, 48, 49, 65, 89]. A regulatory framework refers to a set of principles, rules and incentives to sustain and establish adequate operational structures [15]. Operational structures can refer to technology and DES development standards, grid-connection requirements, islanding procedures, metering and protection schemes.

The three above research areas are all framed by environmental and social aspects. *Environmental aspects* relate to efficiency of technologies (technical), tax and support schemes for DER (economics), and emission targets and governmental policies (regulation) [59]. *Social aspects*, lastly, refer to consumer benefits and participation [61].

DES are increasingly becoming technologically and economically viable. Required regulation and social research aspects, however, still lag behind [2, 16, 28, 45, 49]. To exploit DES benefits to the fullest, they require a multi-faceted system design that balances location-specific needs and stakeholder interests [45]. DES design refers here to appropriate DER selection and siting (synthesis), DER sizing combined with local energy sharing infrastructure planning (design) as well as component interactions [15, 90, 91]. Frameworks for DES design are thus important decision-making tools [82].

1.3 Problem statement: the need for a new design method

DES design is a complex decision-making problem [15, 91]. The specific energy system requirements, design objectives, disciplines, technologies, interactions and constraints will impact the problem and the decision-making process [91]. DES design projects must therefore, on the one hand, be economically attractive, and on the other hand, take into account the needs of the various involved multi-disciplinary stakeholders, such as regulators, engineers, economists, designers, consumers and local government [91, 92]. Adequate DES design frameworks consequently comprise multiple readily quantifiable and less quantifiable aspects [15, 58, 82, 93, 94], see Figure 1.6.

The researched *consumer area* characterises energy demand behaviour and required energy services, such as electricity, heat and/or cooling. The researched *location* determines system boundaries through, amongst others, available renewable resources (e.g.

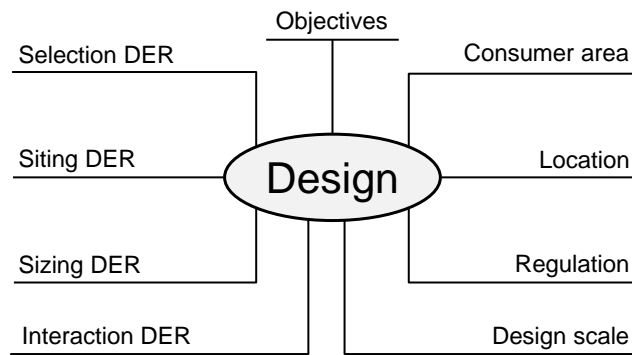


FIGURE 1.6: Energy system design aspects. DER=distributed energy resources.

sun and wind), demand profiles, restrictions on installed DG capacity and potential governmental support schemes in the market. Furthermore, various DER can be considered throughout the design process. The *selected* pool of DER must be matched with the selected consumer area and location. Locally available renewable energy resources, for example, will determine the attractiveness of certain DG units. Optimal balancing of local generation and demand through local energy sharing (energy integration), furthermore, facilitates DG *size* reduction compared with conventional systems. In conventional power systems units, such as boilers, are namely often oversized due to inappropriate balancing of household heat demands [58]. Dimensioning for a cluster of houses rather than for individual houses, in contrast, could allow for more efficient DER operation.

Energy integrated DES, additionally, allow for both multiple energy services (electricity, heating and/or cooling) to be met through a single system to the consumer area, and for the integration of differentiated DER. Hence, *siting* of DER at appropriate locations in the system as well as the level and type of considered energy *interactions* are important DES design decisions. The *depth of DES design* refers either to detailed electrical and/or thermodynamic aspects that enable project development and implementation. Superstructure design, in contrast, enables analysing the integration of multi-disciplinary design aspects and facilitates decision-making. DES decision-making processes therefore enable balancing multiple stakeholder interests that can be translated into multiple design *objectives* [82]. Although energy integrated DES design provides added benefits to neighbourhoods as a whole, individual houses might prefer self-control and not opt into a DES arrangement. Property ownership, high upfront investment costs of infrastructure and individual versus collective benefits, give rise to issues regarding, amongst others, infrastructure ownership and contractual agreements between DES consumers

or between a DES and a third party. DES thus also require appropriately designed and standardised *regulatory* and organisational frameworks.

DES design research has to date mostly looked into isolated design aspects [94]. Regulatory framework aspects – important for policy relevance of design – are especially lagging behind [2, 16, 28, 45, 49]. Strategic DES design is therefore required to attain their benefits; both in terms of readily quantifiable engineering techno-economic and environmental aspects as well as less quantifiable regulatory aspects. A novel DES design method is thus required for bi-directional design and regulatory decision-making.

1.4 Aim and research questions

To alleviate conventional power system challenges through DES and to enable widespread DES implementation, a comprehensive DES design approach is required that encompasses engineering, economic, environmental as well as regulatory aspects. Driven by this need for a new DES design approach, this thesis aims to develop a flexible multi-objective decision-making framework for residential DES design, from an engineering and regulatory perspective, using mathematical programming techniques. A superstructure optimisation approach is adopted that is aligned with the three central energy system objectives (see Section 1.1.3). The developed method provides a framework for design engineers and decision-makers to assess policy relevant design aspects while incorporating consumer preferences. The following research questions are addressed in this thesis:

1. *What is the current status of DES design optimisation?* A review of modelling approaches is conducted to both identify DES design model characteristics as well as the research gap addressed in this thesis.
2. *How can DES be techno-economically designed with cost as driving objective?* A superstructure mixed-integer linear (MILP) optimisation approach is developed for the design of an energy integrated residential DES while minimising total annualised energy cost (competition), building further on the work of Mehleri et al. [95, 96] (see Section 4.2.4). This approach facilitates levelling the playing field for DES as competitive energy supply alternatives within conventional power systems.

3. *How can DES be techno-economically designed whilst balancing multiple stakeholder interests?* The developed MILP model is extended to a multi-objective framework, which enables trading off three objectives in the design process. The three central energy system objectives of competition, security of supply and sustainability are translated into DES design objectives. This design framework ensures DES applicability within the conventional system and its relevance to governing energy policy.
4. *How can DES regulatory and organisational aspects be integrated and assessed within design optimisation frameworks?* The developed MILP optimisation model is employed to analyse DES regulatory aspects through identifying quantifiable relations between design, organisation and regulation of DES, enabling regulatory decision-making.

1.5 Scope

The developed framework is first and foremost a design decision-making tool for residential DES and is not intended to provide practical implementation or operational strategies. DES design is analysed as a system of black-box components (technologies) with interactions on a superstructure scale with respect to several objectives. Mathematical programming techniques are here employed as a tool to facilitate decision-making. An energy integrated residential neighbourhood is under research, in terms of electricity, heating and cooling, with a particular focus on the electrical system. Design aspects that fall beyond the scope of research are detailed below.

1.5.1 Design detail

Practical implementation and operation of DES requires detailed analysis of both thermodynamic [77–79] and electrical [70–73] behaviour as detailed in Section 1.2.2.2. This thesis does not consider the above detailed design aspects. Detailed aspects are either simplified and integrated into the developed superstructure optimisation model, or, beyond the scope of analysis. A black-box approach is used for all considered technologies

and interactions. This implies that a certain power or energy input is transformed in an output through constant efficiency, conversion and loss parameters.

Additionally, the presented methodology does not provide a business model for the deployment and cost effectiveness of DES. Although a techno-economic modelling approach is presented, detailed economic analysis, including payback times of investment, is beyond the scope of this work. Furthermore, other economic issues, such as game-theory, real-time agent based internal DES market operation, trading, unit commitment problems or DES participation in central electricity markets, are not considered (see [86, 97, 98]). Economic viability of DER aggregator schemes is also not addressed.

No environmental impact life cycle analysis of DES is conducted. Water usage, upstream sectors (e.g. the natural gas market) and carbon footprints related to the manufacturing of DER fall beyond the scope of research. Environmental aspects are, however, included in the form of, amongst others, carbon intensities and related emissions of central grid electricity and natural gas usage.

Implementation of DES requires a regulatory framework. Although aspects of regulatory frameworks for DES are analysed, detailed regulatory framework and tariff design, total benefit sharing between stakeholders and remuneration schemes are not addressed [39, 99]. Furthermore, social acceptance of DER is not explicitly considered. Neither are activities, such as demand side management, time of use tariffs, payback schemes and smart metering [97, 99, 100]. These activities are only mentioned where relevant.

The system boundaries are determined by the neighbourhood, which receives inputs from other sectors (gas, water and electricity) and exports outputs to the central power system. Gas and electricity supply are considered available but detailed analysis of their supply chain is beyond the scope of this work. The developed framework focusses on DES design, not operational optimisation. Operational interactions and technology dispatch are, however, optimised under given demand profiles.

1.5.2 Technologies

Considered technologies and energy interactions are selected based on a rational choice of potential, cost-effectiveness, suitability to DES design and their ability to generate

energy with low carbon emissions. As such, less developed technologies, such as tidal, geothermal, and carbon capture and storage, are not considered. Electricity storage is only researched where relevant but the potential of its widespread adoption is not researched. Furthermore, electrical vehicles and other means of transportation are not touched upon since moveable DER are not included in the initial design approach.

1.5.3 Definitions and terminology

Several terms are used throughout literature to describe DER systems [81, 82, 94, 101–105]. Poly-generation units, for example, refer to small-scale energy generation units based on several (poly) energy resources. A ‘distributed energy system’ (DES) or ‘multi-energy system’ refers to a system that combines several DER and multiple energy services (electricity, heating and/or cooling) into one whole. A ‘microgrid’, in contrast, refers to a DES that predominantly provides electrical services. ‘Microgrid operation’, lastly, is used in this thesis as the local sharing of electricity between DES participants.

1.6 Outline

The remainder of the thesis is divided into six Chapters. Chapter 2 addresses the first research question in providing an overview of methods, tools and techniques for DES design optimisation. Several categories to classify previous methods are discussed and the research gap addressed is detailed.

Chapter 3 details the employed methodology and its conceptual framework. The required inputs, considered technologies, design aspects and model outputs are described. Additionally, an overview of the neighbourhood design and interaction alternatives is presented together with the system boundaries. The employed optimisation tool and technique are detailed with respect to three objectives (financial, technical and environmental), aligned with the central energy system objectives (competition, security of supply and sustainability), and regulatory framework aspects.

The second research question is addressed in Chapter 4. A framework for DES design of a small residential neighbourhood is developed as single-objective MILP model. Total

annualised energy cost of a neighbourhood as a whole is minimised while meeting its yearly electricity, space heating and space cooling demands.

Chapter 5 addresses the third research question in extending the developed model in Chapter 4 to a multi-objective framework. Total annualised cost is traded off with two other objectives; electrical system unavailability minimisation (technical/security of supply) and annual CO₂ emission minimisation (environmental/sustainability). This allows for a design that fits in with central energy system objectives.

The fourth research question is addressed in Chapter 6. Regulation relevant to residential DES is introduced. The developed framework in Chapter 4 is extended to include interactions between engineering and regulatory aspects, facilitating decision-making discussions and policy relevance of ‘optimal’ residential DES designs.

Chapter 7, finally, summarises the main contributions of the thesis and provides suggestions for future work.

Chapter 2

Planning and design of distributed energy systems

Modelling distributed energy systems (DES) helps to understand their behaviour and facilitates forecasting, development and design decision-making [82, 106]. Mathematical programming techniques have proven to be suitable tools to assess ‘best’ DES designs constrained by location-specific parameters. This Chapter provides background on mathematical modelling and optimisation and its application to DES design. Previous DES design research is analysed and categorised to identify research gaps and shape the research questions addressed. Section 2.1 introduces system modelling and optimisation as tools to analyse DES design. Optimisation tools and techniques are subsequently reviewed in Section 2.2. An overview of key DES design optimisation research aspects is then presented in Section 2.3. Section 2.4 identifies important research gaps in the field. Section 2.5, finally, concludes this Chapter.

2.1 Mathematical modelling

Model building involves looking at a system and its components by analysing it through an abstract representation [82, 107]. Abstract representations employ mathematical relationships, such as (in)equalities and logical dependencies, to represent the internal relations and structure of a system [107, 108]. To make models applicable to multiple similar systems, they are focussed on system components, relations and structure rather

than inputs [82, 106–108]. Assumptions and simplifications of reality are hence required to (i) reduce the amount of detailed information and cost required to ‘exactly’ model a real system, and (ii) to increase the general applicability of the model [82].

DES design problems are inherently complex and large combinatorial problems. They not only involve multiple alternative configurations and design constraints but also uncertainties related to model design, model analysis and interpretation of results [91]. Modelling DES hence requires balancing complexity, accuracy and model robustness [92]. DES design is an integrated interdisciplinary problem, involving temporal and spatial scales, large numbers of input data, multiple energy resources, technologies and energy interactions, and the consideration of multiple (often conflicting) design objectives [82, 91, 105, 106, 109]. Mathematical programming provides here an appropriate tool to incorporate all the above aspects in identifying ‘optimal’ DES design [91, 105, 110]. Optimisation refers to a group of mathematical techniques that try to obtain the ‘optimal’ or ‘best’ available decision(s)/solution(s) towards a stated minimisation or maximisation objective within a feasible domain determined by constraints [107, 108, 110]. Optimisation requires identifying objectives, decision variables (unknowns), parameters (knowns) and constraints that apply to the system [91, 110]. This is in contrast with simulation approaches where actual behaviour of a system is analysed through a descriptive output by imitating the real system [82].

2.2 Background on mathematical optimisation

Optimisation has received increasing attention for design problems due to developments in computational power and solution tools [82]. The choice of model and optimisation approach depends on the nature of the problem [91]. The following Sections review optimisation models (Section 2.2.1) and solution methods (Section 2.2.2).

2.2.1 Model classification

Optimisation models can be classified based on their type of variables, (non)linearity, convexity or objectives, as detailed below [107, 108, 111, 112].

2.2.1.1 Model classification based on variable type and (non)linearity

Variables can be defined as continuous, i.e. able to take on any real value within a specified continuous interval. Discrete variables, in contrast, can take on a value from a finite set of specified values, often integers. Discrete variables that can only take on either the value 0 or 1, are binary variables. Models with only continuous variables are continuous problems and models with only discrete variables are discrete problems [107, 108, 111, 112]. Models that have both variable types are mixed-integer problems. The combination of both discrete and continuous variables allows for both selection (binary) and operational (continuous) decisions [107, 108, 111, 112].

Non-linear relations (y) between variables (x, z) lead to non-linear models (e.g. $y = x \cdot z$). A problem with only linear relations between variables is a linear model (e.g. $y = x + z$) [107, 111]. The most commonly employed problem types¹ are (i) problems with only continuous variables that can either be linear programming (LP) or non-linear programming (NLP) problems, (ii) problems with both continuous and discrete variables (mixed-integer programming (MIP)) that can be either linear (MILP) or non-linear (MINLP), and (iii) problems with only integer variables, i.e. integer programming (IP) [107, 108, 111, 112]. A general MIP model is represented by Equation 2.1 [111]. The objective Z , function of variables x and y ($f(x, y)$), is minimised subject to either linear (MILP) or non-linear (MINLP) equality ($h(x, y)$) and inequality ($g(x, y)$) constraints with x continuous and y binary variables:

$$\min_{x,y} Z = f(x, y) \text{ s.t. } \begin{cases} h(x, y) = 0 \\ g(x, y) \leq 0 \\ x \in X, y \in \{0, 1\} \end{cases} \quad (2.1)$$

2.2.1.2 Model classification based on convexity

A second model classification can be based on convexity. The function $f(x)$ is convex over $x \in X$, see Figure 2.1b, for any pair of solutions x_1 and x_2 , if any point between the solution pair based on a weighting factor $\lambda \in [0, 1]$ ($\lambda \cdot x_1 + (1 - \lambda) \cdot x_2$) has a function value

¹Other model sub-types can also be classified within, for example LP and NLP, as complementary programming (LCP) and quadratic programming (QP), respectively [111].

$(f(\lambda \cdot x_1 + (1-\lambda) \cdot x_2))$ smaller or equal to the equivalent point between the function values of the solution pair based on the same weighting factor $(\lambda \cdot f(x_1) + (1-\lambda) \cdot f(x_2))$ [108, 113]:

$$f(\lambda x_1 + (1 - \lambda)x_2) \leq \lambda f(x_1) + (1 - \lambda)f(x_2) \quad (2.2)$$

A convex problem has a convex feasible region [108]. Linear models are inherently convex. For strictly convex models, a single optimum solution, i.e. global optimality, exists and is attainable [107, 108, 111]. Non-linear models, in contrast, can have convex or non-convex relaxations [108]. Non-convex problems present the risk of reaching a local optimum/solution and not attaining the global [107, 108, 111], see Figure 2.1a. Non-convex problems thus require more elaborate solution procedures to potentially attain global optimality.

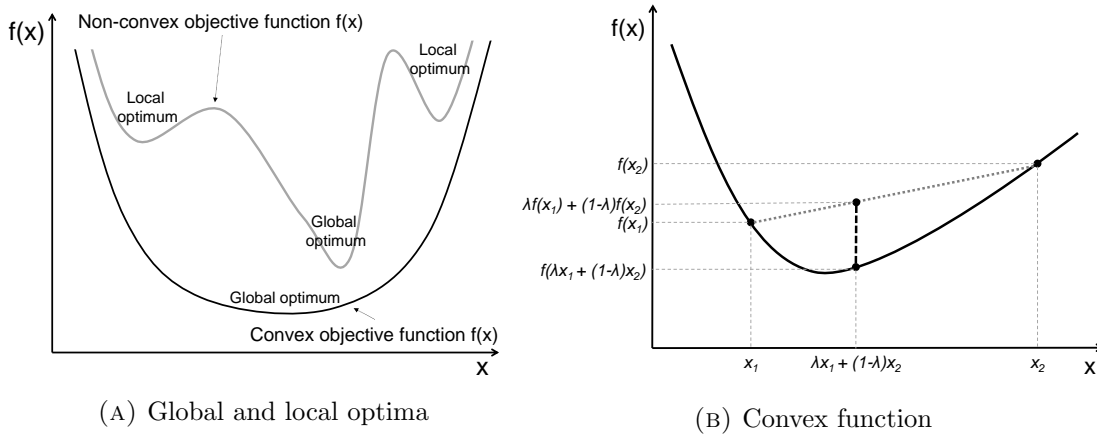


FIGURE 2.1: Illustration of a convex and non-convex objective function with respective global and local optima (left), and convexity of a function (right), adapted from Deb [113] and Floudas [108].

2.2.1.3 Model classification based on type of input data

The type of input data determines whether the problem is deterministic or stochastic [107, 108, 111, 112]. Deterministic problems assume that input parameters are accurately known. Uncertainty surrounding these fixed-value inputs, however, can impact results. Uncertainty arises due to the prediction or choice of a single value from a changing interval. Stochastic optimisation, also termed ‘optimisation under uncertainty’, takes into account this parameter uncertainty. Here random generated values or probability density functions can be employed, leading to a solution that satisfies a range of inputs.

2.2.1.4 Model classification based on number of objectives

Most design problems are inherently multi-objective. Determining the ‘optimal’ solution then requires a trade-off between multiple (often conflicting) objectives f_i with $i \in [1; n]$ [92, 107, 108, 111]:

$$\min_{x,y} Z = [f_1(x, y); f_2(x, y); \dots f_n(x, y)] \text{ s.t. } \begin{cases} h(x, y) = 0 \\ g(x, y) \leq 0 \\ x \in X, y \in 0, 1 \end{cases} \quad (2.3)$$

In contrast with single-objective problems, multi-objective problems do not lead to a single optimal solution but rather to a set of optimal solutions [92, 113]. Multi-objective problems aim at constructing a so-called Pareto trade-off curve of non-dominated solutions between objectives, or, a discrete set of solutions on the curve, a Pareto set. A solution is non-dominated and belongs to the Pareto set of a problem if it cannot be ameliorated with respect to one objective without worsening in another objective [92, 113]. Pareto solutions should be selected based on accuracy (non-dominated solutions), diversity (diversely across the front) and spread (capture points on the whole curve, including extremes) [92, 113]. The ‘best’ trade-off between multiple objectives is a subjective decision [92, 113]. The ‘best’ point will often be at a ‘knee-point’ where a bigger return on an objective is achieved before the ‘knee’ than after [114]. The Pareto concepts are illustrated in Figure 2.2. A Pareto set is constructed between extreme solutions that are obtained through the optimisation of only one objective at a time.

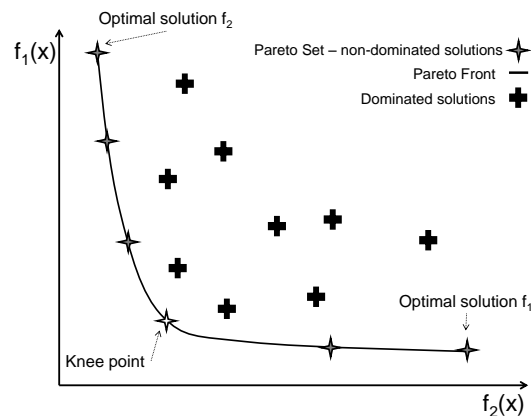


FIGURE 2.2: Pareto trade-off between two objectives ($f_1(x)$, $f_2(x)$) including a Pareto front and set of non-dominated solutions, adapted from Alarcon-Rodriguez et al. [92].

2.2.2 Solution tools and techniques

After model development, an appropriate optimisation tool and software has to be selected. Optimisation software, such as GAMS [115] or AMPL [116], is used to symbolically formulate the problem and analyse solutions based on a set of inputs. Most software have access to various solvers that each use a certain solution method [117]. Solution methods are generally subdivided based on deterministic versus stochastic approaches as detailed in the following Sections [82, 108, 111, 118]. Table 2.1 presents their strengths and weaknesses. Solution approaches for multi-objective problems, in particular, also follow this division with appropriate methods, see Section 2.2.2.3.

TABLE 2.1: Strengths (+) and weaknesses (-) of solution methods to optimisation problems, based on [82, 108, 111, 118].

Solution method		Strengths (+) and weaknesses (-)
Deterministic	Linear	<ul style="list-style-type: none"> + can handle complex problems with large number of variables and constraints + efficient optimisation of large problems through exploitation of binary structure (branch and bound) to global optimality if all nodes are searched (see Section 3.2.1 and Appendix C) - uncertainty of parameters is not accounted for, can be through sensitivity analysis - linearisation and simplification of system behaviour required that can lead to loss of model accuracy - computational time can increase exponentially with number of binary variables (MILP); problem reformulation or cutting plane methods (LP relaxation) can here help to obtain solutions
	Non-linear	<ul style="list-style-type: none"> + efficient optimisation through exploitation of binary structure (branch and bound) + larger flexibility to deal with different problems and their non-linear behaviour - uncertainty of parameters is not accounted for, can be through sensitivity analysis - no guarantee of attaining global optimality and the obtained solution (local/global) can depend on choice of starting point - not appropriate (time and money) for problems with large number of variables and constraints
Stochastic		<ul style="list-style-type: none"> + uncertainty of key input parameters taken into account through probability density functions + readily implementable methods + produce good quality sub-optimal/approximate solutions and may avoid getting stuck in inferior local optima - system modelling not always translatable to recurring moves, required for stochastic solution methods - difficulty handling complex constrained problems - not always rigorous in obtaining global optimal solutions, which is only guaranteed at infinite time. Parallel computing can be used to obtain good solutions within reduced times.

2.2.2.1 Deterministic solution methods

Deterministic approaches are traditionally based on direct search approaches, gradients and differentiable functions [82, 91, 108, 111, 118]. Multiple well-developed solution methods for linear programs exist that can deal with complex problems with millions of variables and constraints [111]. One of the more common and powerful deterministic approaches to solve linear problems (LP) in a finite number of steps is the Simplex method [119]. Other methods include the interior point method [111]. MILP solution methods mostly use a branch and bound based tree-search method (see Appendix C) [120]. The branch and bound method constructs a tree based on binary variables, which systematically branches the problem out in sub-problems with a solution based on a combination of binary variable values [108]. Other methods are the Cutting Plane and Decomposition methods [108, 111]. The Cutting Plane method introduces new constraints (cuts), rather than sub-problems, to reduce the feasible region until optimality is reached [108]. Decomposition methods utilise partitioning of the feasible region into subdivisions, duality concepts and relaxation to exploit the inherent mathematical structure of the problem [108]. CPLEX and GUROBI are common solvers for MILP problems [112].

Deterministic methods for non-linear models include algorithms based on Newton steps requiring multiple iterations, including active set and barrier/interior point methods, second-order information exploitation through automatic differentiation tools, and linear versus trust region methods to enhance convergence depending on starting points [111]. Solution methods for MINLP include the Generalised Benders Decomposition [121] and the Outer Approximation method [122] [108]. Both methods exploit the model structure through an iterative process and a branch and bound based approach. Popular (MI)NLP solvers are ALPHA-ECP, ANTIGONE, BARON, DICOPT and SBB [112].

Other developments in deterministic approaches also employ non-gradient techniques ('derivative free' optimisation) that included steps to reflect, expand and contract the solution space (see, for example, Kelley [123]). The termination criteria of derivative free optimisation do no longer rely on gradient information or stationary points.

2.2.2.2 Stochastic solution methods

Stochastic approaches focus on random generation and are inspired by physical processes that generate points to converge to an equilibrium [118]. Stochastic solution methods approximate global solutions (approximation algorithms). An example of stochastic approaches include ‘classic direct search methods’, often based on heuristics, and a generalisation of heuristic methods, i.e. ‘meta-heuristic methods’.

Heuristic solution methods are simple procedures that aim to find a satisfactory solution from a large set of feasible solutions of often complex problems, but do not necessarily obtain the optimal solution [91, 124]. These approximation methods require less computational effort than deterministic methods [91]. Meta-heuristic methods aim to find a solution within a discrete search-space and combine therefore multiple heuristic methods. Meta-heuristic methods are inspired by natural processes and started their development in the 1980s-1990s [109]. They can be classified based on various aspects: trajectory- versus population-based, memory-based versus memory-less, nature-inspired versus non nature-inspired, etc. [91, 109, 124].

Trajectory-based solution methods, for example, obtain a single solution throughout the search process [124]. The majority of trajectory-based methods follow procedures based on iteratively improving movements together with techniques to move away from local optima [124]. Some examples of trajectory-based solution methods are Simulated Annealing, Hill Climbing and Tabu Search [124–127]. Population-based solution methods employ a population of solutions, which evolves with each iteration following the principles of mutation, genetics, evolution theory or natural selection [124] [128]. Some examples of population-based solution methods are Ant Colony Optimisation, Artificial Bee Colony Optimisation, Evolutionary Algorithms, Genetic Algorithms and Particle Swarm Optimisation [124, 125].

2.2.2.3 Multi-objective solution methods

A Pareto set of multi-objective problems can be obtained through either so-called ‘classical approaches’, such as the weighted-sum and the ϵ -constraint method, or, approaches based on evolutionary algorithms [92, 113]. Classical approaches, or deterministic approaches, typically convert multiple objectives into a single objective problem, either

by combining the objectives into a weighted sum, or, by solving a single objective optimisation with additional inequality constraints for the other objective(s) (ϵ -constraint method) [92, 113]. With the weighted-sum approach, the weights of the objectives are iteratively changed to obtain a Pareto set. The ϵ -constraint method constructs a Pareto set based on iterative changes (ϵ) of the constrained objective. Classical approaches are straightforward in application. However, the weighted-sum approach is only reliable for convex problems as changes in non-convex Pareto fronts might not be captured. Furthermore, the weighted-sum approach becomes complex for a large number of objectives (> 3). The ϵ -constraint method, additionally, requires careful selection of ϵ (constraint variation) to obtain feasible solutions.

Stochastic approaches generate several Pareto solutions simultaneously and do not require iterations of weights or constraints [92, 113]. These methods can also be classified based on trajectory- versus population-based [124]. Currently, the most popular algorithms are the Non Sorting Genetic Algorithm II (NSGA-II) and the Strength Pareto Evolutionary Algorithm 2 (SPEA2) [92, 113, 124]. Stochastic approaches are especially useful for problems with a large number of objectives (>3).

2.3 Optimisation of distributed energy system design

The previous Section provided background on optimisation models and methods. Optimisation is often employed as tool to design distributed energy systems (DES). This Section applies this knowledge to assess and review DES design optimisation models in literature to identify research gaps and shape the research questions addressed. DES can come in various forms, typically tailored to location specific factors and stakeholder interests, taking into account various disciplines, consumer areas, sectors, energy resources, generation and storage technologies, and energy services and integration [101, 102]. Both internal system design and interactions as well as interactions with central energy services require optimisation tools that enable decision-making [101, 102]. Design and planning optimisation of DES thus involves finding a set of energy resources, technologies and interactions to optimally meet the energy requirements of a certain consumer area [103]. DES design optimisation is a field of extensive research [81, 109, 125, 129]. The field has, especially, received increasing interest over the last 15 years [105] since it

allows to analyse supply and demand systems and provide insight into climate-, security- and financial-related challenges of conventional energy systems [104].

2.3.1 Categories

The focus of this thesis is DES design optimisation in terms of selection, siting and sizing of considered distributed energy resources (DER) and their interactions within an urban area. This includes the service of a combination of electricity and thermal energy to a consumer base, potentially employing local energy sharing networks. DES design optimisation models throughout literature can be categorised [81, 82, 94, 101, 103, 105]. A category selection based on four main areas is made here, as illustrated in Figure 2.3: (i) *system*-related aspects [81, 82, 105], including the choice and implementation of energy integration, considered technologies and the model temporal, spatial and implementation detail scales; (ii) *model* aspects [82, 105], including model type, optimisation method and considered objectives; (iii) the case-study location, i.e. *inputs*; and (iv) the considered *disciplines*. A comprehensive literature review has been conducted (see Appendix A) to identify the characteristics of each category.

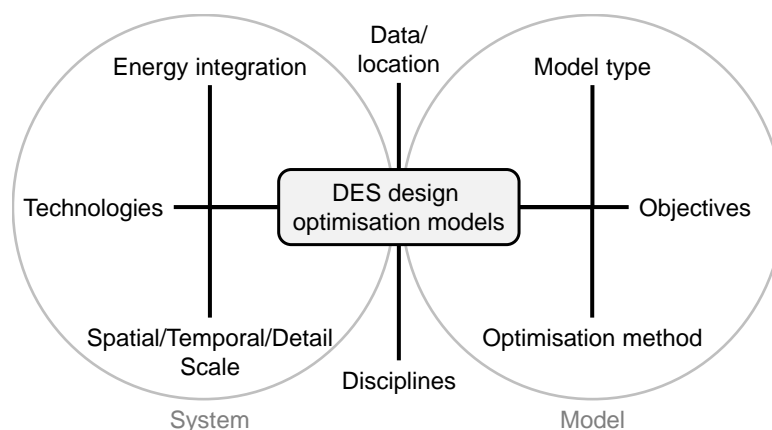


FIGURE 2.3: Categories to classify DES design optimisation models based on system aspects, model aspects, inputs and disciplines.

2.3.2 System aspects

Below system aspects of energy integration, technologies and scales are analysed.

2.3.2.1 Energy integration

Energy integration refers, on the one hand, to multi-generation. This is the combination and integration of various energy services within a certain consumer area, e.g. electricity and/or thermal energy supply [34, 130]. These energy services can be achieved by central grid supply or local generation units [131]. Energy integration can, on the other hand, refer to the sharing of locally generated energy (electrical or thermal) through local networks within a cluster of participating consumers [130].² The focus in this work is on the provision of electricity combined with space heating and/or space cooling to a cluster of consumers. Electricity integration can be achieved through microgrid sharing infrastructure. Thermal heating and cooling integration can be achieved through pipeline networks or larger district systems [131, 132]. Local energy sharing allows for reduced transportation distances for electricity compared to large conventional power systems, making it an ideal service for DES [101, 129]. Additionally, power-heat co-generation systems can increase energy conversion efficiency compared to conventional generation through waste heat utilisation [105, 129, 131]. Most research to date, however, has been focussing on a single energy service, i.e. electricity or district heating [34]. Summer peak demand challenges are increasing the research focus on thermally driven cooling equipment. This equipment can be coupled with co-generation to enable full yearly use of waste heat through seasonal tri-generation, i.e. combined heat, cooling and power systems, increasing their economic viability and overall efficiency [34, 104, 105].

DES design research is thus increasingly focussing on the provision of more than one energy service to a consumer area, employing more and more local optimised energy networks and energy sharing interactions. An extensive body of research looks at the provision of electricity, heating and cooling to single buildings [133–144] or generic co-generation systems [145–147] without energy sharing between consumers (e.g. through pipelines or networks). Various consumer profiles were here considered, including office buildings [135, 148, 149], hospitals [150–160], hotels [135, 148, 155, 161–167], apartment buildings [168, 169], schools [170] or single residential dwellings [150, 171–174]. Additionally, the provision of energy services to a cluster of consumers, which is considered as a whole without explicit energy sharing, has also been researched. The latter has been looked at for, for example, electricity, heating and cooling provision to an

²Note that energy integration is also increasingly referring to the integration of other services, such as chemicals production and transport services [34, 101, 130].

eco-campus [175] or building complexes and urban areas [60, 176–181], and electricity and heating provision to a cluster of residential consumers [182–187]. Electricity and heating provision without energy sharing options has been researched for generic commercial buildings [188–190], pools [191], hotels [192, 193], residential apartments [194] and typical residential dwellings [195]. The provision of electricity combined with space cooling [196] or the combination of heating and cooling provision [197] without energy sharing options to buildings has only limitedly been researched.

Research that includes explicit energy sharing, through pipelines or networks, is more limited. The combination of electricity and heating provision has been researched by, for example, Holjevac et al. [198], Wakui and Yokoyama [199] and Zhang et al. [86] for a cluster of residential consumers that each foresee in their own heating requirement but can share electricity. Bracco et al. [200], Casisi et al. [201], Falke et al. [202], Karschin and Geldermann [203] and Orehounig et al. [204] have researched electricity and heating provision combined with heat sharing networks for (residential) clusters of consumers. Urban districts, seen as a whole for electricity delivery but with district heating networks between regions, have been considered by Fazlollahi et al. [205, 206]. Both electricity and heat sharing options have been researched for a cluster of industrial consumers by Casisi et al. [207], for a town/city of clustered consumers by Haikarainen et al. [208] and Keirstead et al. [93], for a cluster of commercial consumers by Hawkes and Leach [209], and for a small cluster of residential consumers by Mehleri et al. [95, 96], Obara et al. [210], Obara and El-Sayed [211], Omu et al. [212] and Söderman and Pettersson [213]. Additional consideration of space cooling and sharing is still under-represented. Only heat sharing options were considered together with the provision of electricity, heating and cooling to a cluster of apartments by Panone and Anatone [214], for a set of buildings by Bracco et al. [215] and Sugihara et al. [216], and for a community by Wu et al. [217]. Harada and Mori [218] employed an optimised heating network for a city/town level that also transported heating to sites for local transformation into cooling. A combination of both electricity and heat sharing options have here been presented for a cluster of residential consumers by Kopanos et al. [219] and Wu et al. [220], for a cluster of buildings by Piacentino et al. [221], Piacentino and Barbaro [222] and Stojiljković et al. [223], and for a cluster of energy hubs by Salimi et al. [224]. The combination of both heating and cooling sharing without electricity sharing has been

researched by Ameri and Besharati [225] for a residential district, and by Buoro et al. [226] and Chinese [227] for a cluster of residential and commercial consumers.

Full energy integration of the provision and sharing of electricity, space heating and cooling to a consumer area is an upcoming area of research and has been analysed, for example, by Voll et al. [90, 228] with implicit site electricity balancing, by Weber and Shah [229] for an ‘eco-town’ with various consumers and by Yang et al. [230, 231] for an urban area. Full energy integration within a neighbourhood setting has, however, not received the same level of attention, but has been tackled by recent work from Li et al. [232] for a cluster of various consumers.

2.3.2.2 Technologies

DES designers can select various DER with each specific operational and design characteristics [34, 101, 233]. Tabel 2.2 summarises technologies that have been analysed in previous DES design optimisation models. Small-scale DER, located close to consumers in the network, come in various forms and can be distinguished by their operational nature: intermittent, dispatchable or storage [101, 105, 109, 130]. Intermittent DG units are based on renewable energy, such as sun, wind, hydro power or biomass [92, 124]. Dispatchable units are mostly fossil fuel combustion based, such as diesel generators and co-generation units, i.e. micro-turbines, fuel cells and gas engines [80, 92, 105].

Locally generated energy can be stored in either hot or cold thermal storage tanks or electrical storage units [80, 92, 131]. Electrical storage can be provided by chemical processes based on, amongst others, lead-acid and lithium-ion, or, by physical processes, such as hydroelectrics, flywheels and compressed air [131]. Renewable energy generation reduces operational cost due to ‘free’ fuel and facilitates greenhouse gas emission reduction. However, renewable energy generation levels depend on weather and climate [124]. This requires balancing through complementing dispatchable units or storage [101, 132, 234]. Systems that combine two or more dispatchable and intermittent units in a complementing system are so-called hybrid systems or multi-fuel/energy systems [91, 101, 124, 132, 234]. To facilitate DES, additional technologies are also required, including system control and communication devices, such as a central control unit that balances local energy generation and supply [101]. Furthermore, conventional thermal

TABLE 2.2: Technologies in DES design optimisation models that include local energy sharing. CHP=combined heat and power unit, Cogen=co-generation, CST=cold thermal storage, Elec=electrically driven, EST=electrical storage, FC=fuel cell, HST=hot thermal storage, ICE=internal combustion engine, NG=natural gas, RES=renewable energy technology, ST=solar thermal, Therm=thermally driven, PV=photovoltaic unit, WHrec=waste heat recovery, WT=wind turbine.

Technologies		Research
Cogen	FC	Obara et al. [210], Obara and El-Sayed [211]
	ICE+WHrec	Panone and Anatone [214]
	NG CHP	Ameri and Besharati [225], Bracco et al. [200, 215], Buoro et al. [226], Casisi et al. [201, 207], Chinese [227], Falke et al. [202], Fazlollahi et al. [205, 206], Harada and Mori [218], Hawkes and Leach [209], Holjevac et al. [198], Keirstead et al. [93], Kopanos et al. [219], Li et al. [232], Mehleri et al. [95], Omu et al. [212], Piacentino et al. [221], Piacentino and Barbaro [222], Salimi et al. [224], Söderman and Pettersson [213], Stojiljković et al. [223], Sugihara et al. [216], Wakui and Yokoyama [199], Weber and Shah [229], Wu et al. [217, 220], Yang et al. [230, 231], Zhang et al. [86]
RES	PV	Ameri and Besharati [225], Bracco et al. [215], Falke et al. [202], Li et al. [232], Mehleri et al. [95, 96], Obara et al. [210], Obara and El-Sayed [211], Orehounig et al. [204], Sugihara et al. [216], Wu et al. [220]
	PV +WT	Hawkes and Leach [209], Holjevac et al. [198], Omu et al. [212], Söderman and Pettersson [213], Weber and Shah [229], Yang et al. [231]
	ST	Bracco et al. [215], Casisi et al. [207], Fazlollahi et al. [205, 206], Omu et al. [212], Orehounig et al. [204], Panone and Anatone [214], Weber and Shah [229], Wu et al. [217]
Cooling	Elec	Bracco et al. [215], Kopanos et al. [219], Panone and Anatone [214]
	Therm	Buoro et al. [226], Sugihara et al. [216], Voll et al. [228], Weber and Shah [229]
	Elec + Therm	Chinese [227], Harada and Mori [218], Panone and Anatone [214], Piacentino et al. [221], Piacentino and Barbaro [222], Salimi et al. [224], Stojiljković et al. [223], Yang et al. [230, 231], Wu et al. [217, 220]
Storage	HST	Bracco et al. [200], Fazlollahi et al. [205], Haikarainen et al. [208], Kopanos et al. [219], Mehleri et al. [95, 96], Obara et al. [210], Panone and Anatone [214], Piacentino et al. [221], Piacentino and Barbaro [222], Söderman and Pettersson [213], Sugihara et al. [216], Wakui and Yokoyama [199], Weber and Shah [229], Wu et al. [217, 220], Zhang et al. [86]
	HST+CST	Casisi et al. [207], Li et al. [232], Stojiljković et al. [223], Yang et al. [231]
	HST+EST	Bracco et al. [215], Falke et al. [202], Hawkes and Leach [209], Holjevac et al. [198], Obara and El-Sayed [211], Orehounig et al. [204], Salimi et al. [224]

generation units can be considered in consumer premises, e.g. natural gas condensing boilers, gas heaters and electrical air-conditioning systems [92, 101]. Additionally, conventional grid and natural gas service connections can be adopted [101].

Research into the provision of electricity combined with heating and/or cooling and energy sharing to a cluster of consumers almost always considers one or multiple, central or decentral, co-generation units with a predominant focus on natural gas fuelled CHP units (see Table 2.2). A selection of a combination of the above units has also been considered, for example by Mehleri et al. [96]. Heat pumps are also increasingly being

adopted [202, 204–206, 216]. The work of Haikarainen et al. [208], for example, employed heat pumps and a biomass co-generation unit. Karschin and Geldermann [203] employed biomass co-generation. PV units are the most prevailing electrical renewable DG unit (see Table 2.2). The combination of PV and wind turbines, and the consideration of solar thermal are, however, gaining interest. Other renewable units are only limitedly considered, for example, hydro in the works of Söderman and Pettersson [213] and Orehounig et al. [204]. Most co-generation research includes condensing boilers as complementary or supplementary thermal heating units. Gas heaters have only limitedly been researched, for example, by Kopanos et al. [219]. Storage is predominantly adopted in the form of hot thermal storage, either alone, or, in a combination with cold thermal or electrical storage. The combination of electrical, hot thermal and cold thermal storage is touched upon by, for example, Ashouri et al. [140], Guo et al. [154] and Zhou et al. [163] in the context of energy services to a large building without energy sharing, but is not widely addressed. Research that combines co-generation with thermally driven cooling technologies, conventional thermal technologies, electrical storage, hot thermal storage, cold thermal storage, renewable energy resources and a potential grid connection has been touched upon by, for example, Yang et al. [231] for an urban area. These full hybrid system approaches are, however, lagging behind compared to co-generation, district thermal or renewable energy system studies [105].

2.3.2.3 Scale

Multiple scales can be distinguished in DES design models [81, 94, 101]; spatial, time and model detail. The larger the spatial area, the more detailed the time scale and the more model detail, the more degrees of freedom the modelled system has, increasing model and optimisational complexity [130]. Spatial scale refers to the considered consumer area [81, 82, 94, 101, 103]. DES can encompass a region/district, city/town, community, ($\leq 1 \text{ km}^2$) neighbourhood or building level. The smallest geographically aggregated unity (in contrast with an apartment or commercial building) that can exhibit DES planning, is a neighbourhood [103]. Previous research considering both multiple energy services and energy sharing predominantly focussed on either residential areas of various scales or urban areas with various types of consumers, see Table 2.3.

TABLE 2.3: Spatial scale of DES design optimisation models with energy sharing.

Scale	References
Large residential (> 100 houses)	Ameri and Besharati [225], Fazlollahi et al. [205, 206], Holjevac et al. [198]
Medium residential (100–20 houses)	Falke et al. [202], Karschin and Geldermann [203], Kopanos et al. [219], Orehounig et al. [204]
Small residential (≤ 20 houses)	Bracco et al. [215], Buoro et al. [226], Mehleri et al. [95, 96], Obara et al. [210], Obara and El-Sayed [211], Piacentino et al. [221], Piacentino and Barbaro [222], Söderman and Pettersson [213], Wakui and Yokoyama [199]
Clusters of apartments	Panone and Anatone [214]
Cluster of industrial consumers	Casisi et al. [207]
Cluster of commercial consumers	Casisi et al. [201], Harada and Mori [218], Hawkes and Leach [209]
Cluster of various types of consumers in an urban area	Bracco et al. [200], Chinese [227], Li et al. [232], Haikarainen et al. [208], Keirstead et al. [93], Omu et al. [212], Salimi et al. [224], Stojiljković et al. [223], Sugihara et al. [216], Weber and Shah [229], Wu et al. [217, 220], Yang et al. [230, 231], Zhang et al. [86]

Time scale refers to both the planning horizon of the project as well as the time steps employed in the model [81, 82, 94, 104, 130]. This can be a yearly planning horizon or project life time with annual, seasonal, monthly, daily, hourly or minute/second time steps. Seasonal daily profiles with single or multi-hour time-steps are especially useful coarse time-scales with regard to the integration of seasonal tri-generation, day and night demand differences, capturing off-peak demand times and the integration of both renewable energy generation units and storage [104, 130].

Model detail refers to the scope of simplifications and assumptions. The model can encompass detailed thermodynamic or electrical behaviour (see Section 1.2.2.2). Alternatively, a superstructure design can be adopted where different components interact with power or energy flows that might include a transport distance related loss [34, 101]. Integrating various energy services and resources in a complex system with many component interactions and relations can benefit from representing each component and interaction as simply as possible [104]. Coarse scales hence rely on system assumptions and model simplifications, but allow for reasonable computational times and effort [104].

2.3.3 Model aspects

Optimisation concepts were reviewed in Section 2.2. The DES model types and solution methods, employed throughout literature, are presented below.

2.3.3.1 Model types and solution tools used

DES design consists of various optimisation problems at different scales [91]. The selected system aspects (Section 2.3.2) determine the system boundaries, constraints and uncertainties and hence the appropriate modelling and solution methods [91]. DES design is inherently a complex, multi-objective, stochastic and a large combinatorial problem that is most realistically formulated as a non-linear problem to capture real system behaviour [91]. To increase optimisation efficiency and reduce computational efforts and complexity, system behaviour is, nevertheless, often linearised and simplified to obtain (MI)LP problems [91, 104]. Mixed-integer models are here appropriate as they can cope with both selection (on-off/binary variables) as well as siting and sizing (continuous variables) of units [80]. Based on a systematic review of literature regarding tri-generation optimisation work, Unal et al. [105] identified linear and meta-heuristic optimisation methods as most common optimisation methods. MILP models are most popular for DES design optimisation, in terms of both energy integrated services and sharing, mostly employing superstructure or thermodynamic design, see Table 2.4. Genetic Algorithms are also increasingly being adopted by, for example, Falke et al. [202], Harada and Mori [218], Obara et al. [210], and Obara and El-Sayed [211]. If no technology selection is considered, LP (for example, Hawkes and Leach [209] and Orehounig et al. [204]) and NLP (for example, Salimi et al. [224]) models have been used.

TABLE 2.4: Classification of DES design MILP models including energy sharing.

MILP	Research
Superstructure	Ameri and Besharati [225], Bracco et al. [200, 215], Casisi et al. [201, 207], Chinese [227], Kopanos et al. [219], Li et al. [232], Mehleri et al. [95, 96], Omu et al. [212], Söderman and Pettersson [213], Sugihara et al. [216], Wakui and Yokoyama [199], Wu et al. [217, 220], Yang et al. [231]
Thermodynamic	Buoro et al. [226], Haikarainen et al. [208], Piacentino et al. [221, 221], Stojiljković et al. [223], Weber and Shah [229], Yang et al. [230]

2.3.3.2 Types and numbers of objectives

DES can be designed based on several objectives that balance and trade off interests of involved stakeholders [91, 92, 102, 132]. DES design objectives throughout literature are mostly easily quantifiable economic/financial, environmental or technical in nature [80, 91, 92, 101]. System design and implementation is primarily based on the

economic viability of the project and therefore traditionally heavily determined by economic or financial minimisation objectives [91, 101, 102, 109, 233], see Table 2.5. Other objectives have only limitedly been touched upon within studies that include energy sharing. Single-objective models, for example, employed technical objectives related to minimisation of primary energy consumption [199, 211] and minimisation of energy storage differences between time periods [210]. Bi-objective optimisation models are still under-represented and mostly employ a combination of economic and environmental objectives [91, 109, 125, 129, 202, 217, 232], including minimisation of total annual costs and annual CO₂ emissions [200, 214], or, a combination of an economic and technical objective, such as minimisation of total annual cost and minimisation of primary energy consumption [223]. More than two design objectives have only been researched very limitedly, for example, through a weighted-sum approach of economic, technical and environmental performance metrics by Keirstead et al. [93] and through an evolutionary approach by Fazlollahi et al. [205, 206].

TABLE 2.5: Economic objectives in DES design optimisation research with energy sharing. OM=operation and maintenance, NPV=net present value.

Objective	Research
Investment and OM cost minimisation	Ameri and Besharati [225], Haikarainen et al. [208], Omu et al. [212]
Total annual (equivalent) costs minimisation	Bracco et al. [215], Buoro et al. [226], Casisi et al. [201, 207], Chinese [227], Falke et al. [202], Fazlollahi et al. [205, 206], Hawkes and Leach [209], Li et al. [232], Mehleri et al. [95, 96], Weber and Shah [229], Wu et al. [217, 220], Yang et al. [230, 231], Zhang et al. [86]
Energy supply cost minimisation	Harada and Mori [218]
Annual operating costs minimisation	Holjevac et al. [198]
NPV maximisation	Karschin and Geldermann [203], Piacentino et al. [221], Piacentino and Barbaro [222], Salimi et al. [224]
Total cost minimisation	Kopanos et al. [219], Söderman and Pettersson [213]

For energy integrated systems without energy sharing, multi-objective optimisation is more established with a greater focus on life cycle aspects. Considered economic objectives are, for example, minimisation of life cycle costs [136, 137, 197]. Environmental objectives regard, for example, minimisation of life cycle emissions [154, 170, 197], minimisation of life cycle environmental impact [137], maximisation of renewable energy penetration levels [170], minimisation of fossil fuel consumption [138] and minimisation of global warming potential [185]. Technical objectives are increasingly analysed in the form of, for example, maximisation of exergetic efficiency [168], maximisation of overall system efficiency [179], minimisation of a grid interaction index [143, 196], maximisation

of reliability factor [133], maximisation of primary energy savings [179], maximisation of demand satisfaction [159] and minimisation of life cycle primary energy consumption [197]. Note that environmental and technical objectives are often reduced to cost related functions and therefore not inherently different.

2.3.4 Case-study locations

Developed optimisation frameworks are typically demonstrated through location-specific case-studies, see Table 2.6. Previous research on energy integrated areas with multiple energy services but no energy sharing has been heavily focussing on Asian and European

TABLE 2.6: Case-study locations in DES design optimisation research.

Area	Country	Research without energy sharing	Research with energy sharing
Asia	Japan	Aki et al. [177], Bando and Asano [176], Bando et al. [178], Gamou et al. [148], Ooka and Komamura [160], Ren et al. [174], Ren and Gao [175], Weber et al. [149], Yokoyama et al. [145, 146]	Harada and Mori [218], Obara et al. [210], Obara and El-Sayed [211], Sugihara et al. [216], Wakui and Yokoyama [199], Wu et al. [220]
	Greater China	Guo et al. [154], Li et al. [172], Lu et al. [196], Wang et al. [138, 139, 162, 164, 165, 166], Zhou et al. [167]	Li et al. [232], Yang et al. [230, 231], Wu et al. [217]
	South Korea	Ko et al. [170], Oh et al. [134, 135], Seo et al. [194]	
Europe	Italy	Brandoni and Renzi [150], Fabrizio et al. [169], Gimelli and Muccillo [153], Morini et al. [173], Piacentino et al. [161], Stoppato et al. [193]	Bracco et al. [200, 215], Casisi et al. [201, 207], Chinese [227], Panone and Anatone [214], Piacentino et al. [221], Piacentino and Barbaro [222]
	Portugal	Monteiro et al. [191], Safaei et al. [136, 137]	
	Spain	Carvalho et al. [151, 152, 156, 157], Lozano et al. [60]	
	UK	Shaneb et al. [195], Zhang et al. [185]	Hawkes and Leach [209], Keirstead et al. [93], Kopanos et al. [219], Omu et al. [212], Weber and Shah [229]
	Finland		Haikarainen et al. [208], Söderman and Pettersson [213]
	Others	Ashouri et al. [140] (Switzerland), Falke and Schnettler [141] (Germany), Kavvadias and Maroulis [158] (Greece), Mavrotas et al. [159] (Greece)	Falke et al. [202] (Germany), Holjevac et al. [198] (Croatia), Karschin and Geldermann [203] (Germany), Mehleri et al. [95, 96] (Greece), Stojiljković et al. [223] (Serbia), Orehounig et al. [204] (Switzerland)
Americas	USA	Best et al. [179], Mallikarjun and Lewis [133], Pruitt et al. [188, 192], Xu et al. [197], Zachar and Daoutidis [189], Zachar et al. [190]	
Middle East	Iran	Abdollahi and Sayyaadi [168], Akbari et al. [235], Karami and Sayyaadi [171]	Ameri and Besharati [225], Salimi et al. [224]

areas. Research that additionally included energy sharing has been mostly concentrated in Europe with increasing interest in Asian and Middle Eastern locations. The Americas, Africa and Oceania are under-represented locations.

2.3.5 Integrated disciplines

DES design encompasses multiple disciplines and stakeholders [102, 102, 132]. The design problem is seen as an optimisation problem, hence *mathematical programming* techniques form the basis for DES design research. Knowledge of technical behaviour and *engineering* of the thermal and electrical system components and interactions is required to model the researched system. *Economics* determine the viability of projects and knowledge of environmental *science* is required to analyse environmental impacts. These main disciplines readily translate into quantifiable objectives and constraints and have therefore been the major focus of previous research [34, 80, 101, 102, 104, 132]. Social aspects, such as politics, social acceptance and regulation, however, also impact design [102, 104, 132]. These disciplines can form barriers at the project implementation stage leading to uncertainty [94, 104]. Social aspects are, however, not easily quantifiable and are therefore lagging behind with respect to implementation and integration in mathematical models [94, 104, 236]. If integrated within design optimisation, they have mostly been considered in the form of regulatory constraints, such as DG capacity bounds, residential energy export or operational restrictions, or, in the form of input parameters through feed-in tariffs and carbon taxes. An important factor in techno-economic-environmental DES design optimisation is its policy relevance, i.e. the link between novel technologies and systems, and regulation [94]. DES design thus inherently involves a cross-disciplinary and multi-objective decision-making process [94, 132].

2.3.6 Software tools

Designing DES is a popular research topic. Hence various application-specific commercial software tools exist to aid decision-makers, researchers or developers [91, 101, 109, 130]. Several accounting and simulation tools are available, e.g. RETscreen, TrnSys, EnergyPlus and EnergyPLAN [80, 101, 132]. Other tools focus on long-term and national system design levels, e.g. MARKAL/TIMES [81, 102, 104, 130, 234, 237], or specific

technologies, e.g. BALMORAL (CHP and electricity sector) [109, 237] or MODEST (main focus on utility energy service and district heating). Note that this list is not exhaustive and various other developed tools exist (for more information, see for example [80, 130, 234, 237]). The most relevant tools that can be applied to residential energy integrated DES are HOMER and DER-CAM, which are detailed below. Their model characteristics are summarised in Table 2.7.

TABLE 2.7: Characteristics of HOMER and DER-CAM software tools for DES design optimisation [238, 239]. C=cooling, CHP=combined heat and power, CST=cold storage, DH=district heating, E=electricity, EC=electric chiller, EI=energy integration, EST=electric storage, EV=electric vehicles, FIT=feed-in tariff, H=heating, HST=hot storage, MG=microgrid, PV=photovoltaic unit, ST=solar thermal.

Category		HOMER	DER-CAM
EI	Sectors	E/H	E/H/C
	Sharing	E and limited DH	E and DH
Technologies	Dispatchable	hydro/biomass/engines/CHP	CHP/AC/EC/heat pump
	Renewable	PV/Wind	PV/ST/Wind
	Storage	EST	EST/CST/HST
	Others	Grid	grid/building efficiency/EV/load shifting
Scale	Spatial	consumer area	buildings and MG
	Temporal	1 year horizon/up to minute based time steps	typical (single or multi-) year horizon/-time step (1h, 15min, 5min) of daily profiles
	Detail	detailed E	high-level/power flow
Model		semi-optimisation	MILP, mostly deterministic, stochastic efforts
Tool		alternatives ranking	GAMS
Objectives		(1) net present cost	(1) total annual energy cost and (2) CO ₂ emissions
Data		costs, tariffs, load profiles, technology characteristics	costs, tariffs, load profiles, technology characteristics
Disciplines		engineering-economic/emissions	engineering-economic constraints, regulatory aspects (FIT, incentives,...)

The commercial Windows based Hybrid Optimization Model for Electric Renewables (HOMER) has been developed since 1992 by the National Renewable Energy Laboratory in the United States [109, 237, 238]. HOMER can be used for simulation, optimisation and analysis of hybrid systems mainly focussing on detailed electrical design through microgrid operation with various DG units, converters and loads [81, 132, 237]. Despite its classification as optimisation tool, HOMER is a simulation tool that analyses the dynamic behaviour (dispatch optimisation) of user-defined systems in terms of possible sets of sized technologies [132, 237]. Alternative design configurations are ranked based on Net Present Cost through a techno-economic feasibility evaluation including energy, economic and environmental constraints [91, 132, 234, 237, 237]. It is a popular commercial and academic tool, with a main research application of rural and off-grid electrical

DES. The main disadvantages are: only a single cost objective can be considered, and depth of discharge of batteries, intra-hour variability and bus voltages are not considered [234]. The commercial package interface, furthermore, does not allow for flexible or additional implementation of objectives, technologies or other features.

Distributed Energy Resources Customer Adoption Model (DER-CAM) is an integrated community energy system planning tool developed by the Berkeley Lab since 2000 [81, 91, 132, 239]. DER-CAM is an MILP based software tool that designs DES in terms of technology selection, sizing and optimal technology dispatch schedules subject to demands [101, 132]. DER-CAM is developed in GAMS and is available in a free academic web-based version with limited features [239]. System configuration is optimised at minimal annual energy cost and minimal annual CO₂ emissions with a primarily economic angle of reducing consumer costs [101, 132]. The model can handle buildings or aggregated consumer sites [132]. It focusses on both electricity and thermal energy provision both through dispatchable and renewable energy generation. The Berkeley laboratory regularly publishes papers introducing new DER-CAM features and case-studies. The package, however, only limitedly allows for flexible or additional features.

2.4 Discussion

The previous Sections provided an overview of both optimisation models and methods as well as previous DES design optimisation research. This Section discusses the gaps in research to date and challenges involved with modelling DES systems.

2.4.1 Identification of research gaps

An important DES design need is the development of generic decision-making optimisation tools that are not limited to certain locations but flexible to tailor system design to various locations, demand profiles and environments of a wide range of case-studies. Moreover, multiple techno-economic and regulatory aspects need to be included to take into account stakeholder interests and ensure multi-faceted decision-making. Table 2.8 summarises various research gaps that still require addressing. This list is not exhaustive as, for example, different energy services and pools of technologies could be considered.

Electrical transport, for example, is not touched upon in the context of this thesis as it considers a form of moveable storage DER. Furthermore, available software tools do not provide the sought after flexibility in model features, applicability and analysis.

TABLE 2.8: Summary of research gaps in DES design optimisation research.

Category	Research gap
Energy integration	fully energy integrated system considering at least electricity, space heating and space cooling to a consumer area combined with local electricity, heating and cooling sharing options
Technologies	fully energy integrated system (electricity, heating and cooling) with full energy sharing combined with a pools of co-generation, renewable, thermally driven chillers, electrical and thermal storage, and conventional options
Objectives	economic, environmental, technical and social (≥ 2 objectives)
Disciplines	explicit consideration of social aspects, amongst others regulation [105]
Application/Location	consideration of South American, African or Oceanian case-study

The delivery of electrical energy services sometimes combined with space heating and/or cooling without energy sharing has been addressed in previous work. Explicit energy sharing is increasingly touched upon. Hot thermal sharing, for example, is adopted in colder climates with a significant space heating requirement, making co-generation worth exploring, e.g. in Japan [210, 211], North Italy [200, 207, 214], Scandinavia [208, 213] and the United Kingdom [93, 209, 212, 219, 229]. Consideration of cooling integration is needed in environments where seasonal tri-generation might be viable due to considerable winter heating demands and summer cooling demands, like in areas in China [230, 230], Italy [227], Iran [225] and Japan [218]. Fully energy integrated systems considering the service and sharing of electricity, heating and cooling are very limited but are necessary to increase model applicability to various locations.

Additionally, a wide range of DER can be adopted in DES. The focus in previous research was predominantly centred around co-generation combined with thermally or electrically driven chillers [105]. The integration of renewable technologies and storage is, however, gaining increasing interest due to the growing focus on the environment complementing purely economic aspects, and their increased affordability. Furthermore, renewables can contribute to reduce the environmental impact of and dependency on conventional services, making them attractive in an urban setting. Especially fitting out residential areas as DES could more directly help to address conventional energy system challenges (see Section 1.1.4). A full hybrid-storage range of technologies is therefore required to ensure general applicability of the model.

DES design, furthermore, is complex in terms of number of constraints and variables as well as involved disciplines and stakeholders. Its optimisation has, however, largely been focussed on single economic objective problems, since cost is the predominant driver of new investment [105, 221]. Multi-objective, fully energy integrated DES design problems are gaining more research interest, mostly combining an economic with an environmental objective [105]. Technical objectives are still under-represented and mainly relate to efficiency and operational behaviour. Social aspects are – if included – mainly indirectly addressed as capacity and operational constraints. There is thus a need for a multi-faceted DES design framework that includes economic as well as environmental and technical objectives to fit in with central system objectives and regulation. Furthermore, Africa, Latin America and Oceania are still under-represented case-studies despite their potential for DES in rural and remote communities [48, 61, 63–65]. Considering any of the above locations, would increase global applicability of DES design models.

2.4.2 Challenges

Optimisation of DES design involves challenges that can affect the accuracy of implementation and results [82, 92, 94, 104]. Awareness of these challenges is needed to critically assess developed optimisation frameworks. First, DES design models are inherently complex, requiring a trade-off between model accuracy and complexity [82, 92, 104, 240]. Less complexity mostly implies more simplifying assumptions [94]. Over-simplified models, however, solved with global optimisation methods are only able to find sub-optimal solutions for real problems, i.e. ‘*a real solution for a non-problem*’ [92, 240]. Detailed models combined with less powerful solution techniques, in contrast, potentially only result in local optima, providing ‘*a non-solution to a real problem*’ [92, 240]. For decision-making and predictions, simplified models are often adequate enough, compared to more detailed complex models. Simplified models namely allow for shorter computational times and extensive parameter sensitivity analysis to understand the different relations within and impacts on the system [91, 104]. DES optimisation models are therefore not necessarily developed for real project implementation but rather for decision-makers to assess the impact of various aspects on design [82].

Second, the availability, uncertainty, prediction and quality of data, both in terms of inputs and results, needs to be balanced with the level of model detail [82, 91, 94].

Solutions of complex models with low quality inputs will lead to low quality results [91, 94]. Renewable energy resources, especially, can exhibit significant uncertainty, which can be taken into account either through thorough parameter sensitivity analysis in deterministic models or through stochastic modelling [104].

Last, DES optimisation has been strongly focussed on specific techno-economic systems. DES integration into the wider conventional energy system and the inclusion of social aspects are under-represented but are important to ensure DES design model relevance for decision-makers to inform policy making [82, 104].

2.4.3 Contributions of the thesis

This thesis focusses on addressing the research gaps presented in Table 2.8. A decision-making framework will be developed for residential DES design, including the energy service and sharing of electricity, space heating and space cooling, through an optimisation approach. Neighbourhood energy demands can be met through the consideration of hybrid, storage and conventional energy supply as well as energy sharing. An economic objective is considered along with environmental and technical objectives, aligned with the three central energy system objectives (see Section 1.1.3). Additionally, social aspects are included in the form of DES regulatory framework aspects. The approach is applied to a South Australian neighbourhood. South Australia has namely potential for DES in remote load centres and a high availability of renewable energy resources (see Section 3.4). Contributions to DES modelling challenges are made through the inclusion of a measure for renewable resource availability (Section 4.5.2.3) and the analysis and integration of regulatory aspects within an optimisation environment (Chapter 6).

2.5 Summary and conclusion

An overview of optimisation models and methods has been presented in this Chapter as well as a review of DES design optimisation research. Several system and model categories were identified to assess previous work in the field. The identified research gap addressed in this thesis is the development of a generic decision-making framework for fully energy integrated DES design of a small residential area, considering various energy

supply options as well as energy sharing. Furthermore, three objectives and regulatory framework aspects are included, increasing model relevance to various stakeholders and opening up a techno-economic approach to inform policy makers.

Chapter 3

Methodology

The problem addressed is how the energy system of small residential neighbourhoods, framed by location specific parameters, can be most suitably designed to meet its total electricity, heating and cooling demands. This is first and foremost a design problem and does not involve operational optimisation. The optimal dispatch and interaction of units can nevertheless be analysed based on the given demand profiles. ‘Optimal’ distributed energy system (DES) design is obtained through the selection and sizing of distributed energy resources (DER), from a considered pool of technologies, and siting them across neighbourhood houses. Technologies are considered together with potential electrical and thermal energy sharing, and interactions with conventional central energy services. Since system design depends on both techno-economic engineering design principles and organisational-regulatory aspects, the developed framework aims to bridge these disciplines through multi-objective optimisation approaches [241]. The following Sections detail the specific system and model aspects of the developed method.

3.1 System aspects

The energy demands of each house, and the neighbourhood as a whole, are met through the consideration and combined use of a pool of energy supply alternatives, including: (i) DER, (ii) local energy sharing through microgrid and pipeline infrastructure, and (iii) central energy services. This determines the boundaries of the system, see Figure 3.1. Note that not all units need to be installed but an optimal selection is made.

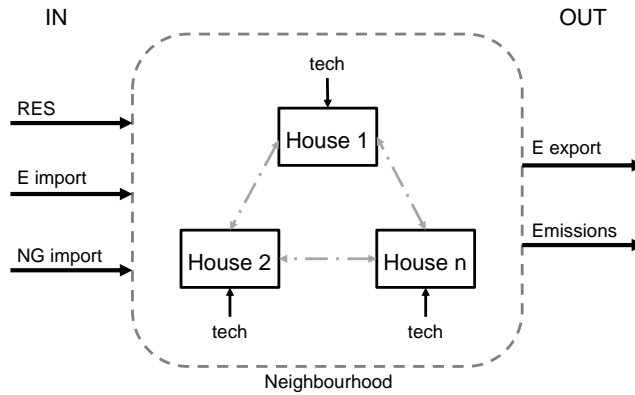


FIGURE 3.1: Boundaries of the energy system of a neighbourhood with n_h houses, including technologies (tech) and energy integration (grey dashed arrows). E=electricity, NG=natural gas, RES=renewable energy resource (e.g. sun, wind).

3.1.1 A hybrid small-scale poly-generation approach

Residential energy demands require small-scale, mini and micro units < 30 kW (see Table 1.1 and [242]). A generic pool of technologies is selected for consideration in the optimisation process. The chosen technologies are established, commercially available and able to exploit locally available resources. As new technologies become available, they can be added to the database. The considered technologies are presented below. Appendix B summarises their technology operational behaviour.

Distributed generation (DG) units encompass small-scale electrical or thermal generation units that can interact with energy sharing infrastructure and the central energy system. The considered intermittent units – based on renewable energy resources – are wall-mounted small-scale wind turbines (wind) and rooftop photovoltaic (PV) units (sun). The considered dispatchable DG unit is a small-scale combined heat and power unit (CHP). CHP units can come in various forms based on operational procedures and fuel [105, 131]. A natural gas fuelled CHP unit is selected due to its appropriate operational parameters and micro-range capacity [105]. By coupling a thermally driven refrigeration unit to the CHP unit, waste heat can also be used for cooling purposes [105]. Absorption chillers – requiring both waste heat and limited electricity for refrigeration – are the most established, suitable small-scale thermally driven cooling technology [105]. Several co-generation operational modes can be considered; electricity demand following or heat (indirect cooling) demand following [105, 129, 131]. Since thermal demands mostly exceed electricity demands in residential applications, electricity-following modes

would require auxiliary condensing boilers for supplementary space heat generation [129]. Heat-following modes, in contrast, require additional electricity supply alternatives in order to meet varying electricity loads [129]. To fully use the installed CHP unit in combination with renewable electrical DG units, heat-following operation is implemented. Additionally, conventional thermal generation units are considered that are only able to supply energy to their accommodating house, i.e. natural gas fired gas heaters or condensing boilers for space heating, electricity fuelled air-conditioning units for space cooling and a potential connection with the conventional distribution network (see Section 1.1.2). Furthermore, both electrical as well as hot and cold thermal storage are considered. Design choices determine whether storage can interact with external infrastructure or can only be employed in the accommodating house. Figure 3.2 details the energy supply and interaction options of each individual house.

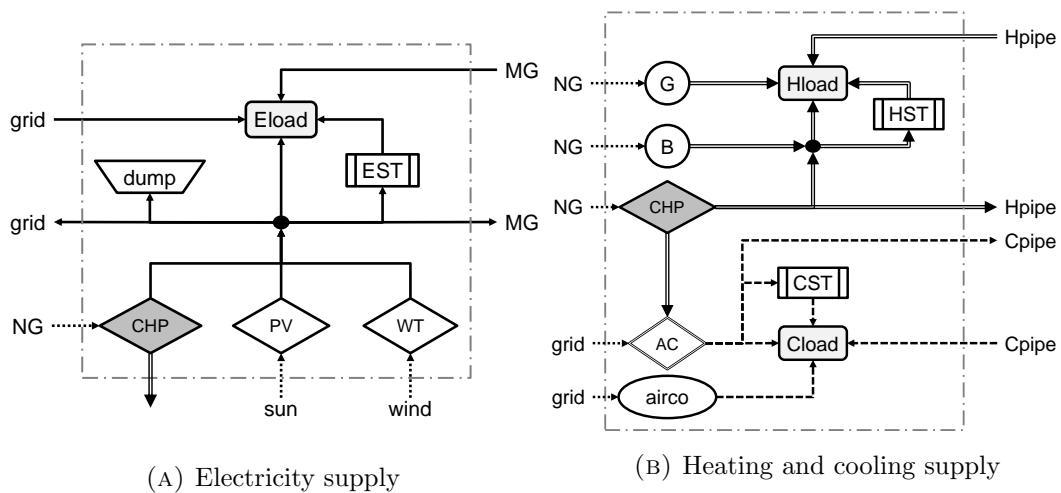


FIGURE 3.2: Black-box diagram of the considered energy supply alternatives for each house in the neighbourhood. Note that the CHP unit forms the link between the electrical and thermal supply systems. AC=absorption chiller, airco=air-conditioning unit, B=boiler, CHP=combined heat and power unit, Cload=space cooling load, Cpipe=cold pipeline network, CST=cold storage, dump=dump load, Eload=electricity load, EST=electrical storage, G=gas heater, Hload=space heating load, Hpipe=hot pipeline network, HST=hot storage, MG=microgrid electricity sharing, NG=natural gas supply, PV=photovoltaic unit, WT=small-scale wind turbine. black lines=electricity, double lines=heat, dashed lines=cooling, diamonds=DG units, circles=conventional thermal technologies.

3.1.2 An energy integrated approach

Energy efficiency improvements and cost savings can be achieved through energy integrating a neighbourhood in terms of energy services and sharing [105]. Microgrid

infrastructure can be installed, allowing for sharing of locally generated electricity between neighbourhood houses facilitated through a central control unit. Residential tri-generation, furthermore, allows for fully integrated thermal supply through optimised thermal pipeline networks with water as working fluid. A schematic of the energy integrated approach is presented in Figure 3.3. Although an energy integrated model is adopted, the main focus is on the electrical system.

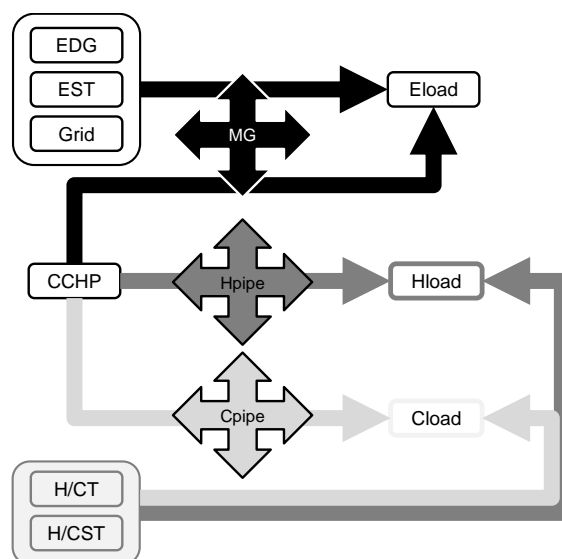


FIGURE 3.3: Energy integrated system design with energy sectors electricity (black/Eload), space heating (dark grey/Hload) and space cooling (light grey/Cload). Energy integration through microgrid (MG) for electricity and optimised heating (Hpipe) or cooling (Cpipe) pipeline networks. CCHP=combined cooling heating power, EDG=electricity distributed generation units, EST=electrical storage, H/CT=conventional heating or cooling technologies, H/CST=hot or cold storage

3.1.3 A superstructure black-box approach

DES design can be analysed through a systems thinking approach [80]. This facilitates flexible model building with building block components and interactions. Each component is represented as a black-box characterised by a set of operational and design parameters, which transform component power/energy inputs to component power/energy outputs [34]. The interactions and relations of implemented component building blocks are hence analysed on a superstructure level with loss-dependent component interactions rather than detailed thermodynamic or electrical analyses [34]. Black-box system building blocks can be aggregated into a superstructure model, which allows for less variables and degrees of freedom for complex energy systems [34]. Superstructure

models allow for high-level design of complex systems with large numbers of components and interactions to aid decision-making. Figure 3.4 presents an example superstructure black-box approach of a section of the considered DES system, namely a single house with an installed CHP unit as main component. The optimisation approach (see Section 3.2.1) selects the implemented components and interactions for each neighbourhood house based on a pool of potential components and interactions, eliminating or adopting features of each neighbourhood house system (illustrated in Figure 3.2).

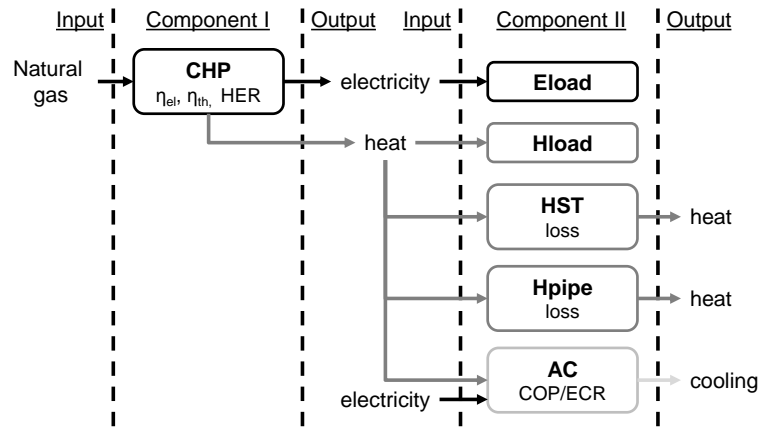


FIGURE 3.4: Superstructure black-box design of a section of the considered DES system with a CHP unit as main component. η_{el} =electrical efficiency, η_{th} =thermal efficiency, AC=absorption chiller, COP=coefficient of performance, ECR=electricity to cooling ratio, Eload=electricity load, HER=heat to electricity ratio, Hload=space heating load, Hpipe=heating pipeline, HST=heat storage unit.

3.2 Model aspects

3.2.1 A mixed-integer linear programming approach

The mathematical structure of DES design problems exhibits discrete/continuous as well as linear and non-linear behaviour. Table 3.1 gives an overview of DES model requirements based on its design aspects. A combination of integer and continuous variables is required, i.e. a constrained mixed-integer optimisation approach. Additionally, DES exhibit inherent non-linear behaviour, such as:

Technology operation: Generation technologies, in reality, often show non-linear relations between input and output. The electrical efficiency of CHP units, for example, is non-linearly dependent on its loading [243]. The closer the CHP can

operate to its rated capacity, the better its efficiency. Furthermore, starting up or shutting down units requires non-linear ramping up and ramping down times.

Technology cost: Technology unit investment cost in reality depends on installed capacity through a non-linear economies-of-scale relation with decreasing unit costs for increased installed capacities [244, 245] (see Section 6.4.1.3).

Energy sharing: Pipeline thermal energy and mass transfer is governed by non-linear thermodynamic relations through pressure and temperature drops, heat exchanges and specific heat loss behaviour [58]. Electricity transfer, furthermore, demonstrates temperature sensitivity as well as voltage and frequency drops.

TABLE 3.1: DES model requirements based on design aspects.

Design aspect	Model requirements
Sizing	continuous capacity range or discrete capacity values
Selection/siting	binary selection variables
Energy relations	continuous positive variables
Pipeline network	integer variables for network house order binary variables for connection of nodes
Costs	continuous or discrete positive variables

This inherent system behaviour renders the problem large and complex. Hence simplifications and linearisation are employed to obtain linear models, which increase efficiency of solution processes for large problems [82, 106] (see Section 2.2). Additionally, selection (switching ‘on’ and ‘off’) of technologies requires binary variables. Hence, a deterministic mixed-integer linear programming (MILP) approach is employed. Uncertainty regarding deterministic input data that employ simplified or linearised input assumptions can, however, impact the obtained solutions. Parameter sensitivity analysis and model robustness is therefore an important aspect throughout the thesis to analyse the effect of selected input parameters on the obtained results. Unless otherwise stated, the developed model is solved with GAMS 23.9.3 [115] using the CPLEX 12.4.0.1 solver [246].¹ CPLEX is suitable for large, complex problems and allows for the flexible consideration of integer, continuous, semi-continuous and Special-Ordered-Set variables [117, 246]. The CPLEX solver employs a branch and bound approach for problems with integer variables [246], see Appendix C.

¹Main computer specifications: Dell Optiplex 990, Intel(R) Core(TM), i5-2500CPU@3.30GHz, Ram 4.00GB, 32-bit operating system.

3.2.2 A multi-objective decision-making tool

Three stakeholder interests are selected to analyse DES design, fitting in with the three central energy system objectives (see Section 1.1.3) as an economic, technical and environmental objective. Since the problem is linear (convex) and a limited number of objectives (≤ 3) is analysed, the multi-objective MILP problem is solved through the weighted-sum approach. The three objectives (f_i) are hereto converted into a unity weighted single objective where the sum of the three weights (λ_i) equals one, with $h(x, y)$ equality and $g(x, y)$ inequality constraints:

$$\min_{x,y} Z = \lambda_1 \cdot f_1(x, y) + \lambda_2 \cdot f_2(x, y) + \lambda_3 \cdot f_3(x, y) \text{ s.t. } \begin{cases} h(x, y) = 0 & \text{and} & g(x, y) \leq 0 \\ x \in X, y \in 0, 1 \\ \sum_i \lambda_i = 1 & \text{and} & \lambda_i \in [0; 1] \end{cases} \quad (3.1)$$

3.3 Relying on other disciplines

DES design depends on both engineering and regulatory aspects [241]. The thesis therefore departs from an energy systems engineering viewpoint where the interactions between bodies are studied through the use of mathematical optimisation. The analysed design is framed by technical requirements of its components, system-related costs and environmental impacts. Additionally, social aspects are considered in the form of regulation to analyse the impact of regulatory and organisational framework aspects on DES design. The energy policy as well as climatic, economic and energy-related aspects of the researched location are all external factors that are included in the optimisation process. The presented method and analysis therefore lies at the interface between engineering design, through multi-objective optimisation, and energy regulation.

3.4 An Adelaide (South Australia) based neighbourhood

The developed model is subsequently applied to a small fictive residential neighbourhood consisting of five typical detached houses. Adelaide, located in South Australia (SA), is

selected as the researched location based on several factors; (i) SA is part of the liberalised National Electricity Market (NEM) of Australia, (ii) Adelaide has peak summer cooling demand days and reasonable winter heating demands [13] making it suitable for seasonal tri-generation, (iii) SA has a high availability of renewable energy resources (sun and wind), (iv) SA has high retail electricity tariffs, and (v) SA has ageing conventional power system infrastructure and remote end-of-line load centres [13], making DES attractive to defer significant network upgrades and investments. The case-study serves as an example to illustrate the developed framework and its capabilities.

3.5 Conceptual framework and approach

The conceptual framework is illustrated in Figure 3.5. DES design is determined by technical component and system behaviour, which translates into an MILP DES model. Location-specific parameters regarding technology characteristics, costs, climate, hourly average daily household electrical and thermal energy demands as well as regulatory constraints serve as input parameters to the model. Selected model outputs are the objective values, ‘optimal’ neighbourhood energy system design as well as ‘optimal’ hourly

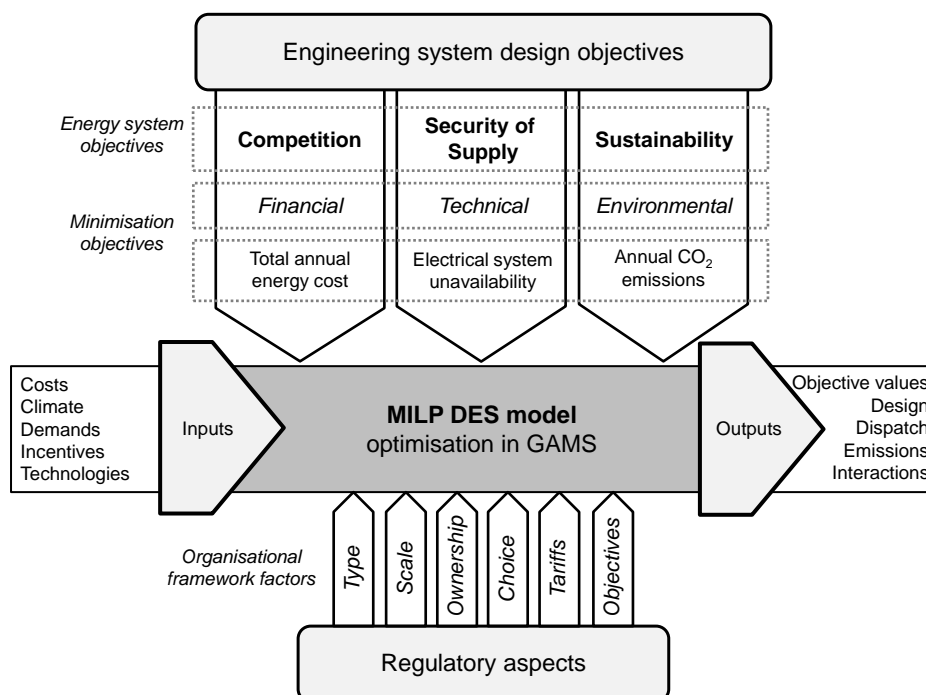


FIGURE 3.5: Conceptual framework of methodology.

average component energy interactions and technology dispatch schedules. Engineering design is determined through three objectives aligned with the three central energy system objectives (see Section 1.1.3). Regulatory aspects are analysed through quantified framework factors. This allows for bi-directional engineering-regulation analysis.

The base model is developed in Chapter 4, analysing optimal neighbourhood energy system design under total annualised energy cost minimisation. Chapter 5 analyses multi-objective engineering system design, building further on the developed base model. The multi-objective framework additionally includes minimisation of electrical system unavailability (technical) and annual CO₂ emissions (environmental) as objectives. DES regulatory framework factors, i.e. type, scale, ownership, choice, tariffs and objectives, are defined and analysed in Chapter 6 through adaptations of the developed model.

3.6 Conclusion

This Chapter developed and detailed the employed methodology to analyse both multi-objective engineering DES design as well as DES regulatory framework aspects for a small residential neighbourhood. The model is formulated as an MILP and solved with GAMS using the CPLEX solver. Three selected design objectives are defined based on the three central system objectives as (i) minimisation of total annualised energy cost, (ii) minimisation of electrical system unavailability, and (iii) minimisation of annual CO₂ emissions. The developed model is applied to a small Adelaide neighbourhood.

Chapter 4

Cost-optimal design of residential distributed energy systems

A framework for residential distributed energy system (DES) design with competitiveness as driving objective is presented (second research question, see Section 1.4). A superstructure mixed-integer linear optimisation approach is hereto developed to select, size and site components and interactions to meet the yearly energy demands (electricity, heating and cooling) of a small neighbourhood at minimum total annualised energy cost. The remaining Chapters will build further on this single-objective base model. The work in this Chapter has been disseminated into the following publications [247–250].

4.1 Introduction

4.1.1 Cost as driving objective for new investment

‘Competitiveness’, when applied to power systems, refers to economic efficiency and affordability of energy services to consumers [1, 17, 18] (see Section 1.1.3). Since implementation of distributed energy systems (DES) is only considered in residential areas if their investment and operation are attractive economic alternatives to conventional supply, their competitiveness is typically measured through economic aspects [221]. Therefore, total annual energy costs for a neighbourhood as a whole to meet its energy demands

is selected as primary driving objective for new investment. This competition inspired objective levels the playing field for DES within conventional power systems.

4.1.2 Chapter overview

The aim of this Chapter is to develop a single-objective competition based model for residential DES design optimisation. A detailed description of the problem and optimisation framework is presented in Section 4.2. The model structure, objective and constraints are detailed in Section 4.3 and applied to a case-study through various scenarios and analyses in Section 4.4. Results are illustrated in Section 4.5 to end with a general discussion (Section 4.6) and conclusion (Section 4.7) of the developed approach.

4.2 Method

4.2.1 Problem description

A generic optimisation strategy is developed to identify the ‘best’ energy system design for a small cluster of houses at a neighbourhood level through the consideration and combined use of a pool of decentral (household-level) distributed energy resources (DER), conventional energy supply options and energy integration. Design and operational behaviour are obtained whilst minimising total annualised energy related costs of a neighbourhood as a whole to meet its yearly energy demands in terms of electricity, space heating and space cooling. Neighbourhood design is optimised through the selection, siting and sizing of energy supply options. Figure 4.1 illustrates the different energy service pools of supply alternatives for each neighbourhood house. Each pool can contain various technologies. The black-box diagrams of the considered energy system components and interactions for each individual house were presented in Figure 3.2, Section 3.1.1. Note that a potential CHP unit forms the connection between electricity and thermal supply through waste heat utilisation. Furthermore, not all technologies or interactions need to be adopted, and combinations of technologies and interactions can be pre-restricted for system analysis (see Section 4.4.4).

The energy demand of each house can be met through potential DG units, i.e. micro CHP units, photovoltaic units (PV) and small-scale wind turbines (WT), natural

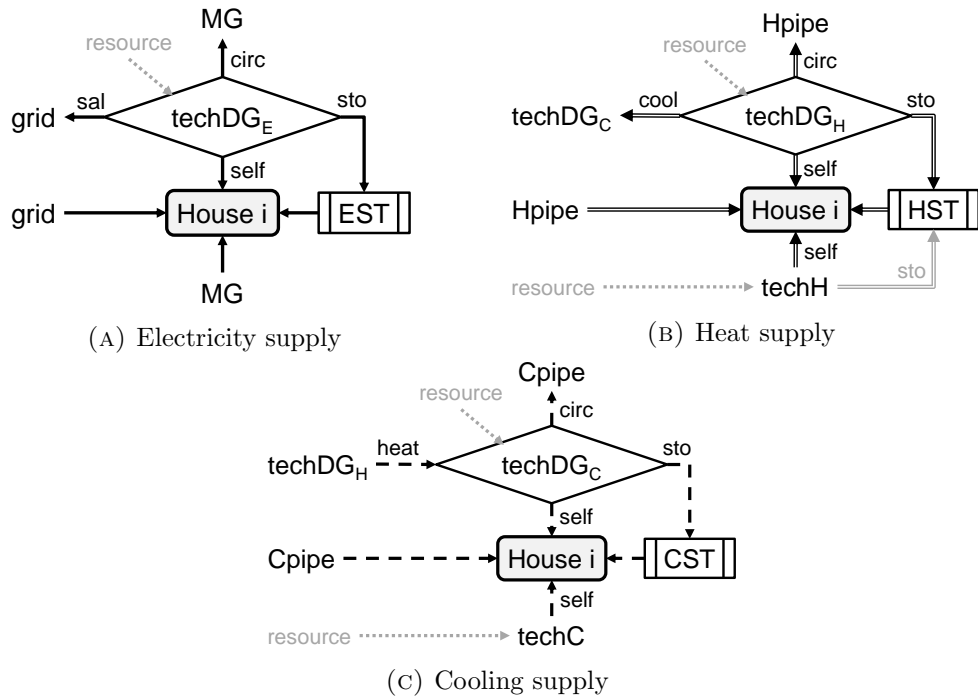


FIGURE 4.1: Generic schematic of pools of energy supply alternatives for each house in the neighbourhood. Cpipe=cold pipeline network, CST=cold storage, EST=electrical storage, Hpipe=hot pipeline network, HST=hot storage, MG=microgrid electricity sharing, techDG_C = cooling generating DG units, techDG_E = electrical DG units, techDG_H = heat generating DG units, techC =conventional cooling technologies, techH = conventional heating technologies.

gas fuelled heating technologies, electrical and (hot and cold) thermal energy storage units as well as electrically and thermally driven cooling technologies with an optional bi-directional interconnection with the central grid. Additionally, dump loads can be installed in case of microgrid operation, required to dump excess local electricity generation to prevent local network overloading and to maintain safe operation. The neighbourhood can furthermore be heat and cooling integrated through optimised pipeline networks that allow for thermal transfer between houses. Furthermore, a microgrid central control unit (MGCC) can be installed, enabling local energy sharing. This energy supply flexibility makes the model useful across a wide range of scenarios and case-studies.

4.2.2 Optimisation framework and model requirements

The system is translated into a mixed-integer linear programming (MILP) model and implemented in GAMS. Figure 4.2 illustrates the optimisation flow chart.

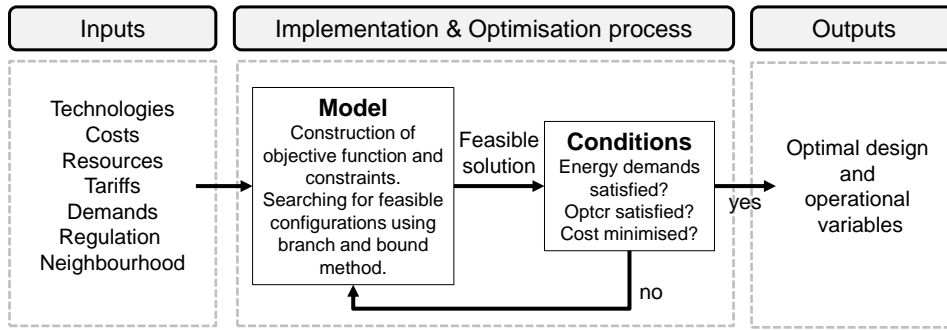


FIGURE 4.2: Flow chart of optimisation problem. Optcr=relative optimality gap.

A yearly planning horizon is adopted with a typical day (24 hours) in each season for the input parameters and variables of the problem. Various case-study-specific input data are required, presented below and detailed in Table 4.1:

Given: (i) neighbourhood layout, (ii) location specific climatological data, (iii) technical specifications of the pool of considered energy supply options, (iv) investment and operation and maintenance (OM) costs, (v) energy tariffs, (vi) state specific regulation, and (vii) spatial distributions of hourly average household energy demands.

Determine: (i) *total annualised energy cost* of the neighbourhood as a whole to meet its total yearly energy demands, (ii) *optimal design* of the neighbourhood energy system in terms of selection, siting and sizing of energy supply options, (iii) *optimal dispatch schedule* of adopted units in hourly average intervals under given demand profiles, and (iv) optimal values of *operational and emission* related variables.

The **objective** is to *minimise the total annualised energy cost* of a neighbourhood as a whole to meet its yearly electricity, space heating and space cooling demands under various operational, technical, economic, environmental and regulatory constraints.

The model is solved to a specified optimality level. Optimality can be defined in problems with discrete variables through relative (optcr) or absolute (optca) termination criteria [115]. Optcr refers to the relative gap between the best possible (current bound on solution, BP) and best found (objective function value of best integer solution found thus far, BF) solutions to an optimisation problem and determines the quality of the solution. The solver terminates its process at the first obtained solution with an objective value within $100 \cdot \text{optcr}$ of the best solution possible. If the relative gap is set to zero in a linear model, global optimality is obtained [115]. Optca refers to the absolute

TABLE 4.1: Generic input parameters of the model. Note that capacity bounds are technology dependent. AUD=Australian Dollar, OM=operation and maintenance cost.

Input	Symbol	Unit	Explanation
Neighbourhood layout	$l_{i,j}$	m	distance between each house pair i, j
Climatological data	$\bar{I}_{s,h}$	kW m^{-2}	average solar irradiation on a tilted surface in hour h in season s
	$V_{s,h}$	m s^{-1}	average wind speed at a defined height above ground level in hour h in season s
Technology specifications	L_{tech}	kW or kWh	lower capacity bound
	U_{tech}	kW or kWh	upper capacity bound
	n_{tech}	%	thermal or electrical efficiency measure
	ϵ	%	electricity network transfer losses
	β	%	pipeline network transfer losses
	ζ	%	static energy storage loss
	χ	%	storage (dis)charging rates
Costs	DOC	%	storage depth of charge
	C_{tech}^C	AUD kW_{inst}^{-1}	unit capacity investment cost
	C_{tech}^{omv}	AUD kWh^{-1}	unit variable OM cost
	C_{tech}^{omf}	AUD kW_{inst}^{-1}	unit fixed OM cost
Energy tariffs	T^{elc}	AUD kWh^{-1}	retail electricity tariff
	T^{gas}	AUD kWh^{-1}	retail natural gas tariff
	T^{CT}	AUD kgCO_2^{-1}	carbon tax
Regulation	\bar{T}_{techDG}^{SAL}	AUD kWh^{-1}	feed-in tariff for DG electricity export
	DG_{techDG}^{UP}	kW	capacity bound on maximum installed residential DG units
	PE_{techDG}^{SALUP}	kWh day^{-1}	capacity bound on export levels of residential DG units
Energy demands	$C_{ELEC,i,s,h}^{LOAD}$	kW	average electricity demand of house i in season s in hour h
	$C_{HEAT,i,s,h}^{LOAD}$	kW	average heat demand of house i in season s in hour h
	$C_{COOL,i,s,h}^{LOAD}$	kW	average cooling demand of house i in season s in hour h

gap between the best estimate and the integer value of the solution to an optimisation problem ($|BP - BF|$). The solver will terminate its process at the first obtained solution with an objective value within $optca$ of the best solution possible.

4.2.3 Model assumptions and decisions

Modelling complex systems, such as the presented, requires implementation decisions and assumptions [82, 106, 107]. The following adopted simplifying assumptions are commonly used within superstructure DES design optimisation models in literature, such as [95, 174, 175, 209, 229]:

- Only the provision of electricity, thermal space heating and cooling are considered. Water requirements, for example, for cooking and showering, are assumed separate services that do not fall under the considered design aspects. The electricity

demand consists of lighting and appliances requirements only. Space cooling and heating demands are separated out from electricity demands. Electrically driven thermal units will therefore lead to a supplementary electricity demand.

- Central services of gas and electricity are considered available to the neighbourhood. Their supply chains are, however, not taken into account. Central energy services might, however, be bound by interaction limitations (see Section 4.5.2.4).
- Energy interaction bounds are set sufficiently high, based on the maximum installed capacity of units, as to not pre-restrict any interactions but to allow for ‘optimal’, ideal energy transfer. Section 4.5.2.4 gives an example of how energy interaction restrictions can influence the obtained results.
- Constant energy conversion efficiencies are employed for technologies. In reality efficiencies often depend on operational aspects (see Section 3.2.1). Variable efficiencies are especially relevant in operational optimisation, in contrast with the here developed superstructure design decision-making approach.
- Constant proportional unit investment costs are adopted. In reality unit investment costs of generation units and pipeline infrastructure experience an economies-of-scale relation (see Section 3.2.1). This is elaborated on in Section 6.4.1.3.
- Ramp-up and ramp-down times of units are not considered based on the same reasoning as the efficiency point. Units are hence assumed to be optimally dispatched to ensure full functionality when required.
- Dependability is not explicitly addressed; the combined use of the selected units is assumed to be 100 % available to meet the local demand at all times, excluding scheduled and unscheduled outages and spare units (see Chapter 5).
- No inherent OM cost is assumed to be associated with pipelines as this cost would arise from pumps in the network. Since pipes are short in residential areas (≤ 100 m), no pumps are assumed to be installed. Energy transfer losses are, however, considered based on energy transfer distances (see Section 4.3.2.3).
- Microgrid operation is assumed to be installed in a neighbourhood with an existing electrical infrastructure. The protection systems are thus already in place and the investment cost is limited to the central control unit.

Additionally, different time scales can be considered. In order to compare the cost of the installed system with conventional neighbourhood energy supply, annualised operation and a yearly planning horizon are employed. To consider seasonal variations, a typical

day (24 hours) for three seasonal brackets is included, i.e. summer, winter and mid-season. Seasonal daily profiles with single or multi-hour time-steps are namely useful coarse time-scales with regard to the integration of seasonal tri-generation, day-night demand differences and the integration of renewable generation and storage [104, 130]. Furthermore, various choices have to be made regarding technology and interaction implementations, where alternatives exist. Section 4.3 details the adopted design choices.

4.2.4 Contributions

The developed model builds further on the work of Mehleri et al. [95, 96] by adding the following new functionalities to increase model generalisation and applicability:

- a full energy integrated approach is employed focussing not only on electricity and heat integration but also cooling through residential tri-generation,
- additional DG options are introduced for different technology pools in the form of small-scale wind turbines, absorption chillers and electrical storage,
- an approach is adopted for heating and cooling networks through the addition of a binary selection variable that only allows each house to either receive or send from or to a pipeline in each hour, or not interact,
- a similar approach is adopted for microgrid operation, i.e. the sharing of locally generated electricity, through a binary variable that decides on the existence and direction of electricity transfer between each house pair,
- an approach for renewable resource variability within MILP models is presented,
- and an Australian case-study, a country with high DES potential, is researched.

4.3 Model implementation and design decisions

The model continues the efforts of Mehleri et al. [95, 96], as detailed in Section 4.2.4, and consists of an objective function bound by design and operational constraints of the considered energy supply options and energy balances. Selected equations are detailed below. Appendix D details the full model.

4.3.1 Objective function

The design objective is to minimise total annualised energy cost, C^{TOT} [AUD y^{-1}], of a neighbourhood as a whole to meet its yearly electricity, space heating and space cooling demands. Cost terms, Equations D.1-D.6 (Appendix D), are selected based on their direct relation to the implementation and operation of the system as; (i) annualised investment cost of technologies and infrastructure (*tech*) installed in the neighbourhood, C^{INV} , (ii) yearly fixed and variable operation and maintenance cost of technologies and infrastructure, C^{OM} , (iii) yearly fuel cost related to the consumption of natural gas by installed technologies in neighbourhood houses (*i*), C^{FUEL} , (iv) yearly cost of purchasing electricity from the central grid, C_{BUY}^{GRID} , and (v) the carbon tax imposed on houses due to on-site consumption of natural gas and grid electricity, C^{CT} . Furthermore, houses can create an income by exporting electricity to the central grid, C_{SAL}^{GRID} , through potential financial support schemes in the market, such as feed-in tariffs:

$$\min C^{TOT} = C^{INV} + C^{OM} + C^{FUEL} + C_{BUY}^{GRID} + C^{CT} - C_{SAL}^{GRID} \quad (4.1)$$

The objective function is bound by (i) technology design and operational constraints of the thermal technologies (Eqs. 4.2, D.7-D.10), DG units (Eqs. D.11-D.23), storage units (Eqs. 4.3-4.4, D.24-D.39) and pipelines (Eqs. 4.5-4.10, D.40, D.41), (ii) energy balances (Eqs. D.42-D.44), (iii) grid interaction constraints (Eqs. D.45-D.47), and (iv) microgrid operation constraints (Eqs. 4.11-4.17, D.48-D.53).

4.3.2 Technology design and operational constraints

Several pools of technologies are implemented, all bound by design and operational constraints. The following Sections illustrate the conventional and DG units, storage technologies, pipeline design and operation, and design choices.

4.3.2.1 Generation units

The pool of conventional thermal technologies (*techTH*) consists of condensing boilers, gas heaters and air-conditioning units, which have upper (U_{techTH}) and lower (L_{techTH}) bounds on their continuous capacity variable, $DG_{techTH,i}^{MAX}$, as well as a binary selection

variable, $B_{techTH,i}$, which decides on technology installation in a house:

$$L_{techTH} \cdot B_{techTH,i} \leq DG_{techTH,i}^{MAX} \leq U_{techTH} \cdot B_{techTH,i} \quad \forall techTH,i \quad (4.2)$$

Natural gas fuelled CHP units, PV units and small-scale wind turbines are the considered DG units ($techDG$). Generated DG electricity can be used to feed the load of the accommodating house, to export to the grid, to circulate through the microgrid to other houses and to charge the battery, see Figures 4.1a and 4.3a. PV and wind turbine output is bound by available average solar irradiation on a tilted surface and wind speed in each hour, respectively. Wind turbines are modelled based on the Weibull distribution with characterising shape parameter and wind speed levels (see Appendix D) [251, 252]. Country specific regulation, furthermore, can place upper bounds on installed DG capacity and daily export to the central grid. CHP units and absorption chillers largely follow the behaviour of the conventional thermal technologies. Waste heat generated by CHP units can be used for space heating purposes or can be fed into the absorption chillers for cooling purposes, see Figure 4.3b. The former can be used to meet the heat

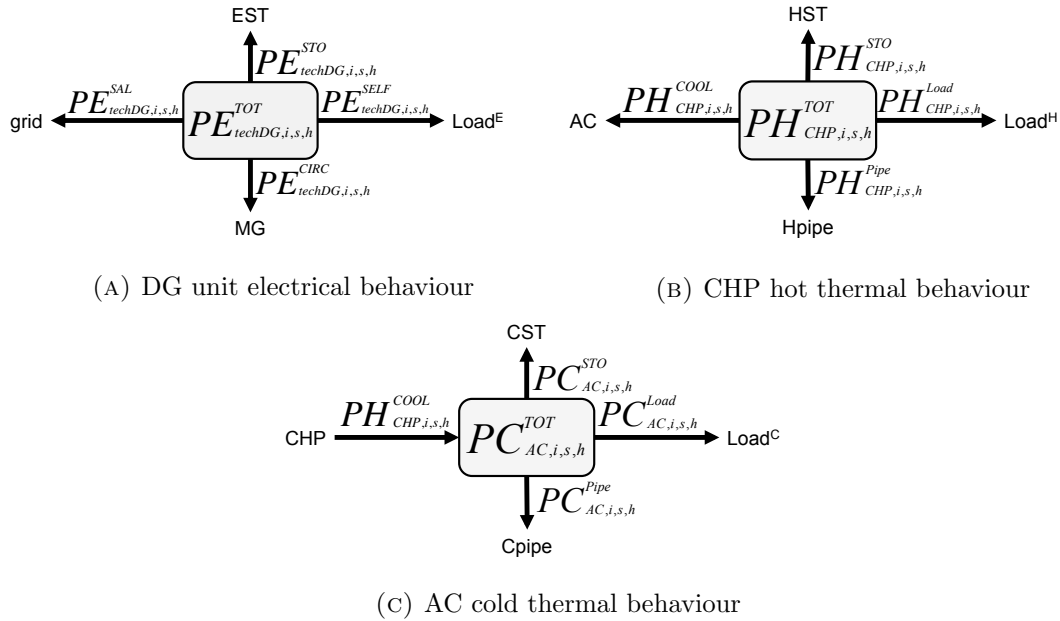


FIGURE 4.3: Schematic of electrical and thermal behaviour of DG units in house i . AC=absorption chiller, CIRC=pipe=power for local sharing, Cpipe=cold pipe, CST=cold storage, EST=electrical storage, Hpipe=hot pipe, HST=hot storage, LoadC=cooling load, LoadE=electric load, LoadH=heat load, PC=cooling power, PE=electrical power, PH=heating power, SAL=electricity for export, SELF=load=power for local load, STO=power stored, techDG=DG technologies, TOT=total generated power.

load of the accommodating house, to store in the storage tank or the transfer to other houses through a pipeline, see Figure 4.1b. Generated absorption chiller cooling can meet similar purposes, see Figures 4.1c and 4.3c.

4.3.2.2 Storage units

Storage can be implemented in various ways. The model assumes a daily roll-over of the stored energy within each season, taking into account seasonal independence by not rolling over between days of different seasons [101]. Roll-over between days allows to analyse the operational behaviour of storage units over a more continuous period [101]. Additionally, various residential storage design choices have to be made, where alternatives exist. Since the main focus of the model is self-generation combined with potential interactions with central services and no time of use tariffs are available in the South Australian market that allow for cheap night time grid-battery charging, it is assumed to only allow the potential battery in each house to be charged through self-generation by its DG units, not through external feeds (microgrid or central grid). Similarly, thermal storage units are assumed to only be charged by self-generation by their accommodating house, not through pipeline transfer (this is expanded upon in Section 6.4.3). Additionally, storage output can only be used to contribute to the demand of its accommodating house and cannot be exported or shared with other houses. Storage capacity is additionally bound and characterised by a binary variable, similar to Equation 4.2.

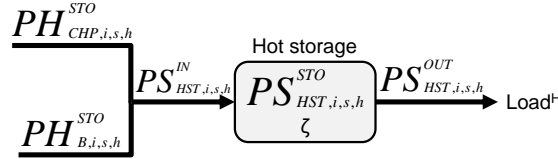
Thermal heating or cooling stored in respective storage tanks ($PS_{i,s,h}^{STO}$) is a function of power stored in the previous hour ($PS_{i,s,h-1}^{STO}$) minus a static loss percentage (ζ) plus an inflow ($PS_{i,s,h}^{IN}$), minus an outflow ($PS_{i,s,h}^{OUT}$), see Figure 4.4 and Equation 4.3. Hot storage inflow can be supplied by a CHP unit or boiler in the accommodating house. Cold storage inflow can be supplied by an absorption chiller installed in the same house.

$$PS_{i,s,h}^{STO} = (1 - \zeta) \cdot PS_{i,s,h-1}^{STO} + PS_{i,s,h}^{IN} - PS_{i,s,h}^{OUT} \quad \forall i, s, h \quad (4.3)$$

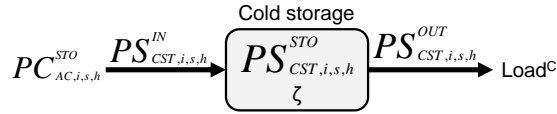
Batteries are modelled similarly to thermal storage units with additional charge (χ [%]) and discharge rates ($\delta\chi$ [%]), maximum charge and discharge rates, upper and lower limits on the state of charge, and a depth of charge. A battery can be charged through

contributions of DG units in the same house, see Figure 4.5:

$$ES_{i,s,h}^{STO} = (1 - \eta) \cdot ES_{i,s,h-1}^{STO} + hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h}^{IN} - hr \cdot \frac{PS_{EST,i,s,h}^{OUT}}{(1 - \delta\chi)} \quad \forall i, s, h \quad (4.4)$$



(A) Schematic of hot storage in house i



(B) Schematic of cold storage in house i

FIGURE 4.4: Schematic of thermal storage operation in house i . ζ =static loss, AC=absorption chiller, B=boiler, CST=cold storage, HST=hot storage, IN=power inflow, Load^C=cooling load, Load^H=heat load, OUT=power outflow, PC=cooling power, PH=heating power, PS=power stored, STO=power stored.

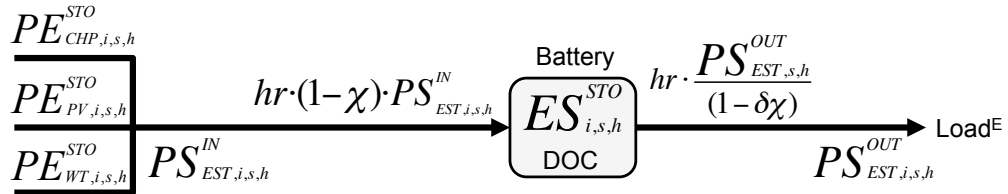


FIGURE 4.5: Schematic of battery operation in house i . $\delta\chi$ =discharge rate, η =static loss, χ =charge rate, CHP=combined heat and power, DOC=depth of charge, ES=energy stored, EST=electrical storage, IN=power inflow, Load^E=electricity load, OUT=power outflow, PE=electrical power, PV=photovoltaic, STO=power stored, WT=wind turbine.

4.3.2.3 Pipeline constraints

Hot thermal pipeline network operation and optimisation is detailed below. Cold thermal networks are modelled similarly. A binary decision variable, $YP_{i,j}$, decides whether a pipeline is installed from house i to house j . Since thermal fluid behaves with more inertia compared to ‘instantaneous’ electrical fluxes, thermal pipelines are assumed unidirectional at all times (Equation 4.5), in contrast with electricity exchanges that can

change direction in each hour:

$$YP_{i,j} + YP_{j,i} \leq 1 \quad \forall i, j \text{ and } i > j \quad (4.5)$$

Furthermore, heat transferred between each pair of houses (i, j) in each hour h of each season s , $QH_{i,j,s,h}$, is bound by the existence of the pipe, $YP_{i,j}$, and an appropriate upper bound, U_{PIPE} . The transfer bound is set sufficiently large as to not pre-restrict the model but allow for ideal optimal pipeline transfer. Optimally transferred heat values can indirectly determine the required pipe dimensions.¹

Multiple pipeline networks can be installed in the neighbourhood and not each house needs to be connected to a network. OH_i is a positive integer variable, which indicates for each house the visiting order in a pipeline network [95, 96]. Closed network loops are not allowed as they can lead to false results where, for example, thermal energy is generated and circulated during times where no thermal demand exist [96]. Since no closed loops are allowed and the system is uni-directional, the order of houses connected to one network is strictly increasing from the source house(s) to the house(s) at the end of the network. This constraint, Equation 4.6, ensures breaking up of internal loops (see Appendix F) [253]. n_h indicates the total number of houses in the neighbourhood:

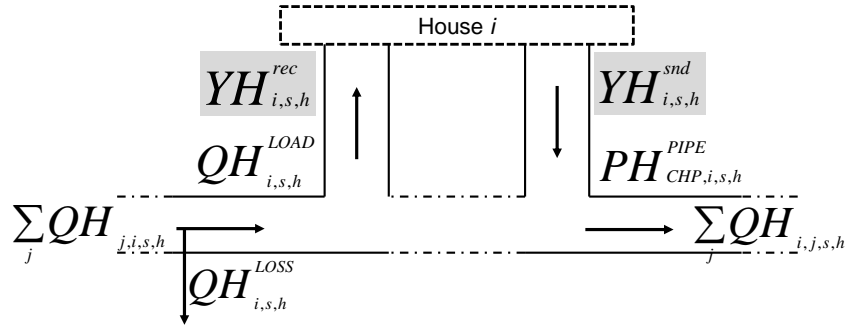
$$OH_j \geq OH_i + 1 - n_h \cdot (1 - YP_{i,j}) \quad \forall i, j \text{ and } i \neq j \quad (4.6)$$

Only CHP units are assumed to be able to send hot water to the network, $PH_{CHP,i,s,h}^{PIPE}$. This heat can then be transferred between a pair of houses, $QH_{i,j,s,h}$, to meet part of the heat load of other houses, $QH_{i,s,h}^{LOAD}$, or can be passed on to more houses in the network, see Figure 4.6. The thermal balances are given:

$$PH_{CHP,i,s,h}^{PIPE} + \sum_j QH_{j,i,s,h} - QH_{i,s,h}^{LOSS} = QH_{i,s,h}^{LOAD} + \sum_j QH_{i,j,s,h} \quad \forall i, s, h \text{ with } i \neq j \quad (4.7)$$

$$\sum_i PH_{CHP,i,s,h}^{PIPE} - \sum_i QH_{i,s,h}^{LOSS} = \sum_i QH_{i,s,h}^{LOAD} \quad \forall s, h \quad (4.8)$$

¹Pipe dimensions could be retrieved from obtained maximum optimal transferred capacity as follows [227]: $\max QH_{i,j,s,h} = \rho \frac{\pi \cdot (d_{dc})^2}{4} \cdot c \cdot v_{max} \cdot \Delta T_{cd}$, with $QH_{i,j,s,h}$ the maximum transferred capacity between houses i and j [kW], ρ the water density [kg m⁻³], d_{dc} diameter class of a commercially available pipe [m], v_{max} the maximum acceptable water velocity in pipes [m s⁻¹], and ΔT_{cd} the temperature difference between pipe in- and outlet.

FIGURE 4.6: Schematic of pipeline operation of house i . Grey=Binary variable.

The model is constructed based on interactions between components through power and energy flows with transfer distance related percentage losses. Hence, no temperature differences or mass transfers are taken into account in the pipeline modelling, consistent with the level of detail in the electrical system, which excludes active and reactive power flows as well as voltage drops. Thermal losses, $QH_{i,s,h}^{LOSS}$, are evaluated as the sum over houses i of the heat transfer between houses j and i multiplied with a fixed percentage heat loss (β) in function of distance between the pair ($l_{i,j}$):

$$QH_{i,s,h}^{LOSS} = \sum_j \beta \cdot l_{i,j} \cdot QH_{j,i,s,h} \quad \forall i, s, h \text{ with } i \neq j \quad (4.9)$$

When connected to a pipeline network, each house can, in each hour, either receive or send hot water, determined by binary variables $YH_{i,s,h}^{rec}$ and $YH_{i,s,h}^{snd}$ respectively:

$$YH_{i,s,h}^{rec} + YH_{i,s,h}^{snd} \leq 1 \quad \forall i, s, h \quad (4.10)$$

Heat send to ($PH_{CHP,i,s,h}^{PIPE}$) and from the network to a house ($QH_{i,s,h}^{LOAD}$) is bound by maximum pipe utilisation rates (U_{snd}) and sending capability ($YH_{i,s,h}^{snd}$), or, the total heat load of the house ($C_{HEAT,i,s,h}^{LOAD}$) and receiving capability ($YH_{i,s,h}^{rec}$), respectively.

4.3.3 Energy interaction constraints

Several energy interactions occur to meet the different energy balances (Appendix D), to interact with the central grid and to share local electricity through microgrid operation. Thermal pipeline energy interactions have already been detailed in Section 4.3.2.3.

4.3.3.1 Energy balances and grid interactions

The electricity load of each house together with potential dump loads - only available in case of microgrid operation - and electricity for the operation of electrically driven cooling technologies is satisfied through a combination of self-generation by DG units, microgrid electricity sharing, grid import and batteries. Thermal balances comprise both heating and cooling and are met by a combination of self-generation by thermal technologies, pipeline transfer and thermal storage.

4.3.3.2 Microgrid operation

Microgrid operation - decided through binary variable Z - requires the neighbourhood to interact as a whole with the central grid, rather than each house individually, see Figure 4.7. Binary variables $X_{i,s,h}^{snd}$ and $X_{i,s,h}^{rec}$ indicate whether house i sends or receives electricity to or from the central grid in each hour h , respectively, $\forall i, s, h$ and $i > 1$:

$$X_{i,s,h}^{snd} - X_{i-1,s,h}^{snd} \leq 1 - Z \quad \text{and} \quad X_{i-1,s,h}^{snd} - X_{i,s,h}^{snd} \leq 1 - Z \quad (4.11)$$

$$X_{i,s,h}^{rec} - X_{i-1,s,h}^{rec} \leq 1 - Z \quad \text{and} \quad X_{i-1,s,h}^{rec} - X_{i,s,h}^{rec} \leq 1 - Z \quad (4.12)$$

A binary selection variable, $MGC_{i,j,s,h}$, is adopted to indicate if electricity is shared from house i to house j in each hour h :

$$MGC_{i,j,s,h} + MGC_{j,i,s,h} \leq Z \quad \forall i, j, s, h \text{ with } i \neq j \quad (4.13)$$

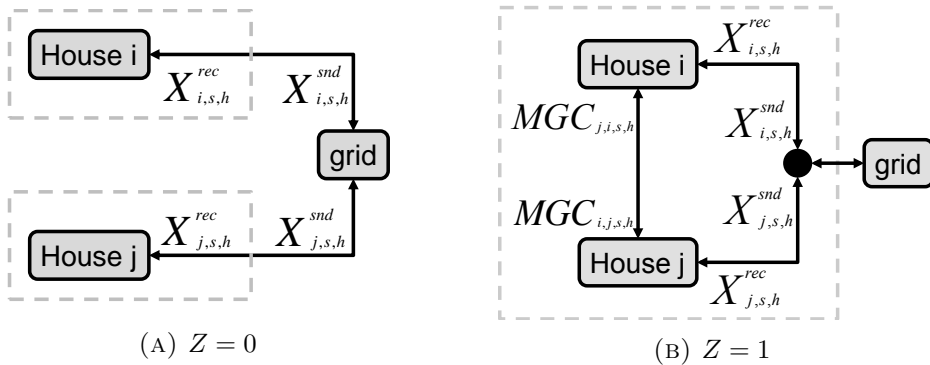


FIGURE 4.7: Grid interaction behaviour of neighbourhood houses without (left) and with (right) installed microgrid Z . Black arrows=potential interactions, black dot=point of common coupling.

Electricity send to, $PE_{techDG,i,s,h}^{CIRC}$, or received from, $PE_{MG,i,s,h}^{rec}$, the microgrid by a house can be divided into house pair interactions, $PE_{i,j,s,h}^{snd}$ and $PE_{i,j,s,h}^{rec}$ respectively:

$$\sum_{techDG} PE_{techDG,i,s,h}^{CIRC} = \sum_j PE_{i,j,s,h}^{snd} \quad \forall i, s, h \text{ with } i \neq j \quad (4.14)$$

$$PE_{MG,i,s,h}^{rec} = \sum_j PE_{i,j,s,h}^{rec} \quad \forall i, s, h \text{ with } i \neq j \quad (4.15)$$

The electricity interactions are posted (positive) variables that can take on any value $\in [0; U_{MGC}] \forall i, j, s, h$ and $i \neq j$:

$$PE_{i,j,s,h}^{snd} \leq U_{MGC} \cdot MGC_{i,j,s,h} \quad \text{and} \quad PE_{i,j,s,h}^{rec} \leq U_{MGC} \cdot MGC_{j,i,s,h} \quad (4.16)$$

The electricity interaction implementation has as goals to ensure (i) that if no microgrid is installed ($Z = 0$), there is no electricity exchange ($PE_{techDG,i,s,h}^{CIRC} = PE_{MG,i,s,h}^{rec} = 0$), and (ii) that the exchange in each hour can only be uni-directional. Both requirements are ensured through Equation 4.13. Note that if there is no electricity exchange between a pair of houses in a certain hour in a season, there could still be a connection enabled ($MGC_{i,j,s,h} = 1$), since these connections are ‘free’ once the microgrid is installed. This behaviour is acceptable since the value of binary variable $MGC_{i,j,s,h}$ is not used for energy system design purposes in the scope of the thesis.

Microgrid balances should be respected in each hour for each house and for the neighbourhood as a whole. Additionally, total DG electricity for microgrid sharing is bound by an upper level U_{MG} and by infrastructure existence (Z). Electricity transfer losses are evaluated by multiplying the transferred electricity with a constant distance dependent loss percentage (ϵ) and the distance between the house pair $l_{i,j}$ [m] (see Table 4.1).

$$PE_{i,j,s,h}^{LOSS} = \frac{\epsilon}{1000} \cdot l_{i,j} \cdot PE_{i,j,s,h}^{snd} \quad \forall i, j, s, h \text{ and } i \neq j \quad (4.17)$$

4.4 Case-study: a small Adelaide based neighbourhood

The researched neighbourhood and case-study scenarios are detailed below (and in Appendix E) through specific inputs regarding environment, technologies and costs.

4.4.1 Neighbourhood characteristics

A fictive small residential South Australian neighbourhood is researched, consisting of five average, typical Adelaide houses in one geographically clustered area. The layout of the neighbourhood is given in Figure 4.8 and Appendix E. Adelaide houses are considered with an average floor area of about 200 m² [254] and the current minimum 6-star new building energy efficiency requirements [255, 256]. Australia is based in the Southern hemisphere. The applicable seasonal months and the number of days in each selected season for a non-leap year are detailed in Table 4.2. Three seasonal days of hourly average demands are implemented to illustrate model capability. The model, however, allows for more refined or coarser seasonal and daily intervals.

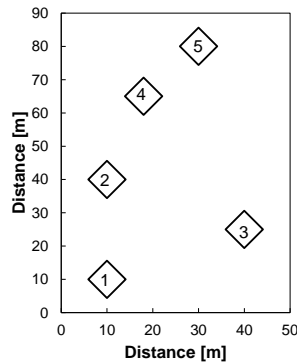


FIGURE 4.8: Layout of a fictive neighbourhood consisting of 5 residential houses with the distance [m] between each pair of houses, adapted from [95].

TABLE 4.2: Details of the selected months and days in each season for Adelaide, South Australia, based in the Southern hemisphere for a non-leap year.

Season	Months	Number of days
Summer	January-February-November-December	120
Winter	May-June-July-August	123
Mid-season	March-April-September-October	122

Each house has daily profiles of hourly average demands of which the derivation is detailed in Appendix E. Electricity demands for an average day in each season are presented in Figure 4.9a for one neighbourhood house (h_3) and are obtained from aggregated measurement data received from the South Australian distribution system operator, SA Power Networks (SAPN) [257]. Heating and cooling demands are derived using the Degree Day method [258, 259] (see Appendix E) and compared with the received aggregated demand data from SAPN, see Figure 4.9b. Note that in winter and summer no space cooling and heating is assumed, respectively. The energy demands of each

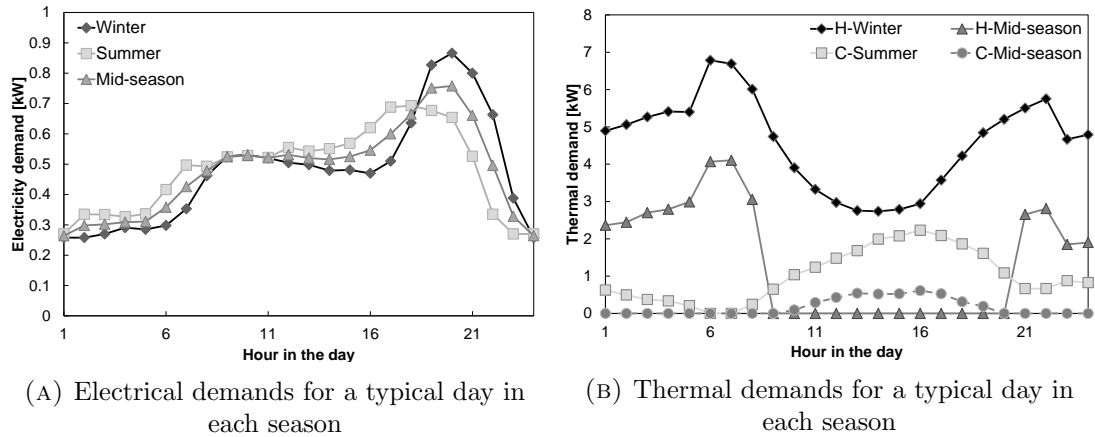


FIGURE 4.9: Daily profiles of hourly average electricity (left) and thermal (right) demands [kW] of a representative house (h_3) in the neighbourhood [kW]. Note that the electricity demands do not include electricity used for space cooling purposes, but only electricity for appliances. C=space cooling, H=space heating.

house are summarised in Appendix E, Table E.10 to E.13. Neighbourhood houses are assumed to have varying demands with a similar profile to mimic demand variations of consumers with similar behaviour. Houses are thus considered to have in percentage varying demands (plus and minus 10 and 20 %) compared to a representative house (h_3), with h_5 the highest and h_1 the lowest (see Appendix E).

Adelaide has a high level of daily solar irradiation, 4 - 5 kWh day⁻¹ m⁻² [260]. The hourly profiles of solar irradiation on a tilted surface are given in Figure 4.10a for a typical day in each season. The 2010 solar irradiation data are retrieved from [260, 261], which are used to derive the global solar irradiance on a tilted surface [262] (see Appendix E). The wind data are obtained from [260] and are transformed to an appropriate hub height using the power law wind speed conversion [263], see Figure 4.10b and Appendix E.

South Australia has State-based regulation, energy tariffs and central energy service characteristics. The model allows for hourly varying electricity and gas tariffs. In this case-study, however, average flat residential tariffs are employed as 0.344 AUD kWh⁻¹ (electricity) and 0.128 AUD kWh⁻¹ (natural gas) [264, 265]. Australian feed-in tariffs vary for each State. In South Australia there is only a tariff for residential PV electricity export. The new tariff, since the second half of 2014, is a minimum retailer payment of 0.06 AUD kWh⁻¹ [266]. Additionally, Australia had a carbon tax in place of 24 AUD tonCO₂⁻¹ in the financial year 2013 to 2014 with the plan of joining the European trading scheme in 2014. This tax has, however, been abolished as of the 1st of July

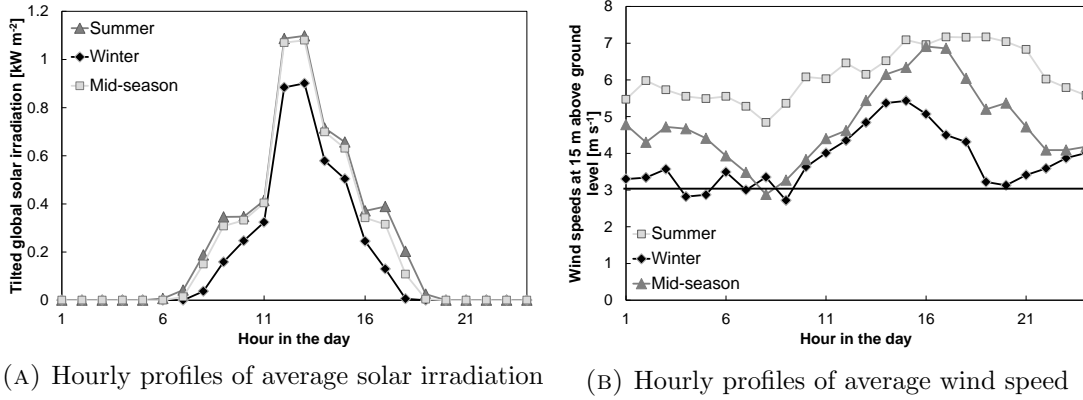


FIGURE 4.10: Daily profiles of hourly average tilted global solar irradiation [kW m^{-2}] (left) and wind speed [m s^{-1}] (right) for a typical day in each season in Adelaide, South Australia. Horizontal line=cut-in wind speed.

2014 [267]. No carbon tax is thus currently in place. The carbon characteristics of central electricity and natural gas services are a carbon intensity of $0.650 \text{ kgCO}_2 \text{ kWh}^{-1}$ and $0.216 \text{ kgCO}_2 \text{ kWh}^{-1}$, respectively [268].

4.4.2 Technology and interaction characteristics

Thermal technology bounds and efficiencies are presented in Table 4.3.

TABLE 4.3: Characteristics of the thermal technologies: efficiency (n_{tech}^{th} or COP), upper (U_{tech}) and lower (L_{tech}) capacity limit. AC=absorption chiller, airco=air-conditioning unit, B=boiler, CST=cold storage, G=gas heater, HST=hot storage.

	AC [60, 269]	airco [270]	B [93, 96, 271, 272]	CST/HST [77, 229]	G [96, 271]
n_{tech}^{th}	-	-	85%	-	75%
COP	0.7	3	-	-	-
U_{tech} [kW]	35	30	35	50	35
L_{tech} [kW]	1.5	1.5	5	0.150	5

Small-scale wind turbines are characterised by a rated capacity (1.5 kW) as well as a cut-in (3 m s^{-1}), a cut-out (25 m s^{-1}) and a rated wind speed (11 m s^{-1}) (see Appendix E) [209, 273]. PV units are characterised by a rated capacity of $0.15 \text{ kW}_{\text{peak}} \text{ m}^{-2}$ and an electrical efficiency of 12 % [96, 274]. South Australian regulation, furthermore, places an upper bound on installed capacity and daily export of residential PV units. In Adelaide these are bound to 10 kW and 45 kWh day^{-1} , respectively [275]. This upper PV capacity level translates to a 67 m^2 surface area [275]. Each house can have a single CHP unit in the range $\in [1; 20] \text{ kW}_{\text{elec}}$ with an electrical efficiency of 25 % and a heat to electricity ratio of $2.6 \text{ kW}_{\text{therm}} \text{ kW}_{\text{elec}}^{-1}$. Batteries are characterised by a depth of charge

of 70 % and an installed capacity $\in [1; 100]$ kWh [273, 276]. A charge controller complements each installed battery. The system losses as well as the charge and discharge battery characteristics are presented in Table 4.4.

TABLE 4.4: Loss terms in the system [229, 273, 276, 277].

Term	β pipeline thermal transfer loss	$\delta\chi$ battery discharge rate	ϵ microgrid electrical transfer loss	ζ thermal storage static loss	η battery storage static loss	χ battery charge rate
Loss	0.1	25	0.03	10	0.1	25
Unit	[% m ⁻¹]	[%]	[% km ⁻¹]	[%]	[%]	[%]

4.4.3 Cost data

Investment costs of technologies are annualised using a capital recovery factor, expressed through: $CRF = (r \cdot (1+r)^n) / ((1+r)^n - 1)$ [95], with n the component life time, set to 20 years for all technologies. Batteries are set to have a life time of 5 years [96, 209, 229]. The interest rate, r , is set to 7.5 % [96, 229]. The costs of the different units are given in Table 4.5. PV units, 15 [AUD kW_{peak}⁻¹ y⁻¹], wind turbines, 72 [AUD kW_{peak}⁻¹ y⁻¹], and batteries, 2.5 [AUD kWh_{peak}⁻¹ y⁻¹], are the only technologies considered to have a fixed OM cost due to yearly maintenance requirements, e.g. panel cleaning [95, 251].

TABLE 4.5: Technology (Tech) investment (C_{tech}^C [AUD kW_{installed}⁻¹]) [60, 77, 93, 95, 96, 209, 229, 270, 278, 279] and variable OM (C_{tech}^{omv} [AUD kWh⁻¹]) [95, 96, 209] costs, unless otherwise stated. AC=absorption chiller, airco=air-conditioning, B=boiler, Cont=battery controller, CST=cold storage, dump=dump load, EST=battery, G=gas heater, HST=hot storage, WT=wind turbine, MGCC=microgrid controller.

Tech	AC	airco	B	CHP	Cont	CST	dump
C_{tech}^C	540	300	150	3100	350	60	150
C_{tech}^{omv}	0.015	0.01	0.01	0.015	–	0.0015	–
Tech	EST	G	HST	WT	MGCC	Pipes	PV
C_{tech}^C	300	100	30	3500	1860	60	2000
	[AUD kWh ⁻¹]				[AUD unit ⁻¹]	[AUD m ⁻¹]	
C_{tech}^{omv}	0.01	0.01	0.0015	0.01	–	–	0.01

4.4.4 Technology combination constraints

Several assumptions have been made based on business practices and differences in working fluid, where alternatives exist, to determine mutually exclusive combinations of installed technologies and interactions for each house. These combinations introduce flexible inequality constraints that can be enabled or disabled to assess and implement

various design choices. Table 4.6 presents the constraints that are adopted in this case-study. Since CHP units are assumed to operate in heat-following mode, they are dimensioned to meet the full heat demand of their accommodating house, plus potential storage and pipeline transfer requirements. Hence a house with a CHP unit is assumed to either send or pass through heat to or from the pipeline network, not receive. Similarly, a house can either have a CHP unit or a gas heater or a boiler to meet its heating demands. Furthermore, when a house has a gas heater installed it cannot be connected to a hot pipeline network or have a hot storage tank. Similarly, cooling technologies are dimensioned to meet the full cooling load of the accommodating house plus potential other services. A house can thus either have an absorption chiller with potential cold storage and pipe sending capacity, or, an electrically driven air-conditioning unit without storage or pipeline connection. A case-study that investigates the relaxation of the boiler-CHP constraint is presented in Section 4.5.2.4.

TABLE 4.6: Assumptions of mutual exclusive technology combinations.

Technology	Binary	OR	Technology	Binary	Constraint $\forall i, s, h$
CHP	$B_{CHP,i}$	OR	boiler/gas heater	$B_{techH,i}$	$B_{CHP,i} + B_{techH,i} \leq 1$
		OR	pipeline receive	$YH_{i,s,h}^{rec}$	$B_{CHP,i} + YH_{i,s,h}^{rec} \leq 1$
Boiler	$B_{B,i}$	OR	pipeline send	$YH_{i,s,h}^{snd}$	$B_{B,i} + YH_{i,s,h}^{snd} \leq 1$
Gas heater	$B_{G,i}$	OR	boiler	$B_{B,i}$	$B_{G,i} + B_{B,i} \leq 1$
		OR	hot storage	$B_{HST,i}$	$B_{G,i} + B_{HST,i} \leq 1$
Absorption chiller	$B_{AC,i}$	OR	pipeline connection	$YH_{i,s,h}^{rec/snd}$	$B_{G,i} + YH_{i,s,h}^{rec/snd} \leq 1$
		OR	air-conditioning	$B_{airco,i}$	$B_{AC,i} + B_{airco,i} \leq 1$
Air-conditioning	$B_{airco,i}$	OR	pipe receive	$YC_{i,s,h}^{rec}$	$B_{AC,i} + YC_{i,s,h}^{rec} \leq 1$
		OR	pipeline connection	$YC_{i,s,h}^{rec/snd}$	$B_{airco,i} + YC_{i,s,h}^{rec/snd} \leq 1$
		OR	cold storage	$BCST,i$	$B_{airco,i} + BCST,i \leq 1$

4.4.5 Analysis and selected energy system scenarios

The model is solved to global optimality (this is expanded upon in Section 4.6) for selected system scenarios to illustrate the flexibility and capability of the model to assess different implementation aspects and operational combinations, and to assess results that can be obtained for a researched case-study location:

- I *Conventional*: each house receives electricity from the grid, heat from a gas heater and cooling through an air-conditioning unit.
- II *Optimal design on-grid*: no restrictions on presented model.
- III *Optimal design off-grid*: grid import and export interactions are prohibited.

IV *Optimal design on-grid without conventional thermal technologies*: gas heaters and air-conditioning units cannot be installed in the neighbourhood.

V *Optimal design off-grid without conventional thermal technologies*: idem to Scenario IV but with additional prohibition of grid import and export interactions.

On- and off-grid configuration comparison allows to assess redundancy requirements to enable islanding operation. The energy system scenarios are implemented through fixing binary variables and restricting interactions. Conventional operation is included as reference. Since a deterministic modelling approach is employed, uncertainty of input data can affect the results obtained. Various analyses can be conducted using the developed framework, such as assessing the impact on design from energy interaction restrictions and technology parameter choices. Selected analyses are therefore performed to assess the robustness of the model and show its capability, with respect to:

- *upscaling* of the neighbourhood,
- *sensitivity analysis* performed on key uncertain input data, i.e. energy tariffs,
- *variability analysis* of available renewable energy resources, i.e. solar irradiation,
- and *implementation aspects* analyses with respect to electricity interaction restrictions, efficiency characteristics of CHP units and the impact of flexible technology combinations on design.

4.5 Results and analysis

Section 4.5.1 illustrates selected scenario results. Section 4.5.2 subsequently analyses model robustness. Table 4.7 presents the model statistics of Scenario II (base model).

TABLE 4.7: Model statistics of Scenario II.

CPU time		64 s	
Blocks of equations	116	Single equations	31 421
Blocks of variables	81	Single variables	23 553
Non zero elements	110 626	Discrete variables	3686

4.5.1 Energy system design scenarios

Figure 4.11 presents the cost breakdown of the neighbourhood for each scenario. A

summary of other results is given in Table 4.8. Total cost and emissions are the highest for the conventional Scenario (I) due to (i) the yearly electricity import requirement with high carbon intensity at high electricity tariffs in the South Australian market, and (ii) the unavailability of DG units to generate income through export to offset costs. Total cost is in all scenarios dominated by natural gas fuel costs for heat generation. Natural gas use also majority contributes to emissions. Houses with the largest cost and emission contributions are the houses with more installed dispatchable DG units, such as CHPs and absorption chillers. Introducing absorption chillers (Scenarios IV and V) as only cooling technology leads to fuel cost (and hence emission) increase due to CHP deployment around the year for seasonal tri-generation instead of only during times with heating demands. Additionally, the installation of absorption chillers reduces dependency on the central grid (Scenario IV) due to yearly CHP operation. Energy integration decreases yearly cost (Scenarios II to V). Furthermore, off-grid configurations are more expensive but lead to less emissions with respect to their equivalent on-grid configuration. This is due to non-existent grid electricity import of the former.

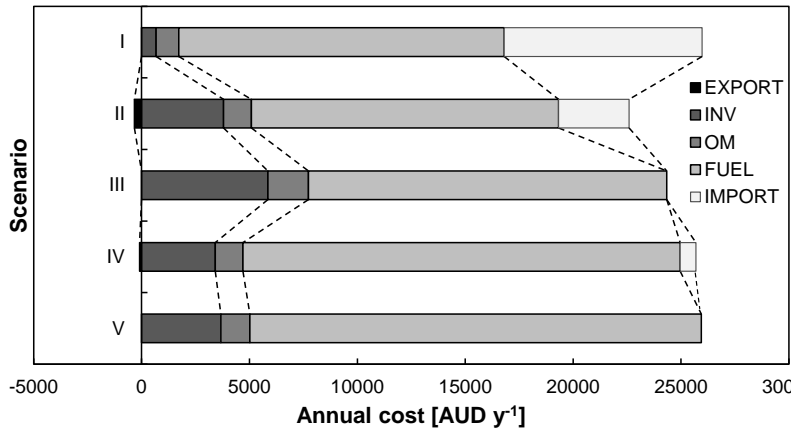


FIGURE 4.11: Neighbourhood annual cost distribution [AUD y⁻¹] for Scenarios I to V. EXPORT=electricity export, FUEL=fuel cost, IMPORT=grid electricity import, INV=investment cost, OM=operation and maintenance cost.

TABLE 4.8: Summary of results of selected energy system design scenarios: yearly CO₂ emissions [tonCO₂ y⁻¹], yearly import (PE_{GRID}^{rec}), export (PE_{GRID}^{SAL}), microgrid (MG) electricity ($PE_{MG,i,s,h}^{rec}$) [kWh y⁻¹] and the installation of a MG.

Scenario	I	II	III	IV	V
CO ₂	42.77	30.19	28.01	35.58	35.30
PE_{GRID}^{rec}	26644	9496	—	2119	—
PE_{GRID}^{SAL}	—	5953	—	6566	—
$PE_{MG,i,s,h}^{rec}$	—	5183	14128	10182	18793
MG	no	yes	yes	yes	yes

Neighbourhood designs are optimised in terms of unit selection, sizing (Figure 4.12) and siting (Figure 4.13) and can be represented in various ways. Table 4.9 summarises the total installed capacity of each unit type in each neighbourhood scenario. Apart from Scenario I, microgrid operation is adopted in all scenarios. No batteries are installed across scenarios due to the combination of (i) their relatively high investment cost, and (ii) the installation of dispatchable and balancing electricity interactions through CHP units and microgrid operation, respectively. Electrical dump loads are installed in selected houses in the off-grid scenarios (III and V) since no balancing bi-directional

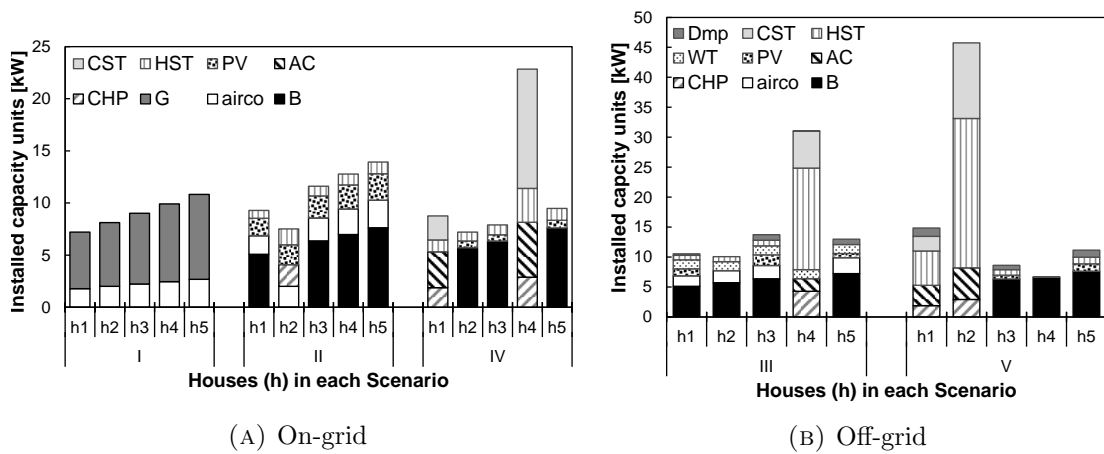


FIGURE 4.12: Installed capacity of units [kW] in the different houses (h1 - h5) in the neighbourhood for Scenarios I to V; on-grid scenarios (left) and off-grid scenarios (right). AC=absorption chiller, airco=air-conditioning unit, B=boiler, CHP=combined heat and power unit, CST=cold storage, Dmp=dump load, G=gas heater, HST=hot storage, PV=photovoltaic unit, WT=wind turbine.

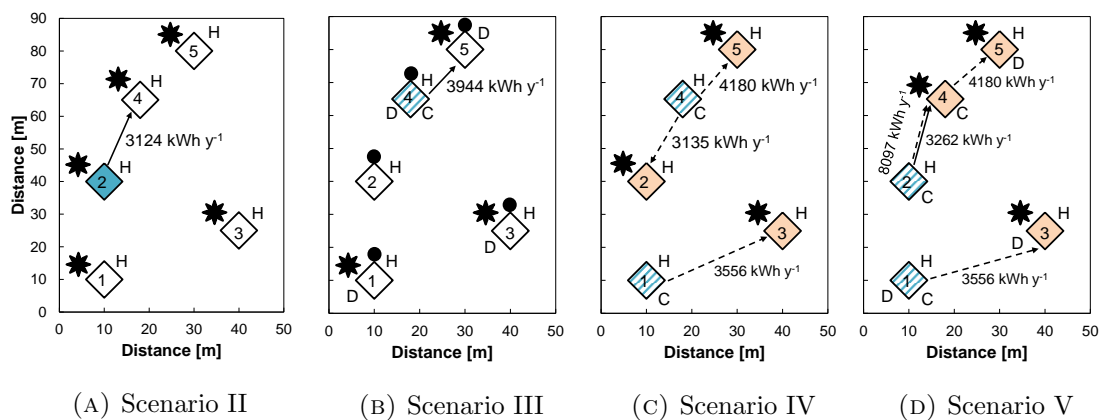


FIGURE 4.13: [colour] Neighbourhood layout for each scenario. Note that no batteries are installed. sun=PV unit, black dot=WT, H=hot storage, C=cold storage, D=dump load, dark grey diamond (blue)=CHP and air-conditioning, white diamond=boiler and air-conditioning, grey (blue) hatched diamond=CHP and absorption chiller, light grey diamond (orange)=boiler without cooling generation unit, black arrow=annual pipeline heat transfer, black dashed arrow=annual pipeline cooling transfer.

TABLE 4.9: Total installed unit capacity in neighbourhood per scenario [kW]. AC=absorption chiller, airco=air-conditioning, B=boiler, CHP=combined heat and power, CST=cold storage, dump=dumplload, G=gas heater, HST=hot storage, PV=photovoltaic, WT=wind turbine.

<i>tech</i> Scenario	G	B	airco	PV	WT	CHP	AC	HST	CST	dump
I	33.9	–	11.2	–	–	–	–	–	–	–
II	–	26.0	11.2	10.5	–	2.1	–	5.4	–	–
III	–	24.3	8.7	3.7	7.5	4.3	2.1	19.5	6.1	2.2
IV	–	19.6	–	2.0	–	4.8	8.7	7.3	13.7	–
V	–	20.5	–	2.0	–	4.8	8.7	32.7	15.1	3.3

grid connection is available. Additionally, absorption chillers are feasible in the off-grid scenarios since they reduce electricity demand requirements for cooling compared to air-conditioning units. Energy integration is adopted in Scenarios II to V in terms of electricity and limited heating and cooling. Note that the same capacity of CHP and absorption chiller is installed in Scenarios IV and V, but different storage units. The latter is due to different pipeline and siting configurations (see Figure 4.13).

Neighbourhood energy interactions and unit dispatch schedules are also indirectly optimised under the given demand profiles and can hence be analysed on various levels. Figure 4.14, for example, illustrates the share of seasonal electricity generated by different neighbourhood DG units for either self-use by accommodating houses, export, sharing through microgrid or pipelines, or, storage. Electricity generated by CHP units is the predominant source of electricity for microgrid sharing. PV electricity, in contrast, is predominantly used for export due to the potential to generate an income through a

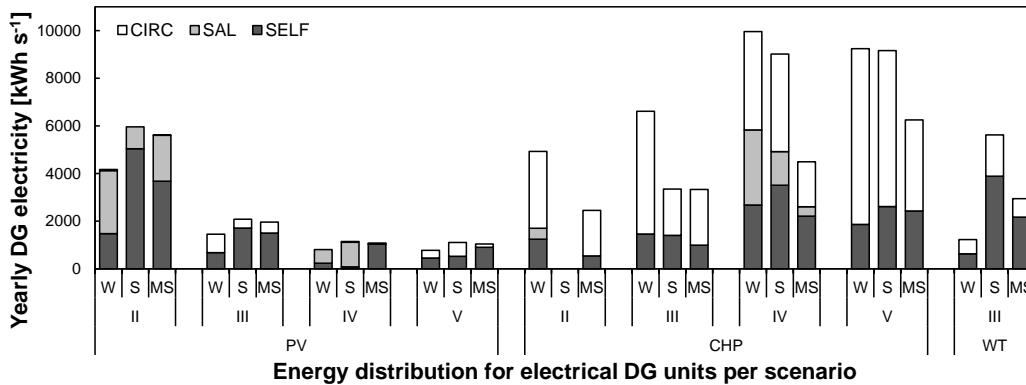
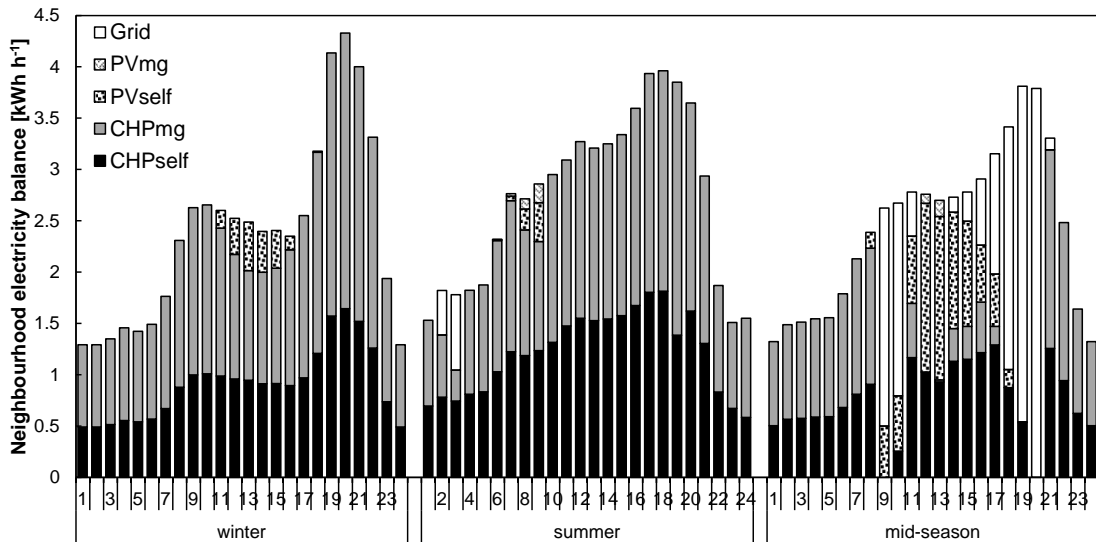
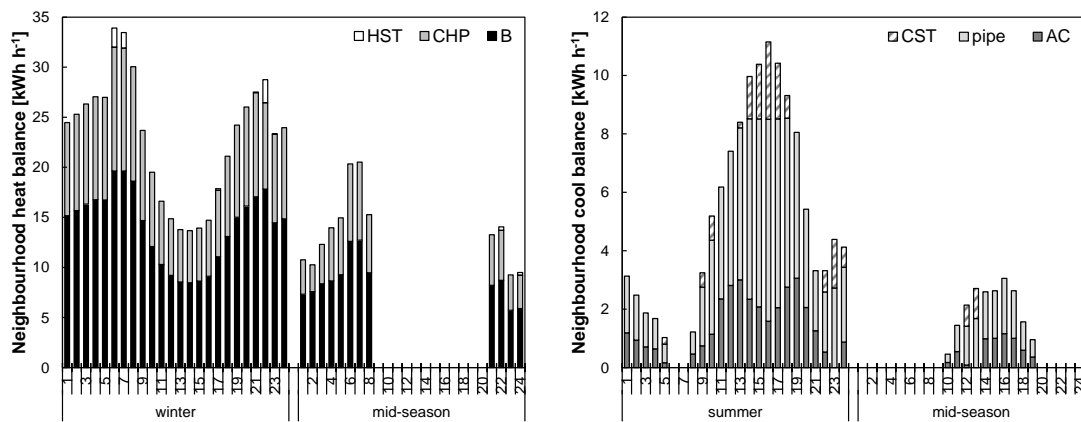


FIGURE 4.14: Yearly DG electricity interactions in the neighbourhood per season (s) [kWh s⁻¹] for Scenarios I to V for the total neighbourhood distribution of DG electricity. CHP=CHP, CIRC=energy transferred to other houses, PV=photovoltaic, SAL=exported electricity, SELF=energy for self use by accommodating houses, STO=energy stored, WT=wind turbine.

feed-in tariff in the market. Resulting energy balances, furthermore, can be analysed on several scales, for example, a detailed scale with balances for each house for a typical day in each season, or, a coarse scale with the yearly energy balance of the neighbourhood as a whole. An intermediate detail level is presented in Figure 4.15 for Scenario IV for a typical day in each season for the neighbourhood as a whole. This is an example of dispatch and operational variable values that can be obtained through the model. Energy integration, cooling sharing and seasonal tri-generation are important features in



(A) Electricity balance



(B) Heating balance

(C) Cooling balance

FIGURE 4.15: Yearly neighbourhood energy (electricity, space heating, space cooling) balances to meet demand [kWh h⁻¹] for a typical day in each season for Scenario IV. Example of dispatch and operational variable values. AC=absorption chiller, B=boiler, CHP=combined heat and power, CST=cold storage, grid=grid import, HST=hot storage, mg=microgrid operation, pipe=pipe transfer, PV=photovoltaic, self=self use by accommodating house.

the optimal design. Furthermore, energy integration mainly occurs through the use of CHP units (and absorption chillers). Hence, if heating or cooling demands in the neighbourhood are not met by CHP waste heat, no electricity is generated by CHP units and no electricity sharing is adopted.

4.5.2 Impact of decisions: model robustness

Robustness of results with respect to model inputs is illustrated below through upscaling, sensitivity and variability analysis, and examples of implementation decisions.

4.5.2.1 Neighbourhood upscaling

The base model (Scenario II) is scaled up to fictive neighbourhoods with 10 and 20 houses to assess the applicability of the model on general neighbourhoods. Appendix E details the household energy demands of the respective upscaled neighbourhoods. The model statistics are given in Table 4.10 and the optimised neighbourhood designs are illustrated in Figure 4.16. Note that a relaxed optcr of 1% is used. Both cases have PV units (1.7 - 2.5 kW) and air-conditioning units (1.8 - 2.7 kW) in each house, CHP unit(s) (2.4 - 3.3 kW) and an operational microgrid. A similar trend can be seen as in the optimal design of the five-house neighbourhood; heat integration does not comprise all houses, all houses have air-conditioning units as well as PV units, and cooling integration, wind turbines and batteries are not adopted.

TABLE 4.10: Model statistics of upscaled neighbourhoods.

Number of houses	5	10	20		5	10	20
CPU time [s]	64	453	5069	optcr	0 %	1 %	1 %
Blocks of equations	116	116	116	Single equations	31 421	84 656	256 376
Blocks of variables	81	81	81	Single variables	23 553	65 198	202 788
Non zero elements	110 626	301 801	923 251	Discrete variables	3686	11 071	36 941

4.5.2.2 Sensitivity analysis

Uncertainty of deterministic input data can affect results. Hence sensitivity analysis is performed to gain insight in the influence of key parameters on design and operation. Among the numerous input parameters of the model, future energy prices show a high level of uncertainty. Both retail electricity and gas tariffs are consequently analysed

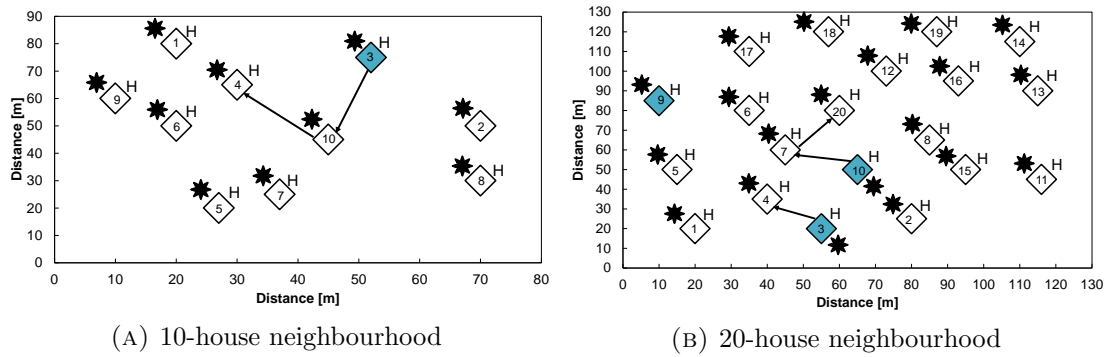


FIGURE 4.16: [colour] Layout of upscaled neighbourhoods with 10 (left) and 20 (right) houses for the base model of Scenario II. All houses have air-conditioning and PV units installed. Diamonds=houses, grey (blue) diamond=CHP and airco, white diamond=boiler (B) and airco, arrows=heating pipeline connection.

for incremental increases of 20% until a doubling of current tariffs, see Figure 4.17, for Scenario II. Figure 4.18 illustrates the equivalent cost of energy generation for each technology, i.e. its annual technology cost (investment, OM and fuel) divided by its total yearly generated energy, for percentage increases of energy tariffs for Scenario II.

Adoption of technologies is strongly related to their equivalent cost of energy generation under the governing energy tariffs. An increasing gas tariff leads to the same design as in Scenario II until an increase above 40 % from which a constant neighbourhood design is obtained without CHP unit, pipelines or microgrid operation. The 40 % increase reflects the point where generating heating through CHP units becomes too expensive compared to boilers, see Figure 4.18b. Since the gas tariff is relative low in the Adelaide market compared to electricity, design shifts to more installed boilers with increasing gas tariffs as boilers have an overall higher heat generation efficiency than CHP units (see also Section 5.6.1). Total annualised costs are dominated by fuel costs. Hence an increasing

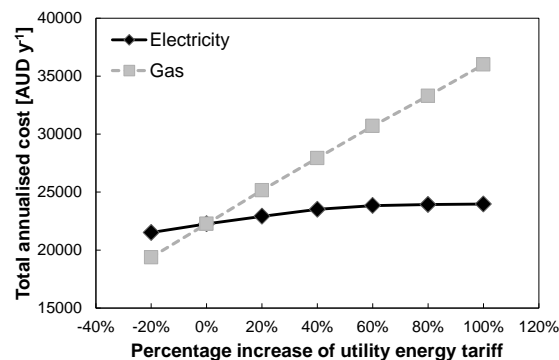


FIGURE 4.17: Total annualised cost [AUD y⁻¹] versus percentage increase of retail energy tariffs of electricity and gas.

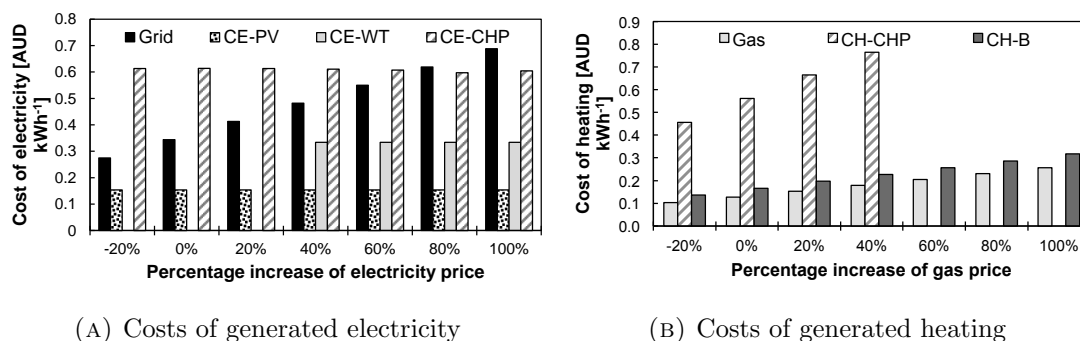


FIGURE 4.18: Technology costs of yearly generated energy in the neighbourhood [AUD kWh⁻¹]: electricity (left) and heat (right). Note that when the technology is not installed, its cost is zero. The costs of electricity generated by renewable energy units is independent of retail energy tariffs since their fuel (i.e. renewable energy resource) is free. B=boiler, CHP=combined heat and power, CE=cost of electricity, CH=cost of heating, gas=gas tariff, grid=electricity tariff, PV=photovoltaic, WT=wind turbine.

gas tariff leads to a stronger increase of total cost than an increasing electricity tariff. Increasing gas tariffs thus result in decreased local energy sharing and DER installation but more individual house conventional thermal units combined with a grid connection.

An increasing electricity tariff, in contrast, leads to more significant design changes. One CHP unit is installed in all cases in house 2, together with a pipeline to house 4 and microgrid operation. Since the cost of generating electricity with DG units becomes more affordable with increasing electricity tariff due to their ‘free fuel’ in the form of renewables or electricity generated by the heat-following CHP (Figure 4.18a), the following design changes occur: (i) CHP unit capacity increases gradually from 2.1 to 3 kW; (ii) total neighbourhood PV capacity increases gradually from 6.3 to 11 kW until an increase above 40 %, from which it gradually decreases to 6.4 kW due to the appearance of wind turbines combined with a relatively fixed level of CHP electricity generation coupled with its heat-following mode; (iii) from an increase above 20 %, wind turbines become cost effective; and (iv) an absorption chiller and accompanying cold storage unit are additionally installed in house 2 from a tariff increase above 40 % due to the ‘free waste heat’ fuel from CHP electricity generation. CHP electricity generation will namely be preferred to balance renewable generation due to the cheap gas tariff as compared with grid electricity tariffs. Increasing electricity tariffs hence lead to increased self-sufficiency of the neighbourhood through more DG units.

4.5.2.3 Variability analysis

Deterministic models employ average input data. Especially the unpredictability of renewable energy sources is not accounted for through this approach. A measure of solar irradiation variability is presented here through the use of real time PV output data from Adelaide. The collected data for 2010 are combined into daily PV output levels [kWh per m² per day] [260]. Figure 4.19 indicates the number of days throughout the year ($d_{l,s}$) that each daily PV output level (l) occurs in each season (s). An average hourly daily profile is then obtained per output level per season by averaging the daily output profiles of the days that fall within each output level for each season, $It_{l,s,h}$ (see Appendix E). The output for each PV panel for an average day (24 hours) in each season is then determined through a weighted average based on days of occurrence in each season of the PV output levels per installed square meter, with $PE_{PV,i,s,h}^{TOT}$ the total electricity generated by a PV unit in house i , hour h of season s , d_s the days in each season, A_i^{PV} the PV surface area and n_{PV}^{elec} the PV electrical efficiency:

$$PE_{PV,i,s,h}^{TOT} = \sum_l \frac{d_{l,s} \cdot It_{l,s,h}}{d_s} \cdot A_i^{PV} \cdot n_{PV}^{elec} \quad \forall i, s, h \quad (4.18)$$

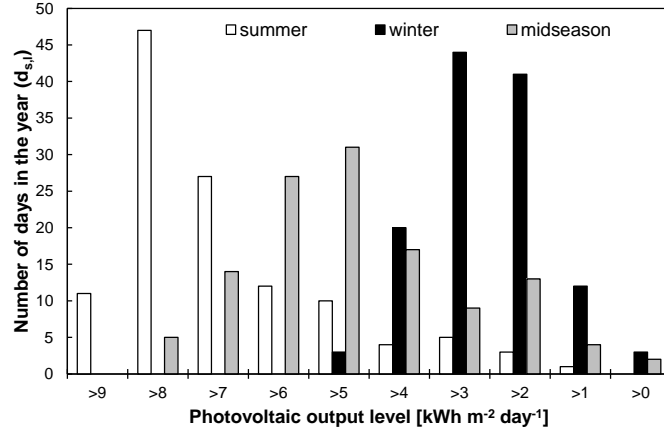


FIGURE 4.19: Occurrence rate of different daily PV output levels in each season [kWh m⁻² day⁻¹].

Optimal design reduces costs by 2.3% compared to the previous approach (Scenario II). Design and operational characteristics are presented in Figure 4.20 for the model with and without variability for Scenario II. Overall design is not significantly affected by

the introduction of variability. The same heating pipeline as well as microgrid operation maintain installed. Without variability, however, the model leads to slight overdimensioning of PV units of which the output is mainly exported to the central grid. The yearly PV electricity generation decreases by 16.5 % with variability and focusses more on self supply. The incorporation of variability thus limitedly affects the objective and design but does influence the interaction with the central grid.

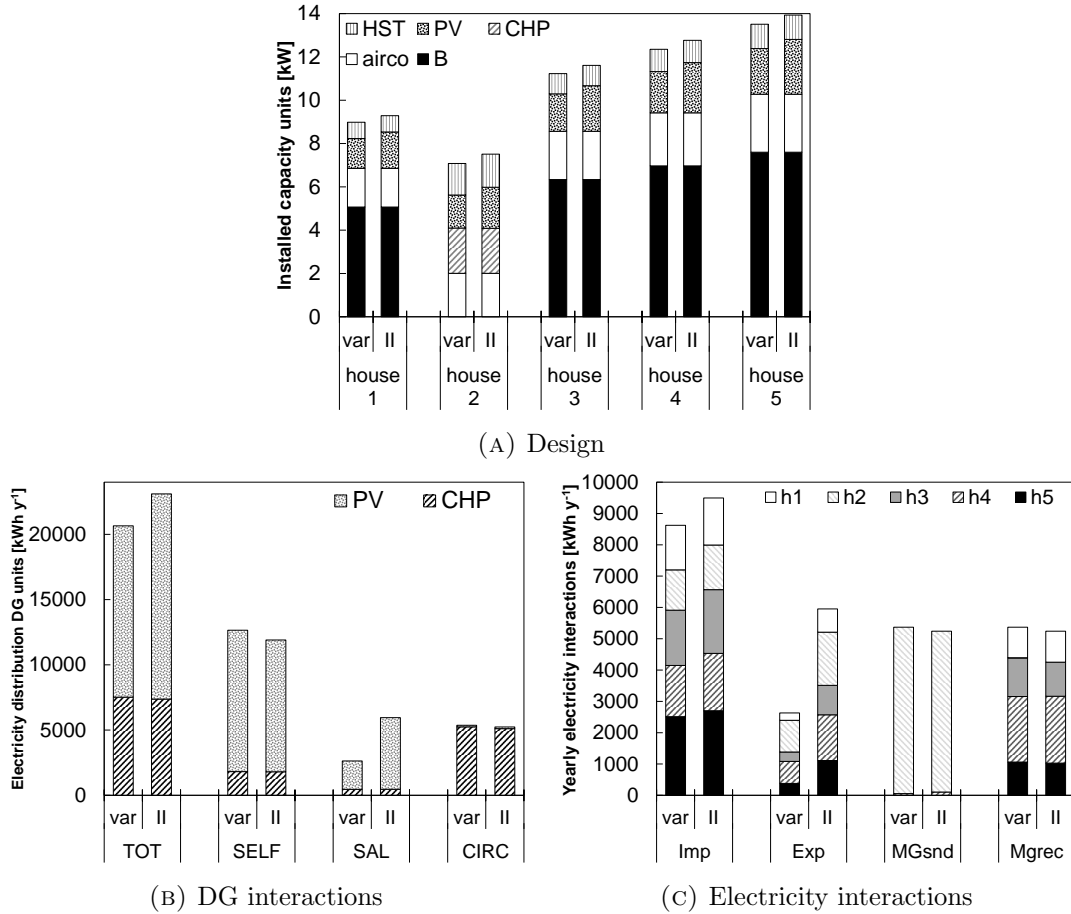


FIGURE 4.20: Characteristics of neighbourhood with and without solar variability. h=house, var=with variability, II=Scenario II, distributed generation (PV, CHP) electricity, total (TOT), for self use by its house (SELF), for export (SAL), for MG circulation (CIRC), yearly neighbourhood electricity import (Imp), export (Exp), microgrid (MG) sending (MGsnd), MG receiving (MGrec).

4.5.2.4 Implementation aspects

The model can also be used to analyse various implementation aspects. This Section presents examples of the impact of electricity interaction restrictions, technology parameter selection and technology combination constraints on the results of Scenario II.

Electricity export restrictions An important aspect to assess DES economic viability for a certain case-study is its ability to export electricity to the central grid. This interaction allows local excess generation to be exported in order to avoid safety issues due to local generation being higher than local demand. Furthermore, export allows houses to create an income through feed-in tariffs in the market. Energy interaction allowances of DES are therefore determining economic and safety factors for local system design. Residential electricity export, however, requires distribution system upgrades to allow for bi-directional power flows. Distribution system operators are thus inclined to bound and decrease export allowances of each house, either through an energy equivalent of a percentage (p^{SAL}) of the installed DG capacity ($DG_{techDG,i}^{MAX}$) that can be exported at each time, or, a daily export bound (U_{snd}^{day}):

$$\sum_{techDG} PE_{techDG,i,s,h}^{SAL} \leq p^{SAL} \cdot \sum_{techDG} DG_{techDG,i}^{MAX} \quad \forall i, s, h \quad (4.19)$$

$$\sum_{techDG,h} hr \cdot PE_{techDG,i,s,h}^{SAL} \leq U_{snd}^{day} \quad \forall i, s \quad (4.20)$$

The impact of export allowances on optimal design of Scenario II is researched through a percentage decrease of the upper limit of total DG electricity export, p^{SAL} . The daily export limit in South Australia is included as reference point (45 kWh day⁻¹). Figure 4.21 presents the results of total DG electricity (PV, CHP, wind turbines) export restrictions. Neighbourhood design remains fairly constant with increasing export allowance in that it has PV units and heat storage tanks in each house, one CHP unit of 2.1 kW in house 2, one pipeline connection from the house with CHP unit to house 4, as well as microgrid operation. No batteries, absorption chillers or wind turbines are installed. Neighbourhood PV capacity gradually increases from 6.3 kW at zero export allowance to 10.5 kW from an export allowance above 40 %. The CHP unit and corresponding uni-directional pipeline remain the same as in Scenario II for all export levels. Additionally, from an export allowance above 40 %, dump loads are no longer required. Neighbourhood design and interaction behaviour becomes constant from a total DG export allowance above 50 % of the total installed DG capacity in the neighbourhood. This analysis allows to assess the best export level to make DG units viable.

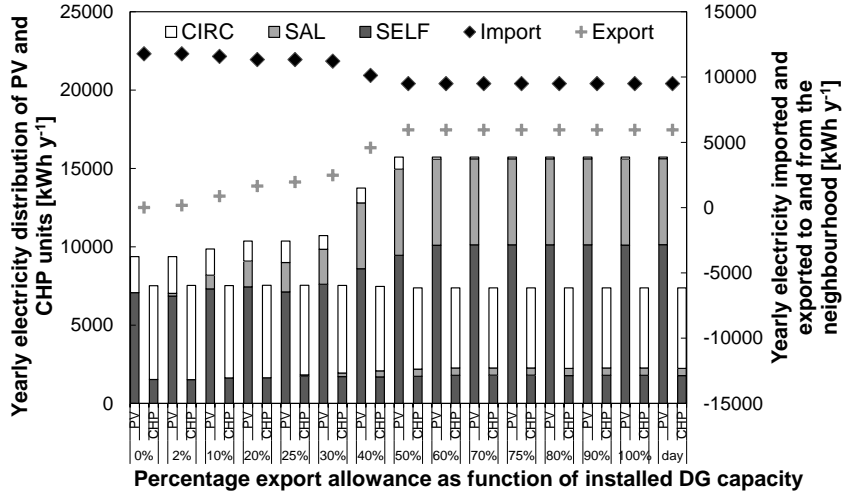


FIGURE 4.21: Share of total yearly PV and CHP electricity generation for either self use by the accommodating houses, for grid export and for MG circulation [kWh y^{-1}] (see left vertical axis and bar charts) as well as the yearly electricity export and import of the neighbourhood as a whole [kWh y^{-1}] (see right vertical axis and points) in terms of percentage export allowance as function of total installed DG capacity. CHP=combined heat and power, CIRC=microgrid circulation, day=daily export allowance, PV=photovoltaic, SAL=export, SELF=self use. No wind turbines are installed.

Impact of technology parameters To allow for efficient optimisation of complex non-linear models, simplifying constant technology assumptions are often adopted to obtain linear and MILP problems. Uncertainty in the selection of these parameters might, however, affect the obtained design. Since CHP units are able to exploit waste heat from the electricity generation process for heating and cooling purposes, they are often analysed and put forward in DES design environments as key components [280]. Hence analysing design robustness with respect to input CHP efficiency parameters, for example, is an important factor to determine DES economic and operational viability. Total constant CHP efficiency (η_{CHP}^{tot}) in Scenario II is hereto varied together with a varying constant electrical (η_{CHP}^{el}) and thermal (η_{CHP}^{th}) efficiency. The reference case is: $\eta_{CHP}^{tot} = 90\%$ with $\eta_{CHP}^{el} = 25\%$ and $HER = 2.6$ (Scenario II). Total efficiencies of 99, 95, 90, 85 and 80 % are analysed in combination with an η_{CHP}^{el} of 25, 35 and 45 %. Note the relations: $\eta_{CHP}^{tot} = \eta_{CHP}^{el} + \eta_{CHP}^{th}$ and $HER = \eta_{CHP}^{th} \cdot (\eta_{CHP}^{el})^{-1}$.

CHP efficiency determines CHP and absorption chiller installation (Figure 4.22), and CHP operational behaviour (Figure 4.23). An installed CHP facilitates DES economic viability. A microgrid (CIRC) is viable together with an installed CHP. For high electrical efficiency ($> 25\%$), the relative CHP efficiency values become a determining factor

for microgrid viability; a high η_{CHP}^{th} ($> 55\%$) is required to ensure enough electricity and heating is generated to facilitate sharing. Additionally, absorption chillers become economic viable for $\eta_{CHP}^{tot} > 90\%$ with $\eta_{CHP}^{el} > 25\%$. This is because from this point onward, more waste heat is generated than locally used for space heating. This ‘free’ fuel leads to absorption chillers becoming economically viable for cooling compared to air-conditioning units that are fuelled by expensive grid electricity. Heat transfer pipelines appear for $\eta_{CHP}^{tot} > 80\%$ combined with an $\eta_{CHP}^{el} < 45\%$ and a $\eta_{CHP}^{th} > 55\%$.

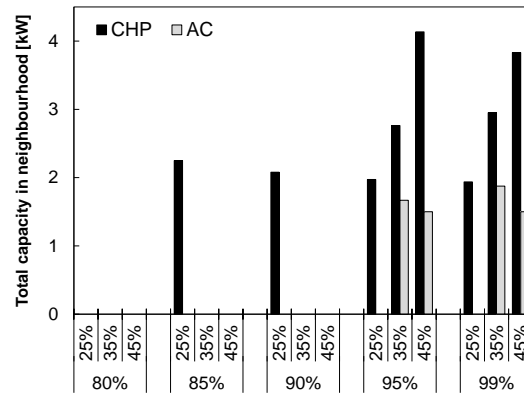


FIGURE 4.22: Total installed CHP and absorption chiller (AC) capacity in the neighbourhood [kW] for varying CHP efficiencies. 80 % to 99 % = total efficiency, 25 % to 45 % = electrical efficiency.

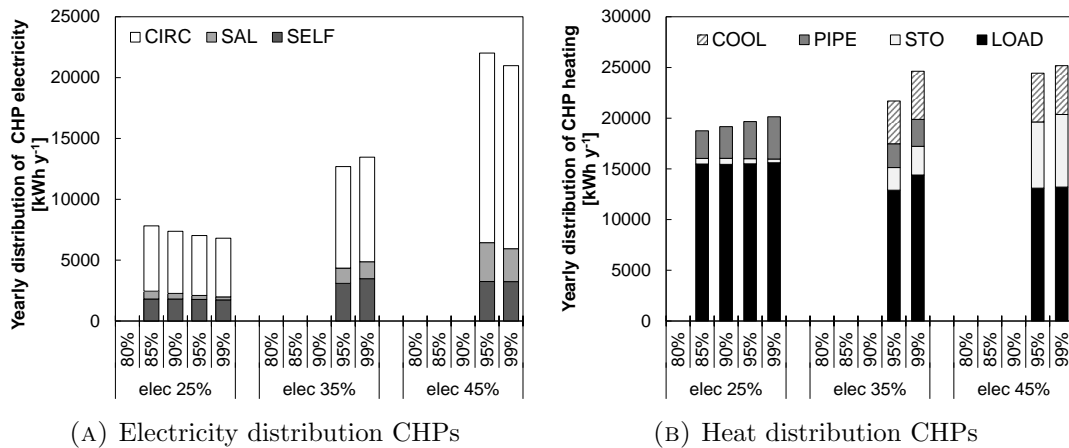


FIGURE 4.23: Yearly energy distribution of neighbourhood CHPs [kWh y⁻¹]. CIRC=CHP electricity for MG sharing, COOL=CHP heat for cooling, LOAD=CHP heat to feed load, PIPE=CHP heat to pipes, SAL=CHP electricity for export, SELF=CHP electricity for self use by its house(s), STO=CHP heat for storage.

Impact of flexible technology combination constraints Several technology combination constraints were adopted in this case-study (see Section 4.4.4). The model thus allows for flexible inclusion or removal of technology combination constraints to

explore various design preferences or business practices. To demonstrate the flexibility of the model, the results of the base model (Scenario II) are compared with and without the mutually exclusive ‘boiler or CHP unit’ constraint. The model with relaxed constraint (II_{rel}) solves in about half the time as the model with constraint (II). The neighbourhood designs and total unit capacities in the neighbourhood are given in Figure 4.24 and Table 4.11, respectively. Although the same technologies are installed in the neighbourhood and the total unit capacities in the neighbourhood are comparable, it is the number of units and their location in the neighbourhood that change. Rather than a single CHP unit of 2.1 kW in house 2 that provides heating to house 4 through a single pipeline, the relaxed model (II_{rel}) now results in a design whereby each house has an installed boiler combined with two smaller CHP units (1 kW) in houses 4 and 5. Pipelines are not adopted in the design without constraint.

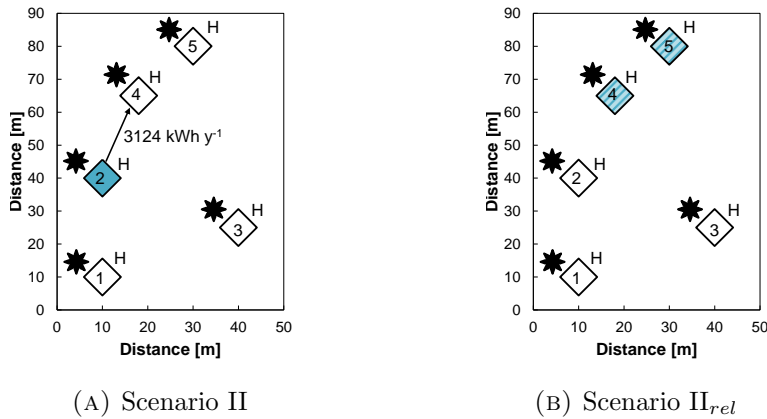


FIGURE 4.24: [colour] Neighbourhood layout for Scenario II with and without (II_{rel}) B-CHP restriction constraint. Note that no batteries, WTs, ACs, G and CST are installed. sun=PV unit, H=hot storage, dark grey diamond (blue)=CHP and airco, dark-light grey hatched diamond (blue)=CHP, B and airco, white diamond=boiler and airco, black arrow=annual pipeline heat transfer.

TABLE 4.11: Total installed unit capacity in neighbourhood for Scenario II with and without (II_{rel}) B-CHP restriction constraint [kW]. airco=air-conditioning, B=boiler, CHP=combined heat and power, HST=hot storage, PV=photovoltaic.

Scenario	B	airco	PV	CHP	HST
II	26.0	11.2	10.5	2.1	5.4
II_{rel}	27.5	11.2	10.5	2.0	6.5

Table 4.12 summarises cost, design and operational results of both cases. The seasonal electricity distribution of the neighbourhood DG units is presented in Figure 4.25. With the exception of pipelines, the energy interaction behaviour and results of the two cases largely follow trends of the same order of magnitude. PV electricity is, however, more

TABLE 4.12: Summary of results of Scenario II with and without (Π_{rel}) B-CHP restriction constraint: annual cost C^{TOT} [AUD y^{-1}], yearly CO₂ emissions [tonCO₂ y^{-1}], yearly import (PE_{GRID}^{rec}), export (PE_{GRID}^{SAL}), microgrid (MG) electricity ($PE_{MG,i,s,h}^{rec}$) [kWh y^{-1}] and the installation of a MG and pipelines.

Scenario	C^{TOT}	CO ₂	PE_{GRID}^{rec}	PE_{GRID}^{SAL}	$PE_{MG,i,s,h}^{rec}$	MG	Pipe
II	22264	30.19	9496	5953	5183	yes	(h_2 to h_4)
Π_{rel}	22027	29.88	9451	4648	3297	yes	no

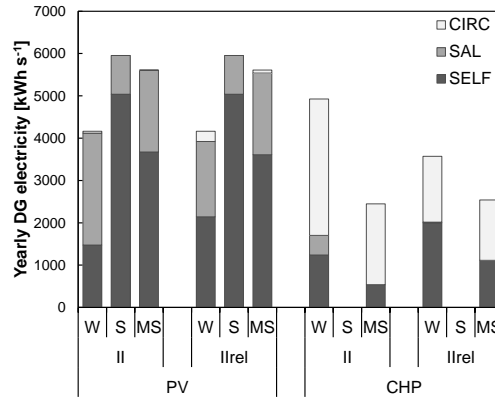


FIGURE 4.25: Yearly DG electricity interactions in the neighbourhood per season (s) [kWh s^{-1}] for Scenario II, with and without B-CHP constraint for the total neighbourhood distribution of DG electricity. CHP=CHP, CIRC=energy transferred to other houses, PV=photovoltaic, SAL=exported electricity, SELF=energy for self use by accommodating houses, STO=energy stored.

used for microgrid circulation, whereas total CHP electricity generation is reduced by about 40 % compared to Scenario II. CHP electricity is still the driving source for microgrid operation. In this case-study, total neighbourhood design and behaviour is thus not much affected by relaxing the ‘boiler or CHP unit’ constraint. Significant design and operational changes, however, occur when looking at house and technology level. Analysing various technology combinations, allows to identify different energy system designs that are worth exploring by the neighbourhood.

4.6 Discussion and generalisation of approach

Several decisions, where alternatives exist, have been made throughout the model definition, implementation, case-study, scenarios, optimisation process and presentation of results. The presented aspects in this Chapter have been employed to highlight the capability of the developed framework. The model is, however, general and flexible to be adapted to different requirements. Table 4.13 summarises examples of adaptations

TABLE 4.13: Adaptability and flexibility of the developed framework.

Stage	Adaptations & flexibility
Implementation	<ul style="list-style-type: none"> - more and different considered types and numbers of technologies (plug-and-play) - different considered technology capacities (discrete/continuous) - different technology combination restrictions (see Table 4.6) - different technology implementation (e.g. battery also charged by external feeds) - non-linear technology behaviour
Case-study	<ul style="list-style-type: none"> - different neighbourhood locations, layouts and number of houses - different sets of demands, not always electricity <i>and</i> space heating <i>and</i> cooling - additional typical days for more seasons and months - hourly changing parameters, such as tariffs - different time horizon and time steps (few hours, half hourly, ...) - specific peak event demand analysis
Optimisation	<ul style="list-style-type: none"> - opter - different applicable feasible solutions - analysis of different energy system scenarios through pre-setting different binaries
Results	<ul style="list-style-type: none"> - role of technologies in case-study location - impact of technology and interaction bounds on results - impact of regulation on results (CT, FIT, rebates, restrictions) - minimum technology requirements to become feasible (cost/efficiency) - different levels of detail in result presentation

that can be made at different modelling stages to illustrate the model applicability and flexibility to be tailored to different sets of requirements.

Different technologies, such as solar thermal, could be readily considered within each pool (e.g. renewable, DG, storage) and be implemented in a plug-and-play approach similar to other technologies in the same pool. Different capacity implementations can also be considered, either discrete possible capacities that are available in the market, or, a continuous range. Continuous capacity intervals were adopted in the base model to allow for decision-making with unrestricted optimal levels.² Additionally, different or no mutually exclusive technology combinations can be adopted to increase system degrees of freedom. A boiler can, for example, be seen as complementary to CHP units rather than mutually exclusive through removing the applicable constraint (see Table 4.6 and Section 4.5.2.4). Furthermore, the current pipeline implementation does not restrict the configuration whereby a single sink house can receive thermal energy from two source houses. In practice this is however not an ideal design since bringing two flows of water together requires complex (temperature, pressure, flow) controlling infrastructure.

Implementation decisions, where alternatives are available, can thus restrict system behaviour. Implementation assumptions and decisions are, nevertheless, always an approximation of reality. The adopted decisions and assumptions in this Chapter were in the

²An example of discrete capacity implementation of CHP units is given in Appendix F.

first instance used to demonstrate the model capability. Other implementations might, however, increase system flexibility in terms of technologies and interactions. Electrical storage, for example, could be implemented to allow charging from and discharging to the central grid and other DES participants. Allowing these interactions could increase DES economic viability and model applicability.

Inherent non-linear technology behaviour, such as introduced in Section 3.2.1, could be integrated either within the developed MILP approach through piecewise linearisation of non-linear technology characteristic trends (see Section 6.4.1.3) or as a non-linear relation within an MINLP environment (see Section 6.6.2.2). The consideration of these trends could affect the results obtained.

The framework can be applied to both retrofitted and greenfield neighbourhoods, as long as its layout, the number of consumers and demands are known. Additionally, different combinations of case-study demands can be employed from electricity, space heating and space cooling. Parameter time scales can also be refined, such as hourly changing tariffs (T_h^{elec}). More typical demand days, different time horizons and refined time steps can be considered and readily implemented by changing or adding input parameters. Moreover, design requirements for extreme demand years could be analysed, such as peak cooling demand days in South Australia (up to four times the average [257]).

Due to assumptions and uncertainty, global optimality leads to an ‘optimal’ solution for an approximate system [82, 92, 94, 104]. Hence, relative optimality gaps are satisfactory to find solutions for approximate systems. The presented case-study, however, results in very different feasible designs for small optcr changes below 10 % (see Appendix F). To enable comparison of solutions across scenarios and analyses, and because of reasonable CPU times, global optimality has been mostly employed throughout the analysis.

A wide range of results can be analysed based on different time and consumer levels, such as hourly or yearly, and house or neighbourhood level. Examples of the impact of inputs and bounds have been presented in Section 4.5.2 but numerous more parameter analyses could be conducted. Additionally, the impact of location-specific regulation, such as support schemes, can be assessed by comparing results with or without regulatory change (see Section 4.5.2.4). Furthermore, minimum required performance levels to enable technology adoption can be researched, such as minimum CHP efficiency levels to make microgrid adoption economically viable (Section 4.5.2.4). The presented analysis in this

Chapter thus provided examples of how the developed generic framework can be analysed and adapted to accommodate for various case-study requirements and scenarios.

4.7 Summary and conclusion

A generic deterministic MILP model for residential energy system design has been developed with cost as driving objective. The framework has been applied to an Adelaide neighbourhood to illustrate its capability. Model robustness, flexibility and applicability were analysed and highlighted through neighbourhood case-studies, upscaling, sensitivity and variability analyses as well as through analyses of the impact of implementation decisions on results. Cost is, however, not the only objective involved in project decision-making, as various stakeholder interests need to be considered (see Chapter 1). Chapter 5 builds further on the developed framework in this Chapter, extending it to a multi-objective approach enabling the trade-off of three design objectives.

Chapter 5

Multi-objective design of residential distributed energy systems

A framework for optimal multi-objective residential distributed energy system (DES) design is developed (third research question, see Section 1.4). The model presented in Chapter 4 is hereto extended to enable trading off three objectives in the design process. The included minimisation objectives are aligned with the central energy system objectives of competition, security of supply and sustainability to ensure DES applicability within conventional power systems; i.e. total annualised energy cost, electrical system unavailability and annual CO₂ emissions, respectively. Part of the work in this Chapter has been disseminated into the following publication [281].

5.1 Introduction

5.1.1 Driving stakeholder interests

Apart from a competitive design (see Chapter 4), other design requirements also play an important role in distributed energy system (DES) development [82, 91]. DES design optimisation has therefore increasingly been focussing on multi-objective approaches (see Section 2.3.3.2) [91, 92]. Not all stakeholder interests are, however, readily quantifiable

into design objectives. Additionally, design objectives are often conflicting in nature. Hence a decision-making trade-off approach is required to determine ‘optimal’ energy system design, which can be facilitated through multi-objective optimisation tools.

5.1.2 Chapter overview

This Chapter aims to develop a multi-objective framework for residential DES design shaped by energy system objectives. Section 5.2 provides background on the selected objectives. A detailed problem description is subsequently presented in Section 5.3. Section 5.4 details the model, building further on Chapter 4. A case-study in Section 5.5 serves to apply the framework through various scenarios and analyses. Results are illustrated in Section 5.6 to end with a discussion (Section 5.7) and conclusion (Section 5.8).

5.2 Objectives in distributed energy system optimisation

To address conventional system challenges through meeting energy system objectives (see Section 1.1.3), DES ideally fulfil a tri-faceted role to consumers; being a competitive energy supply alternative, providing sustainable energy supply and enhancing energy security. Multi-objective optimisation enables translating these roles into an economic, environmental and technical objective, respectively [92]. The following Sections detail the chosen environmental (5.2.1) and technical (5.4.3) objective as minimisation of annual CO₂ emissions and minimisation electrical system unavailability, respectively.

5.2.1 Emissions as environmental objective

5.2.1.1 Emissions as attribute of sustainability

Sustainability mostly refers to the environmental impact of energy systems (see Section 1.1.3) [1, 18]. In power systems, and more particularly in DES, this relates to and can be measured through (i) greenhouse gas emissions, (ii) renewable energy generation, or, (iii) energy efficiency [10, 11, 17]. Environmental aspects are receiving growing interest in energy integrated DES design optimisation but have only limitedly been researched

as explicit design objectives (see Section 2.3.3.2). Here the minimisation of yearly carbon emissions has been the predominant implemented objective [200, 214]. Care must, however, be taken when defining carbon emissions. Emissions can be direct and localised through on-site consumption of natural gas and grid electricity. Renewable energy technologies, in contrast, might not lead to direct on-site emissions, but their technology life cycle from development to recycling does lead to emissions [137, 154, 170, 185, 197]. With regard to shares of specific energy resources for energy generation, maximisation of renewable energy penetration levels [170] or minimisation of fossil fuel consumption [138] have been introduced as measures. Efficiency measures, furthermore, have been defined as either environmental or technical objectives throughout literature (see Section 2.3.3.2). Additionally, environmental impact has often been internalised (indirectly taken into account) through economic measures, such as a carbon tax.

The aim of this thesis is not to analyse full life cycle impacts. Additionally, double counting of environmental impact, through both a tax within a cost minimisation objective (indirectly) and minimisation of yearly emissions (directly), is typically avoided. For the current case-study, the carbon tax (currently not in place in the Australian market, see Section 4.4.1) is thus removed from the cost objective (see Equation 4.1). Note, however, that both a carbon tax as well as emission reduction targets could be in place in certain circumstances. CO₂ emissions are already commonly monitored and measured within current energy systems. Technology emission data is thus readily available. The environmental objective is therefore quantified as minimisation of total annual neighbourhood CO₂ emissions. CO₂ emissions are here defined through on-site fossil fuel consumption, or, through central grid electricity import.

5.2.1.2 Determining annual CO₂ emissions

CO₂ emissions are selected as environmental minimisation objective as this reflects the choice of resources, indirectly provides a measure for the maximisation of renewable energy resources, and encompasses the different neighbourhood energy services. Installed CO₂ emitting technologies generate electrical or thermal energy through direct on-site fossil fuel consumption. CHP units only generate electricity directly related to fossil fuel consumption. Their waste heat is seen as a by-product. Electricity imported from the central grid is also partly generated by fossil fuel consumption, leading to a carbon

intensity. Total annual CO₂ emissions of the neighbourhood thus relate to the yearly electricity generated by the installed CHP units, the yearly grid electricity import, and the yearly heating generated by the installed boilers and gas heaters, see Figure 5.1.

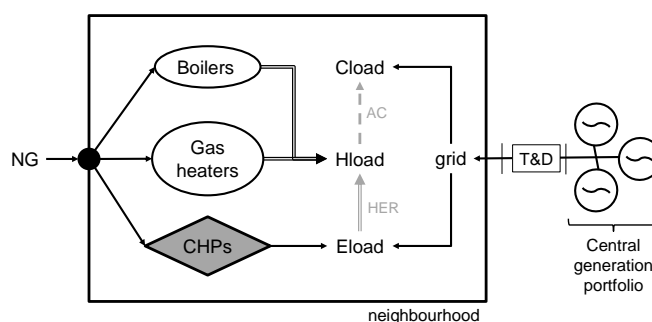


FIGURE 5.1: Energy generation technologies directly based on fossil fuels. AC=absorption chiller, C=cooling, E=electricity, H=heating, HER=heat to electricity ratio, load=energy demand, NG=natural gas, T&D=transmission and distribution.

5.2.2 Unavailability as technical objective

5.2.2.1 Unavailability as attribute of security of supply

Security of supply in energy systems refers to energy security and system dependability. System dependability refers to trusting the services it is supposed to deliver [1, 23, 24] (see Section 1.1.3). Dependability relates to quality of energy supply standards, operational safety and outages [1]. DES introduce various potential benefits to consumers of which increased electrical system dependability is often highlighted [28, 35, 48]. Especially within distribution networks, responsible for over 90 % of consumer interruptions [30], they can provide added security of supply through local energy generation and sharing. Security of supply can hence be determined through several probabilistic or deterministic indices related to system up and down times [24, 25]. Alternatively, security of supply could be measured through generation and primary energy resource portfolio diversification, component redundancy or self-sufficiency [53, 282].¹

¹*Diversification* refers to increasing the variety of primary energy resources used for energy generation rather than relying on a single source. *Redundancy* refers to implementing components that are on stand-by in case of unit failure in order to maintain energy supply to consumers. Components can be in hot or cold redundancy. The latter need a start-up period once required to step in to maintain generation. The former are ready to operate when required. *Self-sufficiency* refers to having own generation and resources rather than relying on external sources. See for more information [23, 25, 51–56].

5.2.2.2 Unavailability as attribute of dependability

‘Fault-tolerance’ related aspects relate to system dependability. A system is ‘fault-tolerant’ if it works correctly despite one or more component (or software) failure [23]. In small-scale DES this refers in particular to the correct service (providing energy supply) at a certain time. System dependability is measured through attributes, caused by threats and controlled by means as illustrated in Figure 5.2 by a so called ‘dependability tree’ [23, 24, 51–53, 283–286]. The two most employed attributes to measure system dependability are availability and reliability, which serve different purposes highlighted by their definitions [23, 51–53, 283, 284]:

Availability is the probability that a system can be correctly operated and employed at a certain time t , i.e the readiness for correct service. Availability measures the dependability of repairable systems. Unavailability is its complement.

Reliability is the probability that a system correctly operates during a certain time interval Δt , provided it worked correctly at the start of this interval. Reliability is most often employed for irreparable or continuously operating systems. The complement of reliability is unreliability.

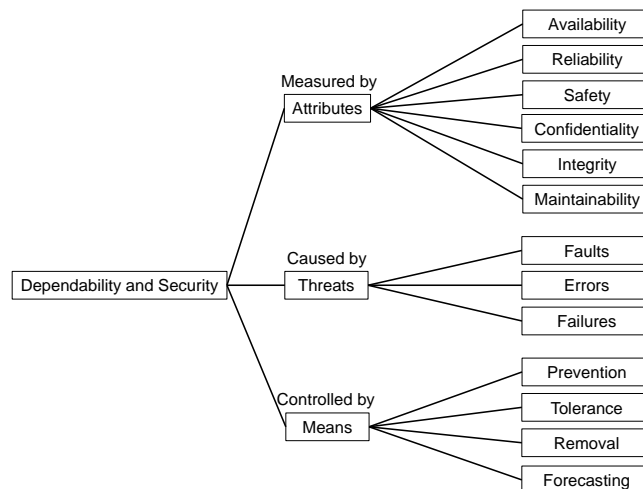


FIGURE 5.2: Dependability tree, adapted from [24, 287, 288].

Reliability is important in critical systems to ensure safety and continuous operation. Residential DES, in contrast, are generally not operationally critical. Availability is therefore chosen as measure since residential DES are: (i) non-critical in operation in contrast with, e.g. continuous chemical processes [288], (ii) readily maintainable and

repairable within reasonable time frames [289], and (iii) expected to work at a certain time t , i.e. consumers expect the light to go on when flicking a switch. Availability refers here to the probability of providing (full) power to the load at any time t [289].

5.2.2.3 Determining availability

Availability can be quantified based on several definitions of which an overview is given in Appendix G. This Section summarises DES-relevant definitions. Electrical system availability is typically expressed through so-called ‘nines’ [290]. Central grid supply, for example, can range from 3-nines availability, i.e. 99.9 %, to 6-nines, 99.9999 %. This percentage indicates the hours throughout a year a component or system is available. Availability is thus directly related to system up and down times, determined by component failures and outages [53]. A combination of outages of system components determines the state of the system at a certain time [282].

Components fail based on time dependent failure rates, characterised through a failure rate function. This function determines the expected outages of a certain component type over a certain time period. A component failure rate function is typically represented through a so-called ‘bathtub’ curve with three failure periods over a component’s life: early, useful and end of life [51–53, 290], see Figure 5.3. The early failure period occurs when a new component is installed due to so-called ‘infant mortality’. The failure rate decreases rapidly over time. Useful life occurs when component failures are stabilised. Failures occur randomly and at an approximate uniform rate, i.e. constant failure rates. The end of life period is characterised by component wear-out. The failure rate increases again until component replacement. In this work, components are

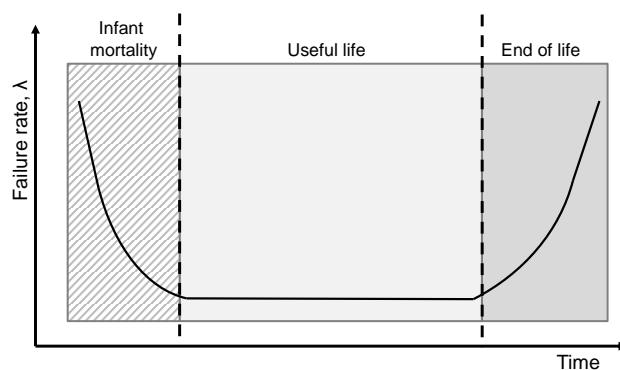


FIGURE 5.3: Bath tub component failure rate curve, adapted from [51–53, 290].

assumed to be in their useful life since steady-state aspects are analysed. This implies that component failure, λ_c [%], and repair rates, μ_c [%], are constant with time (see Equation 5.1 and Appendix G) [53, 291].

Availability of a *system* that consists of components used to be assessed through deterministic criteria [30, 292]. Deterministic approaches, however, are not able to grasp stochastic failure behaviour. Therefore, probabilistic techniques have gained increasing interest. Herein two major groups can be distinguished;

Analytical approaches are based on statistical data of component failures and repairs that define several probabilities and indices of system states through mathematical relations [30, 293, 294]. Hence a specific set of indices can be found from a specific data set. However, simplifying assumptions have to be made in this process. Blanchard [51], Villemeur [53], Billinton et al. [55] and Karki et al. [54] provided overviews of analytical probabilistic techniques to assess system dependability. The most common techniques are the Series-Parallel Reduction/Block Diagram Method, the Event Tree Analysis, the State Space Diagram/Markov methods and the Tie/Cut Set methods (see Appendix G). In terms of specific probabilistic system indices, the System Average Interruption Duration Index (SAIDI) is most commonly used for electrical system availability. SAIDI is a measure for the percentage duration of an outage and is often employed as measure for conventional network availability [30, 54, 283, 292–295].

Simulation based techniques, in contrast, determine expected values of indices by averaging the results obtained through simulations [51, 54, 55]. Each simulation generates random numbers, i.e. probability of occurrence of system states. The most commonly known simulation techniques are Monte Carlo simulations. Based on a defined domain of possible values, inputs are randomly generated in each simulation from a probability distribution over the domain. The results of hundreds of simulations are then aggregated to obtain index values. The obtained results depend here on the number of simulations. In theory, an infinite amount of simulations is required to obtain exact index values. Simulation techniques are especially appropriate for large and complex systems.

DES systems are small and their components are quantifiable through probabilistic data. Hence an analytical approach is taken. Since the neighbourhood system is not reducible to series and parallel component connections due to energy sharing and multiple simultaneous applications for local energy generation, the Series-Parallel method is ruled out

(see Appendix G). Furthermore, DES consist of multiple redundant energy supply options. Not only total system failure probability thus needs to be obtained, but also the probability of the system to be fully or partially available, which is obtainable through both the Event Tree Analysis or Markov models. Both methods are readily adaptable to include additional components and system states. The Markov model, however, additionally allows for the inclusion of component repair. Hence a Markov State Space Diagram is selected to obtain DES availability.

The Markov model mathematically describes a time related random process of a system that moves between defined states through step-wise transitions [23, 55, 285]. System states are based on the status of the system components. State transitions therefore occur due to component failures and repairs, see Figure 5.4. Since system availability is here analysed based on a steady-state analysis of a system with a finite number of components and system states, a finite Markov chain is constructed [23, 55, 285]. The state of a system is fully defined at each time t . The probability that a system finds itself in a certain state at time $t + \Delta t$ namely only depends on the probability of being in that state at time t and the probability of transitioning to or from other states [282, 296]. At each time, the system can thus be in one of the defined states with each having a probability of occurrence [282], i.e. the sum of the state probabilities is equal to 1 at all times. The time dependent availability of a repairable system with one component, illustrated in Figure 5.4, with exponential failure and repair rates is [53, 55]:

$$A(t) = \frac{\mu_c}{\lambda_c + \mu_c} - \frac{\lambda_c}{\lambda_c + \mu_c} e^{-(\lambda_c + \mu_c)t} \quad (5.1)$$

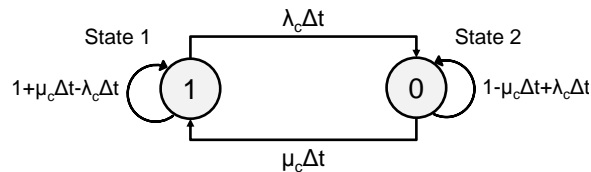


FIGURE 5.4: State Space Diagram of a one-component system with two states. Δt =time step, λ_c =constant component failure rate, μ_c =constant component repair rate, state 1=component works, state 2=component failed.

The system moves between its defined states with each time step Δt , determining the state probabilities at each time t . After a certain number of time steps, state probabilities do not change any longer, i.e. the steady-state probabilities are obtained. The related asymptotic availability and unavailability of a component (c), which are used in this

thesis, are then respectively [53, 289]:

$$\lim_{t \rightarrow \infty} A(t) = A(\infty) = a_c = \frac{\mu_c}{\lambda_c + \mu_c} \quad U(\infty) = 1 - A(\infty) = ua_c = \frac{\lambda_c}{\lambda_c + \mu_c} \quad (5.2)$$

The steady-state availability of a system with more components can be found as follows. Figure 5.5 illustrates the State Space Diagram of a two-component system. Each of the states represents a combination of up or down conditions of the system components. The probability of the system being in state s , P_s , can be obtained by multiplying the asymptotic total (un)availabilities of the different components in the state as indicated in Equation 5.3. System availability, a_{xc} , and unavailability, ua_{xc} , can then be found as the OR-gate (sum) of the probability of being in available and unavailable system states respectively (see Appendix H). If both components are individually able to meet the operational requirement of the system, states 1, 2 and 3 are considered available.

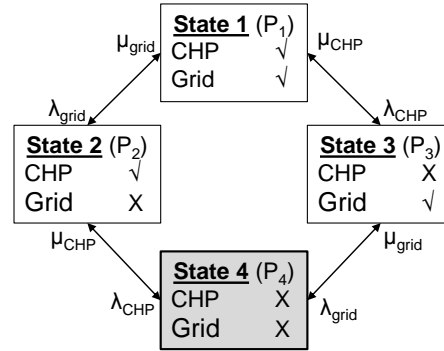


FIGURE 5.5: State Space Diagram of a two-component system with a CHP unit and grid connection as available energy supply options, adapted from Haghifam and Manbachi [295]. State transitions occur through constant failure, λ , and repair, μ , rates.

$$\begin{aligned} P_1 &= a_{CHP} \cdot a_{grid} & P_2 &= a_{CHP} \cdot ua_{grid} & (5.3) \\ P_3 &= ua_{CHP} \cdot a_{grid} & P_4 &= ua_{CHP} \cdot ua_{grid} \\ a_{xc} &= P_1 + P_2 + P_3 = 1 - P_4 = 1 - ua_{xc} \end{aligned}$$

5.2.2.4 Availability in DES optimisation

Dependability evaluation of DES has not received as much attention as other potential DES benefits [131, 289, 292]. Research regarding dependability as a technical criterion can be divided in three major categories: a posteriori assessment, as indirect design

objective/constraint, or, as direct design objective. Most research regards a posteriori determination of availability or reliability of a known system without optimising this. Several alternative system topologies are selected and compared regarding cost, reliability or availability when an ‘optimal design’ has to be selected. A model for electrical and thermal reliabilities of a known CHP system, for example, was introduced by Haghifam and Manbachi [295], employing a State Space Markov process. A similar analysis was conducted for a building cooling, heating and power system by Wang et al. [297].

Within DES optimisation, availability or reliability have been mostly indirectly adopted as design constraints. Ren et al. [298], for example, presented a multi-objective linear model for the optimal operational strategy of a DES, minimising energy cost and CO₂ emissions. Equipment availability was here integrated through a constant availability factor placing an upper bound on DG energy generation. A planning strategy for DG units within electrical power systems was presented by Zangeneh et al. [299], employing a multi-objective normal boundary intersection algorithm with four cost-related objectives. The cost of energy not supplied was the reliability measure whereas availability was included through availability factors.

Availability and reliability are technical objectives but have not been used explicitly, including system and component states, within superstructure DES design optimisation. They have, in contrast, been used as objectives in the context of selecting the optimal number of redundant identical components in generic networks. Fiori de Castro and Lucchesi Cavalca [291], for example, suggested a genetic algorithm to maximise availability of a series engineering system configuration. An evolutionary optimisation approach to maximise redundancy availability in a generic parallel/series system was, additionally, suggested by Ratle et al. [300]. Within the application of DES, research is limited. Frangopoulos and Dimopoulos [301] analysed reliability for optimal design and operation in the selection of a number of generic co-generation units through a genetic algorithm. Each system state probability, obtained through a Markov State Space approach, served to analyse expected cost and energy values. A planning tool with financial and technical objectives was developed by Yassami et al. [302]. Reliability was, however, integrated as a cost through customer damage functions. Singh and Goswami [303], in their turn, proposed a genetic algorithm for optimal planning of DG units in terms of siting and sizing. The overall objective was formulated as a

multi-objective performance index employing weighted indices for reliability of service, efficiency and power quality. Only overall system reliability indices were used, such as SAIDI. A strategic technology-policy framework for DER allocation under technical, financial and environmental objectives was presented by Mallikarjun and Lewis [133] for a commercial building. A reliability factor efficiency was employed as technical objective within an unoriented data envelopment analysis (DEA) for factor efficiency comparison. Goal Programming was subsequently used to optimally match energy resources with energy end-uses. Lastly, a recent body of research looked at component sizing for electrical DES design while minimising both cost and an energy supply reliability measure, such as loss of power supply probability or expected energy not served, through genetic algorithms or particle swarm optimisation [304–308].

5.2.2.5 Availability quantification

Since a steady-state MILP modelling approach is employed, steady-state system availability is chosen as optimisation objective. Several objective formulations can here be employed. Each neighbourhood house has an individual energy system, which can interact with other house systems within a neighbourhood system. This leads to closed loops and complexity. Hence system availability of individual houses should be considered within the objective function. This system availability will be determined based on its installed energy supply options. Additionally, since energy integration combines the different houses within a whole, the objective should also include a measure for overall neighbourhood system availability. Hence average house energy system availability in the neighbourhood is optimised, i.e. *minimisation of unavailability*, as this reflects both individual houses and the neighbourhood as a whole. Furthermore, to illustrate the methodology, and since availability is most relevant to and established in the electricity sector, the focus is in the first instance on the electrical system (un)availability.

5.2.3 Summary and research gaps

Multi-objective DES design optimisation employing an economic, environmental and technical objective is still a developing area of research. Cost and emissions have been touched upon within energy integrated DES. An explicit technical measure for system

dependability based on its components, and a tri-objective approach that fits in with central energy system objectives, have not been addressed and are therefore developed in this Chapter through a multi-objective DES design trade-off framework.

5.3 Method

5.3.1 Problem description

A generic multi-objective strategy is developed, building further on the developed base model (see Chapter 4). Three conflicting objectives are now traded off in the DES design process: minimising (i) annualised energy costs (economic), (ii) annual CO₂ emissions (environmental), and (iii) electrical system unavailability (technical).

5.3.2 Optimisation framework and model requirements

The new objectives and constraints are integrated into the developed MILP model. In addition to the model requirements of Chapter 4 (Section 4.2.2), technology availability input data is required. The objective is to trade off minimising (i) *total annualised cost* of the neighbourhood as a whole to meet its yearly demands, (ii) *average house electrical system unavailability*, and (iii) *total yearly neighbourhood CO₂ emissions* under various operational, technical, economic, environmental and regulatory constraints. The three objectives (f_i) are combined into a single objective function through a weighted-sum:

$$\min_{x,y} Z = \lambda_1 \cdot f_1(x, y) + \lambda_2 \cdot f_2(x, y) + \lambda_3 \cdot f_3(x, y) \text{ s.t. } \begin{cases} \sum_i \lambda_i = 1 \text{ and } \lambda_i \in [0; 1] \\ h(x, y) = 0 \text{ and } g(x, y) \leq 0 \\ x \in X, y \in 0, 1 \end{cases}$$

bound by equality ($h(x, y)$) and inequality ($g(x, y)$) constraints (see Section 3.2.2). Trading off the objectives by varying weights λ_i of functions i , where the sum of the three weights equals one, enables creating a Pareto set of optimal solutions.

Figure 5.6 illustrates the steps in implementing unavailability. First, total unavailability values of the electrical components are obtained (see Section 5.5.1). Second, potential component combinations, available to supply the electrical load of individual houses, are

determined, i.e. potential house electrical system configurations. A Markov State Space Diagram is subsequently constructed for each system configuration to obtain its steady-state unavailability (see Section 5.5.3). These system unavailabilities are model inputs. System configurations are then implemented through the use of logic-gate operations and binary integer programming. The model optimises average house electrical system unavailability as a combination of implemented house system configurations. Optimised neighbourhood design thus implements one of the considered system configurations in each house. Additionally, for a technology to be considered available, it might require a minimum installed capacity, introducing capacity constraints.

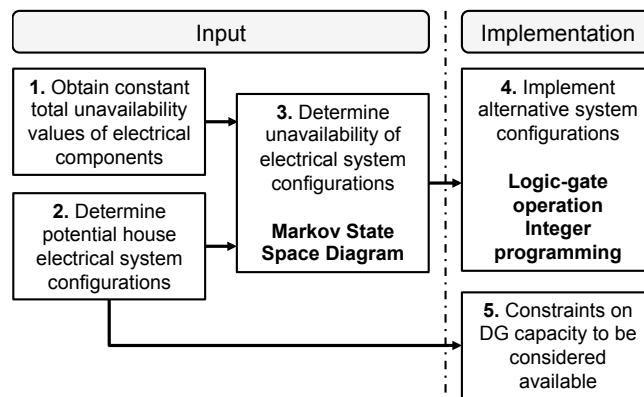


FIGURE 5.6: Conceptual diagram of unavailability implementation.

5.3.3 Model assumptions and decisions

Modelling complex systems requires implementation decisions and assumptions to set boundaries on the system [82, 106, 107]. The developed model follows the same assumptions as the base model of Chapter 4, Section 4.2.3. Electrical components are, however, no longer considered 100 % available. The specific assumptions are:

- Only the electrical system is under availability optimisation.
- No carbon tax is considered.
- All components are in their useful lifetime [309].
- Steady-state availability assessment is made, no dynamic processes, such as relay switching, are considered. Instead, different system configurations are determined.
- No fault occurs within repair intervals [309].
- No common-mode² failures are considered [309].

²*Common-mode failures* are failures where multiple components fail due to a single event.

- Neither cold standby nor switched redundancy³ are included [53, 282].
- Components are independent in terms of failure and repair [309].
- Variability of renewable energy resources introduces challenges. Hence a single electricity generation source (PV units) is in the first instance considered. Wind turbines are thus not taken into account but could be implemented similarly.
- Authorised islanding is assumed. Without authorised islanding, installed DG units have to be switched off in case of central system outages, limiting DES redundancy and dependability advantages compared to conventional operation.

Similarly to Chapter 4, annualised operation and a yearly planning horizon are employed for an average day (24 hours) in three seasons. Furthermore, various implementation choices have to be made, where alternatives exist (see Section 5.4).

5.3.4 Contributions

The developed framework of Chapter 4 is extended with two objectives, adding the following new features and functionalities to the model:

- implementing unavailability as an explicit technical objective through system configurations and the state of their components,
- combining logic-gate operation and State Space Diagrams with integer programming within a superstructure MILP framework to model availability,
- and a tri-objective economic-environmental-technical framework for DES design.

5.4 Model implementation and design decisions

The model consists of a tri-objective function (Eqs. 5.4-5.7) bound by the design and operational constraints presented in Chapter 4. Additional constraints regard (i) capacity threshold constraints (Eqs. 5.9-5.18, and Eqs. I.19-I.24 (Appendix I)) and (ii) house electrical system constraints (Table 5.1, Eqs. 5.19-5.22).

³*Cold standby* is equal to cold redundancy. *Switched redundancy* defines a component that is redundant but needs a switching action to become available to supply the load, introducing lag times.

5.4.1 Objective function

Design is optimised by minimising the scaled total annualised cost of the neighbourhood, $C^{TOT,S}$ [kAUD y^{-1}], the scaled yearly neighbourhood CO₂ emissions, EM^S [tonCO₂ y^{-1}], and the scaled average house electrical system unavailability, $UA^{TOT,S}$:

$$\min_{x,y,z} \begin{cases} C^{TOT,S} \\ EM^S \\ UA^{TOT,S} \end{cases} \quad (5.4)$$

with x technology options, y capacity ranges and z neighbourhood locations. The objective function is constructed as a weighted sum of the scaled objectives, with $\lambda_i \in [0, 1]$:

$$\min_{x,y,z} [\lambda_c \cdot C^{TOT,S} + \lambda_e \cdot EM^S + \lambda_a \cdot UA^{TOT,S}] \quad \text{and} \quad \sum_i \lambda_i = 1 \quad (5.5)$$

The cost model was detailed in Chapter 4. Note that the total cost, C^{TOT} , has been scaled to kAUD y^{-1} ($C^{TOT,S}$). The additional objectives and constraints of the tri-objective model are detailed in Sections 5.4.2 and 5.4.3.

5.4.2 Environmental objective

Total yearly neighbourhood CO₂ emissions, EM [kgCO₂ y^{-1}] come from natural gas fuelled thermal technologies, gas heaters ($PH_{G,i,s,h}^{TOT}$) and boilers ($PH_{B,i,s,h}^{TOT}$), from electricity generated by natural gas fuelled CHP units ($PE_{CHP,i,s,h}^{TOT}$) and from central grid electricity import ($PE_{i,s,h}^{GRID}$) (see also Equation D.5, Appendix D):

$$EM = \sum_{i,s,h} hr \cdot d_s \cdot CI_{elec} \cdot PE_{i,s,h}^{GRID} + \sum_{i,s,h} hr \cdot d_s \cdot CI_{gas} \cdot \left(\frac{PH_{B,i,s,h}^{TOT}}{n_B^{th}} + \frac{PH_{G,i,s,h}^{TOT}}{n_G^{th}} + \frac{PE_{CHP,i,s,h}^{TOT}}{n_{CHP}^{elec}} \right) \quad (5.6)$$

Note that the objective is scaled to tonCO₂ per year: $EM = \frac{EM^S}{1000}$.

5.4.3 Technical objective and constraints

Average house electrical system unavailability, $UA^{TOT,S}$, in a neighbourhood is determined by the sum of the system unavailability of each house i , UA_i , divided by the total

number of houses in the neighbourhood, n_h :

$$UA^{TOT,S} = \frac{\sum_i UA_i}{n_h} \quad (5.7)$$

Individual house electrical system unavailability is determined through a parallel connection of unavailability values of its mutually exclusive potential system configurations, represented by an OR-gate (see Appendix H). The output to an OR-gate can be found as the sum of mutually exclusive binary inputs [51–53]. Each considered house (i) electrical system configuration, con , is represented by a binary variable, $B_{con,i}$, and a constant system unavailability, ua_{con} . The latter is obtained through a Markov chain (see Section 5.5.3). Note that the potential configurations are mutually exclusive since only one configuration can be adopted in each individual house (i.e. $\sum_{con} B_{con,i} = 1 \forall i$). Mutual exclusivity has been ensured through AND-NOT configuration modelling, see Section 5.4.3.2, as only one technology combination will in this way be enabled in each house. Neighbourhood average system unavailability hence optimises the combination of house system configurations. A logarithmic transformation of obtained unavailability inputs is employed to bring objectives within similar range and to indirectly measure unavailability as *availability* through a number of ‘nines’ (see Section 5.2.2.3):

$$UA_i = \sum_{con} B_{con,i} \cdot \log_{10}(ua_{con}) \quad \forall i \quad (5.8)$$

5.4.3.1 Capacity constraints

Potential house electrical system configurations are each a combination of available electricity generating technologies to a house, i.e. a CHP unit, a PV unit, a battery, a microgrid connection fed by CHP units in other houses, and a potential grid connection. In practice, the electrical supply availability of a component (part of its total availability) is a function of its installed capacity. A first analysis is conducted in this thesis with one availability–capacity step rather than a gradual relationship between both (see Section 5.7). Installed units consequently require a minimum installed capacity to be considered available to supply the load of their accommodating house. A lower capacity is allowed but the corresponding unit is then considered unavailable. In the first instance, two discrete electrical component capacity levels are thus allowed, unavailable and 100% available. The latter is a capacity, able to fully meet the load of the accommodating

house in each hour. The former combines all unavailable and reduced available capacity values into one unavailable level. For an installed PV unit or battery to supply their accommodating house, their installed capacity ($DG_{tech,i}^{MAX}$) should be greater or equal than a threshold capacity, $T_{tech,i}^{av}$ [m² or kWh]. Their capacity can thus fall within one of two categories, characterised by binary variables $B_{tech,i}$ (installed and unavailable) and $B_{tech,i}^{av}$ (installed and 100% available), respectively as illustrated in Figure 5.7. Total installed technology capacity should additionally fall within bounds $[L_{tech}; U_{tech}]$. With $tech$, PV units or batteries:

$$L_{tech} \cdot B_{tech,i} + T_{tech,i}^{av} \cdot B_{tech,i}^{av} \leq DG_{tech,i}^{MAX} \leq T_{tech,i}^{av} \cdot B_{tech,i} + U_{tech} \cdot B_{tech,i}^{av} \quad \forall i \quad (5.9)$$

$$B_{tech,i} + B_{tech,i}^{av} \leq 1 \quad \forall i \quad (5.10)$$

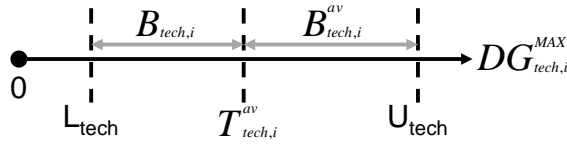


FIGURE 5.7: Schematic of PV and battery capacity intervals.

Note that PV units are only considered available to supply the load of their accommodating house, not to supply the whole neighbourhood through microgrid sharing. CHP units, in contrast, can perform the different tasks of (i) meeting the electricity load of their accommodating house, and (ii) meeting the electricity demand of the whole neighbourhood through microgrid sharing. Their installed electrical capacity, $DG_{CHP,i}^{MAX}$ [kW], should fall within bounds $[L_{CHP}, U_{CHP}]$. Depending on the task of the CHP unit, its capacity should be at least equal to threshold capacities $T_{CHP,i}^{av}$ [kW] (available for its accommodating house) or $T_{CHPmg,i}^{av}$ [kW] (available for the microgrid), respectively. This characterises three CHP capacity categories, unavailable ($B_{CHP,i}$), 100 % available for house i ($B_{CHP,i}^{av}$) and 100 % available for microgrid operation ($B_{MG,i}^{av}$), see Equations 5.11-5.12 and Figure 5.8. These three availability levels are represented by three binary variables CHP_i^A , CHP_i^B and CHP_i^C that impose alternative upper and lower bounds on installed CHP capacity:

$$L_{CHP} \cdot CHP_i^A + T_{CHP,i}^{av} \cdot CHP_i^B + T_{CHPmg,i}^{av} \cdot CHP_i^C \leq DG_{CHP,i}^{MAX} \quad \forall i \quad (5.11)$$

$$DG_{CHP,i}^{MAX} \leq T_{CHP,i}^{av} \cdot CHP_i^A + T_{CHPmg,i}^{av} \cdot CHP_i^B + U_{CHP} \cdot CHP_i^C \quad \forall i \quad (5.12)$$

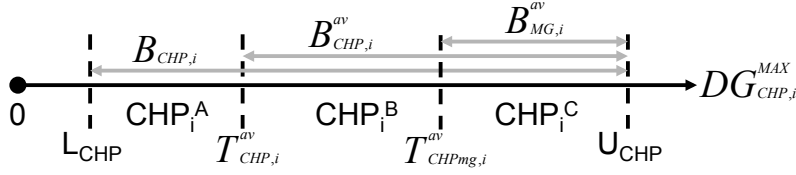


FIGURE 5.8: Schematic of CHP capacity intervals.

These three mutually exclusive binary variables each represent a combination of the three CHP capacity categories (AND (\wedge) - NOT (\bar{B}) gate, see Appendix H):

$$CHP_i^A = B_{CHP,i} \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{MG,i}^{av}} \quad \forall i \quad (5.13)$$

$$CHP_i^B = B_{CHP,i} \wedge B_{CHP,i}^{av} \wedge \overline{B_{MG,i}^{av}} \quad \forall i \quad (5.14)$$

$$CHP_i^C = B_{CHP,i} \wedge B_{CHP,i}^{av} \wedge B_{MG,i}^{av} \quad \forall i \quad (5.15)$$

An AND-gate represents a product of binary variables and has been linearised using the procedure presented in [107, 310] (see Appendix H). A NOT-gate inverts its binary input. Equation 5.13 has, for example, been linearised as, $\forall i$:

$$\begin{aligned} CHP_i^A &\geq B_{CHP,i} + (1 - B_{CHP,i}^{av}) + (1 - B_{MG,i}^{av}) - 2 \\ CHP_i^A &\leq B_{CHP,i} \text{ and } CHP_i^A \leq (1 - B_{CHP,i}^{av}) \text{ and } CHP_i^A \leq (1 - B_{MG,i}^{av}) \end{aligned} \quad (5.16)$$

Additionally, the three binary variables are constrained by CHP existence:

$$CHP_i^A + CHP_i^B + CHP_i^C \leq B_{CHP,i} \quad \forall i \quad (5.17)$$

Furthermore, the hierarchical relation between the binary variables that characterise CHP existence, 100 % availability and 100 % microgrid availability is:

$$B_{CHP,i}^{MG} \leq B_{CHP,i}^{av} \leq B_{CHP,i} \quad \forall i \quad (5.18)$$

5.4.3.2 Potential house electrical system configurations

Potential house electrical system configurations are each characterised by a binary variable ($B_{con,i}$), see Table 5.1, of which its value is determined through an AND–NOT relation (see Appendix H) between all the binary variables (enabled, or, disabled (NOT))

of the individually considered available electrical technologies to each house. Different component combinations can in this way be represented by a series of ones and zeros, which enables (‘switching on’) and disables (‘switching off’) the implementation of components to represent different house system configurations. System configurations are thus feasible combinations of the five individually available components to each house, i.e. a grid connection, a CHP unit, a PV unit, a battery and an operational microgrid with a number of microgrid-available CHP units in houses j (with $i \neq j$) $\in [0, n_h - 1]$, see Figure 5.9. Each house can thus have one of 2^5 possible component combinations, i.e. system configurations, including the option of no installed components. Only certain combinations are, however, feasible, see Table 5.1. An appropriately sized battery, for example, is only considered available together with an appropriately sized (available) PV unit or CHP unit in the same house. Binary variables of some of the considered components are clarified below. A house has an available grid connection, GC_i , if it imports electricity from the grid, $X_{i,s,h}^{rec}$, in at least one hour, h , throughout the year:

$$X_{i,s,h}^{rec} \leq GC_i \leq \sum_{s,h} X_{i,s,h}^{rec} \quad \forall i, s, h \quad (5.19)$$

The number of microgrid-available CHP units available to house i ($k = 0 \dots n_{chp,i}$), adopted in houses j in the neighbourhood ($B_{MG,j}^{av}$), can vary from zero to $n_{chp,i}$ ($n_{chp,i} = n_h - 1$). $Y_{i,k}^{chp}$ is a binary variable that decides whether a number of CHP units (k) in the neighbourhood is available to house i through microgrid operation:

$$\sum_{j \neq i} B_{MG,j}^{av} = \sum_{k=0}^{n_{chp,i}} k \cdot Y_{i,k}^{chp} \quad \text{and} \quad \sum_k Y_{i,k}^{chp} \leq 1 \quad \forall i \quad (5.20)$$

For a CHP unit to be available for microgrid operation, both a CHP unit of available capacity and a microgrid central control unit (binary variable Z) must be available

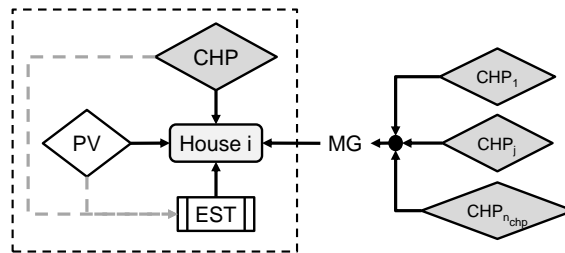


FIGURE 5.9: Potential electrical supply options for each house i .

TABLE 5.1: AND-NOT expressions of electrical system configurations for house i . CHP=combined heat and power, EST=battery, GR=grid, MG=microgrid, PV=photovoltaic.

Binary ($B_{con,i}$)	Technology combination	AND-NOT expression	$\forall i, k$
GC_i	GR	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
C_i	CHP	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
P_i	PV	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$MG_{i,k}$	MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
XC_i	GR and CHP	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
XP_i	GR and PV	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$XMGC_{i,k}$	GR and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
CP_i	CHP and PV	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
CE_i	CHP and EST	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$CMGC_{i,k}$	CHP and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
PE_i	PV and EST	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$PMGC_{i,k}$	PV and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
XCP_i	GR, CHP and PV	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
XCE_i	GR, CHP and EST	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$XCMGC_{i,k}$	GR, CHP and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
XPE_i	GR, PV and EST	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$XPMGC_{i,k}$	GR, PV and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
CPE_i	CHP, PV and EST	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$CPMGC_{i,k}$	CHP, PV and MG	$\overline{X_i} \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$CEMGC_{i,k}$	CHP, EST and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$PEMGC_{i,k}$	PV, EST and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$CPEX_i$	CHP, PV, EST and GR	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k}$	
$XCPMGC_{i,k}$	GR, CHP, PV and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$XCEMGC_{i,k}$	GR, CHP, EST and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$XPEMGC_{i,k}$	GR, PV, EST and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$CPEMGC_{i,k}$	CHP, PV, EST and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	
$CPEXMGC_{i,k}$	CHP, PV, EST, GR and MG	$GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge MGA_{i,k}$	

Nonfeasible technology combinations:
EST, (GR and EST), (MG and EST), (GR, MG and EST), and no installed technologies.

(binary variable $MGA_{i,k}$). This leads to the following AND-relation:

$$MGA_{i,k} = Z \wedge Y_{i,k}^{chp} \quad \forall i, k \quad (5.21)$$

and resulting linearisation [107, 310] (see Appendix H), $\forall i, k$:

$$MGA_{i,k} \geq Z + Y_{i,k}^{chp} - 1 \quad \text{and} \quad MGA_{i,k} \leq Z \quad \text{and} \quad MGA_{i,k} \leq Y_{i,k}^{chp}$$

Each house (i) system configuration can thus be modelled as an AND-NOT gate (Appendix H) of combinations of considered individual components, see Table 5.1. The house configuration with an available CHP and grid connection, for example, is then:

$$XC_i = GC_i \wedge \overline{B_{CHP,i}^{av}} \wedge \overline{B_{PV,i}^{av}} \wedge \overline{B_{EST,i}^{av}} \wedge \sum_k MGA_{i,k} \quad \forall i \quad (5.22)$$

5.5 Case-study: a small Adelaide based neighbourhood

Section 4.4 presented the researched case-study. Additional aspects are detailed below.

5.5.1 Component availability data

Each component – i.e. the CHP, PV and battery – has a total electrical unavailability (UA_{tech}^{tot}), obtained as a series relation (see Appendix G) of its resource availability (A_{tech}^{res}), its component availability (A_{tech}^{com}) and its supply availability (A_{tech}^{sup}) [295]:

$$UA_{tech}^{tot} = 1 - (A_{tech}^{res} \cdot A_{tech}^{com} \cdot A_{tech}^{sup}) = 1 - (1 - UA_{tech}^{res}) \cdot (1 - UA_{tech}^{com}) \cdot (1 - UA_{tech}^{sup}) \quad (5.23)$$

Resource availability of CHP units relates to natural gas supply availability. PV unit resource availability relates to the hourly average probability of available solar irradiation in each hour to meet the load in that hour (see Appendix I). Battery resource availability is based on its state of charge [311]. The latter is determined by the availability of a PV and/or CHP unit in the same house that can charge an available battery in hour h in order to sustain battery discharge during autonomy time (see Appendix I). Battery autonomy time refers to the hours or days it can fully meet the load if fully charged [311]. For a PV or CHP unit to be able to charge the battery for full autonomy discharge, an installed capacity is assumed that not only allows them to meet their house peak load in hour h but also charge the battery in that hour (worst case). Battery resource availability in house i is thus either the probability of an appropriately sized available CHP unit in house i , an appropriately sized available PV unit in house i , or, both appropriately sized available CHP and PV units in house i (see Appendix I). *Component unavailability* refers to the unavailability of the component to perform, based on the state of its internal mechanical and electrical parts. *Component supply availability* relates to the probability that the component can supply the load in each hour throughout the year, dependent on its installed capacity or state of charge [311]. In this work, discrete supply availability steps are employed (see Section 5.7), i.e. 100 % available or unavailable, based on capacity thresholds. Total component *availability* values are presented in Table 5.2.

Apart from technologies, each house can also have available electrical supply through a grid connection or a connection with a microgrid fed by a certain number of CHP

TABLE 5.2: Component availabilities [%]. CHP=combined heat and power unit, EST=battery, MGCC=microgrid central control unit, PV=photovoltaic unit. Solar availability is determined by the average probability that the hourly available sun can meet the load in that hour, detailed in Appendix I.

Availability [%]	Components		
	CHP	PV	EST
Technical	96.0000 % [295]	99.9990 % [312]	99.9967 [312]
Supply	100 %	100 %	100 %
Resource	99.9975% [289]	22.2489 % (Appendix I)	95.9976 % (CHP) or 22.2487 % (PV) or 96.8881 % (PV and CHP) (Appendix I)
Total a_{tech}	95.9976 %	22.2487 %	95.9944 % (CHP) or 22.2479 % (PV) or 96.8849 % (PV and CHP)

units. Central grid unavailability in South Australia is 0.060 %, i.e. availability of 3 nines (SAIDI) [313, 314]. $(UA_{CHP}^{tot})^k$ is the total unavailability of k CHPs available for microgrid operation to a house. A microgrid is, however, only available together with an available control unit with 0.0200 % component unavailability (UA_{MGCC}^{tot}) [289]. Total microgrid unavailability ($UA_{MG,k}^{tot}$) then becomes:

$$UA_{MG,k}^{tot} = 1 - (1 - UA_{MGCC}^{tot}) \cdot (1 - (UA_{CHP}^{tot})^k) \quad \forall k \quad (5.24)$$

5.5.2 Threshold capacities

Component threshold capacities are detailed in Appendix I. To be available to supply a house electrical load, component threshold capacities are set to the peak hourly accommodating house electricity load for available PV and CHP units, and to the peak hourly neighbourhood electricity load for microgrid-available CHP units. Battery threshold capacities are based on being able to supply the average hourly electricity demand of their accommodating houses for a certain autonomy time (on-grid: 3 hours, off-grid: 2 days [315, 316]). Note that electrical threshold demands include electricity demand for both appliances and cooling through air-conditioning units (maximum possible electricity demand of each house).

5.5.3 House electrical system configurations

For each potential house electrical system configuration, a State Space Diagram can be constructed to determine its system (un)availability [295]. The State Space Diagram and system (un)availability of the configuration with a CHP unit and a grid connection

was illustrated in Figure 5.5, Section 5.2.2.3. Availability determination of the other configurations is detailed in Appendix I.

5.5.4 Analysis and selected energy system scenarios

Trade-offs and key design changes are researched to illustrate the framework capability:

- I Minimisation of total annualised energy cost and average house electrical system unavailability trade-off; the environmental weighting factor (λ_e) is set to zero.
- II Minimisation of total annualised energy cost and CO₂ emissions trade-off; the availability weighting factor (λ_a) is set to zero.
- III Minimisation of average house electrical system unavailability and CO₂ emissions trade-off; the economic weighting factor (λ_c) is set to zero.
- IV Minimisation of total annualised energy cost, average house electrical system unavailability and annual CO₂ emissions trade-off. The three weighting factors are varied to enable the relative trading off of three objectives in the design process.

The developed framework allows assessing the robustness of results with respect to:

- *upscaling* of the neighbourhood,
- *sensitivity analysis* performed on key uncertain component unavailability inputs,
- and *implementation aspects* to assess component redundancy requirements to allow for islanding by comparing on- and off-grid unavailability-cost trade-offs.

5.6 Results and analysis

Selected results of the presented scenarios are illustrated in Section 5.6.1. Model robustness is subsequently analysed based on upscaling, sensitivity analysis and redundancy analysis. The model statistics and ‘knee-point’ CPU times are given in Table 5.3.

5.6.1 Energy system design trade-offs

Figure 5.10 illustrates the Pareto sets of the first three defined scenarios. Total neighbourhood installed unit capacities of selected lambda values (λ) for the three trade-offs

TABLE 5.3: Model statistics of multi-objective model and ‘knee-point’ CPU times [s].

Blocks of equations	326	Single equations	34 306
Blocks of variables	130	Single variables	24 373
Non zero elements	122 065	Discrete variables	4131
‘knee-point’ CPU unavailability-cost			2420 s
‘knee-point’ CPU emissions-cost			183 s
‘knee-point’ CPU emissions-unavailability			232 s

are summarised in Table 5.4. Note that the end points on each set in Figure 5.10 dominate all smaller or larger λ values. Smaller values could, for example, occur due to unit capacity maximisation for the same unavailability or emissions objective when cost has a small weighting. In case of the unavailability-emissions trade-off this is true for $\lambda_e = 0.995$, which dominates any point with a greater λ_e . Greater λ_e values will maximise PV capacity under full emission minimisation, for the same unavailability level. Additionally, discrete Pareto sets are obtained rather than smooth curves. This is due to discrete threshold capacity intervals and design choices (see Section 5.7).

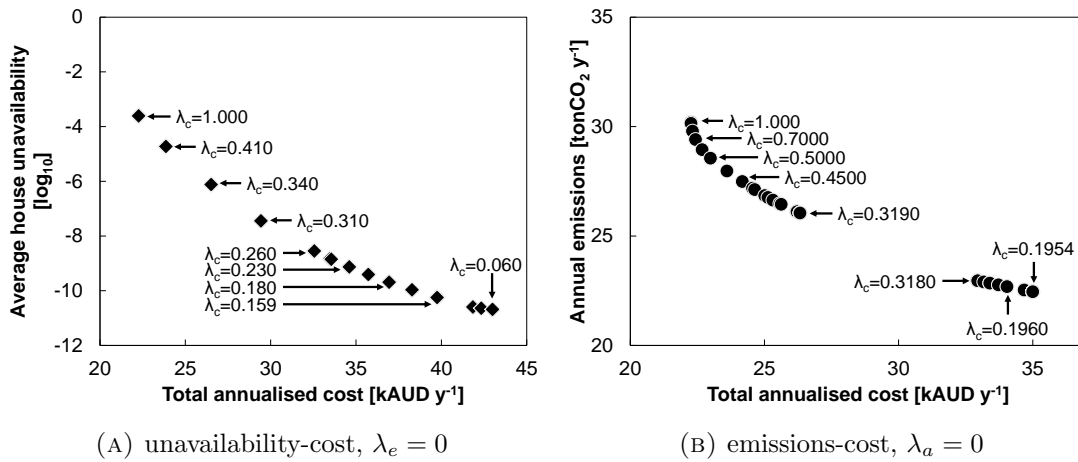


FIGURE 5.10: Pareto trade-offs between objectives. weights λ_a (availability), λ_c (cost), λ_e (emissions).

TABLE 5.4: Total neighbourhood installed unit capacities [kW or kWh], micro-grid existence (MG) and objective values ($C^{TOT,S}$ [kAUD y^{-1}], EM^S [tonCO₂ y^{-1}], $UA^{TOT,S}$ [\log_{10}]) for selected λ values for each trade-off. B=boiler, CHP=combined heat and power, EST=battery, HST=heat storage, MG=microgrid installation, PV=photovoltaic. A total airco capacity of 11.2 kW is installed in all cases.

	PV	CHP	B	EST	HST	MG	$C^{TOT,S}$	EM^S	$UA^{TOT,S}$
unavailability-cost ($\lambda_e = 0$)									
$\lambda_c = 1.000$	10.5	2.1	26.0	0	5.4	✓	22.264	30.194	-3.611
$\lambda_c = 0.410$	10.5	8.0	25.0	0	4.9	✓	23.866	29.754	-4.729
$\lambda_c = 0.230$	10.0	34.1	7.6	2.1	20.4	✓	33.473	32.729	-8.829
$\lambda_c = 0.159$	13.5	45.4	0	13.5	11.1	✓	39.753	33.017	-10.248
$\lambda_c = 0.060$	25.0	52.2	0	13.5	5.5	✓	43.000	31.935	-10.684
emissions-cost ($\lambda_a = 0$)									
$\lambda_c = 1.0000$	10.5	2.1	26.0	0	5.4	✓	22.264	30.194	-3.611
$\lambda_c = 0.9000$	10.7	2.1	27.4	0	2.1	✓	22.266	30.145	-3.589
$\lambda_c = 0.3190$	22.7	1.9	28.3	19.9	3.0	✓	26.325	26.051	-3.698
$\lambda_c = 0.3180$	25.0	0	33.6	57.4	0.6	–	32.944	22.957	-3.440
$\lambda_c = 0.1954$	25.0	0	33.9	68.4	0	–	35.000	22.454	-0.219
unavailability-emissions ($\lambda_c = 0$)									
$\lambda_e = 0.995$	46.5	0	175	61.9	250	✓	42.422	22.454	-3.440
$\lambda_e = 0.600$	50.3	20	140	77.1	250	✓	49.986	23.560	-5.117
$\lambda_e = 0.300$	47.7	100	0	69.6	250	✓	73.474	29.363	-10.684

Average house system availability increases from 3 to 10 nines when traded off with cost (see Figure 5.10a). Figure 5.11 illustrates selected design changes. In between the illustrated designs, the transition is more gradual with an increasing number of microgrid-available CHP units and batteries. Available PV units are installed in all houses until $\lambda_c = 0.230$. From this point, batteries start to appear. The combination of PV and CHP charging sources for batteries, combined with an increasing number of batteries in the neighbourhood, leads here to a more gradual trade-off. Discrete jumps between Pareto points occur due to the discrete relationship between unavailability and unit capacity (see Section 5.7). A 31 % drop in unavailability, i.e. availability increase

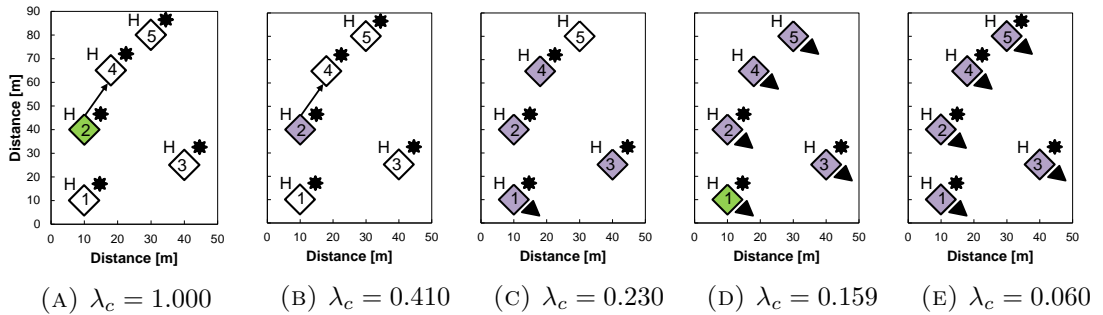


FIGURE 5.11: [colour] Major design changes for unavailability-cost trade-off for several values of λ_c . white diamonds=boiler and airco, grey diamond (green)=available CHP for house and airco, dark grey diamond (purple)=available CHP for MG and airco, sun=PV, triangle=battery, black arrow=heating pipe, H=heat storage unit. Note that all houses have a grid connection.

of 1 nine, combined with a relative small cost increase of 7.2 % occurs between the first ($\lambda_c = 1.000$) and second point ($\lambda_c = 0.410$). The only installed neighbourhood CHP unit capacity increases here from available for its accommodating house to available for microgrid operation. The latter design is most favourable in the trade-off decision-making, i.e. the sought-after ‘knee-point’, since it leads to the highest availability increase for the lowest additional cost (largest gradient).

Yearly CO₂ emissions decrease from 30 to 22 ton when traded off with cost (see Figure 5.10b). Figure 5.12 illustrates selected design changes. In between the illustrated designs, there is a more gradual trend towards increased individual house self-sufficiency. The single neighbourhood CHP unit capacity reduces and is eventually eliminated in $\lambda_c = 0.3180$. The number of PV-battery systems increases with decreasing λ_c . Household grid import, furthermore, reduces and neighbourhood energy sharing is eliminated with decreasing λ_c . The major gap in the otherwise smoother transitions occurs between $\lambda_c = 0.3190$ and 0.3180 . At $\lambda_c = 0.3190$, the smallest possible CHP unit is installed in the neighbourhood. Since house 1 has the lowest demand and houses are not allowed to have a CHP unit together with a boiler due to design implementation choices (see Section 4.4.4), this unit is installed in house 1. At $\lambda_c = 0.3180$, this CHP is eliminated due to the more efficient heat generation by boilers. This elimination requires a significant increase in both PV and battery capacity in all houses, leading to a significant cost increase and emission drop. The smallest overall cost increase (0.01 %) for the relatively highest drop in emissions (0.16 %) occurs from the first ($\lambda_c=1.000$) to the second point ($\lambda_c = 0.900$). The installed PV in house 1 reduces here in size (becomes unavailable). Electricity import is limitedly reduced and electricity sharing and export increases little.

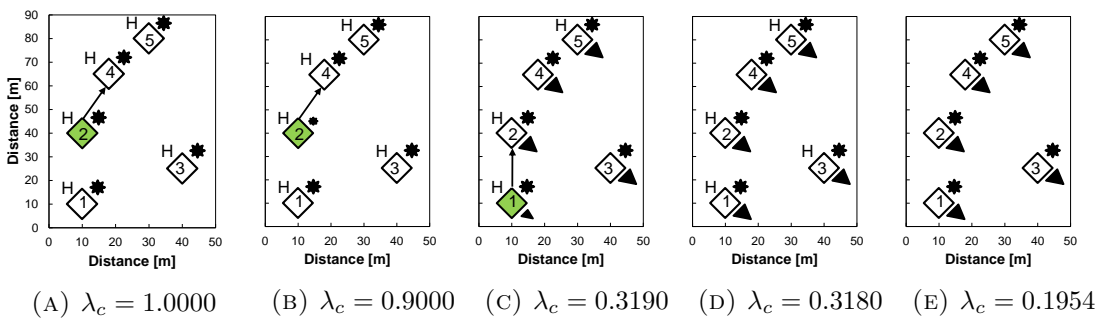


FIGURE 5.12: [colour] Major design changes for emissions-cost trade-off for several values of λ_c . white diamonds=boiler and airco, grey diamond (green)=available CHP for house and airco, sun=PV, triangle=battery, black arrow=heating pipe, H=heat storage unit, small symbols=unavailable. Note that all houses have a grid connection.

Average house system availability increases from 3 to 10 nines when traded off with emissions (see Figure 5.10c). Figure 5.13 illustrates selected design changes. Similar discrete behaviour as in the unavailability-cost trade-off occurs. Since cost is excluded from the objective function, installed units will often be maximised. Available PV units and batteries are installed in all houses across the front. Additionally, increased uptake of microgrid-available CHP units occurs across the front. A 49 % drop in unavailability, i.e. availability increase of almost 2 nines, with relative small emission increase of 4.9 % occurs between the first ($\lambda_e = 0.995$) and second point ($\lambda_e = 0.600$). A single microgrid-available CHP unit is adopted in this latter ‘knee-point’ design.

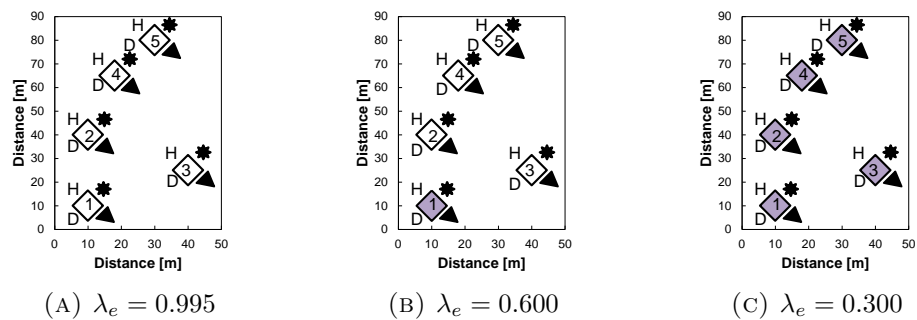


FIGURE 5.13: [colour] Major design changes for unavailability-emissions trade-off for several values of λ_e . white diamonds=boiler and airco, dark grey diamond (purple)=available CHP for MG and airco, sun=PV, triangle=battery, H=heat storage unit, D=dumpload. Note that all houses have a grid connection.

Figure 5.14 illustrates the trade-off of the three objectives in terms of number of nines in availability (bubble size) for different combinations of cost and emissions, leading to discrete solutions. A reasonable availability level would be about 4 to 6 nines (dashed area). The change in slope between iso-availability fronts increases here most and leads to the highest availability increase for the lowest additional emissions and cost. Note that cost-optimal design (Scenario II of Chapter 4) is reflected by the three-nine availability with the highest emissions (far-right three-nine point). The ‘knee-point(s)’ would be in the area of the far-right points of the four- to six-nine availability levels. The ‘best’ four-nine design leads to an availability improvement of one nine with a cost increase of 9 % compared to cost-optimal. Emissions are here reduced by 5 %. The only design change, compared to cost-optimal design, is here an increase of the installed CHP capacity in house 2 to microgrid-available. The far-right five-nine availability point improves availability with two nines compared to cost-optimal, by increasing cost by 22 % combined with an emission reduction of 11 %. The ‘best’ five-nine design has one

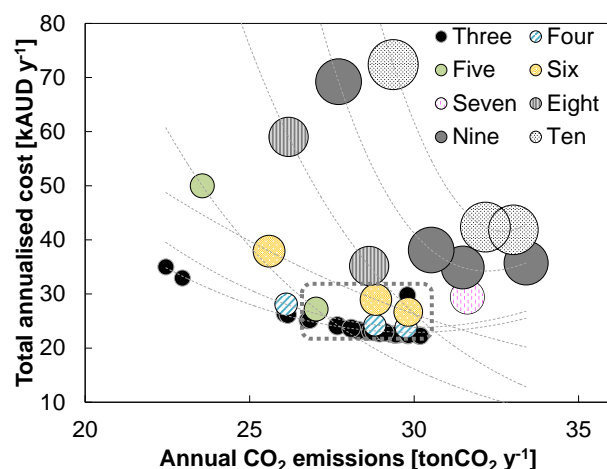


FIGURE 5.14: [colour] Bubble chart of three objective trade-off. Cost and emissions are indicated on axes and the size of the bubbles indicates the number of nines of the average house electrical system availability. Dotted lines=iso-availability curves.

microgrid-available CHP in house 1, two hot pipelines (1 to 4 and 4 to 5) and batteries implemented in 4 houses. The five-nine point is, however, relatively more expensive to increase system availability than the six-nine right-most point. In this six-nine point, availability is increased by 2 nines compared to cost-optimal, for a cost increase of only 20 %. Emissions are here, however, only reduced by 1 %. This cheapest six-nine design has two microgrid-available CHP units in houses 1 and 2 and no batteries or pipelines installed. Electricity sharing and an available PV unit in each house are adopted in each design. A trade-off between three objectives thus does not determine a single straightforward ‘knee-point’ design. The relative importance of objectives/stakeholder interests determines here the most suitable neighbourhood system design.

5.6.2 Impact of decisions: model robustness

Model robustness is illustrated in this Section through neighbourhood upscaling, sun availability sensitivity and islanding design implementation requirements.

5.6.2.1 Neighbourhood upscaling

The unavailability-cost trade-off ($\lambda_e = 0$) is scaled up to a 10-house neighbourhood (n_h), see Figure 5.15. Note that a relaxed optcr of 5% is used.⁴ Table 5.5 illustrates the model

⁴The results have been obtained using UCL research computing services (socrates.ucl.ac.uk).

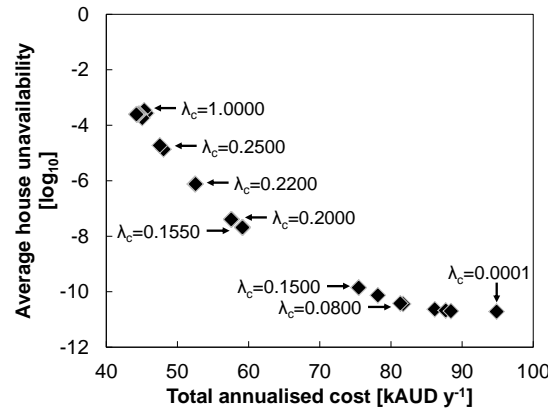


FIGURE 5.15: Pareto set of unavailability-cost trade-off ($\lambda_e = 0$) for the 10-house neighbourhood.

TABLE 5.5: Model statistics for upscaled unavailability-cost trade-off ($\lambda_e = 0$).

Number of houses	5	10		5	10
'knee-point' CPU time [s]	2420	663160			
Blocks of equations	326	325	Single equations	34 306	95 411
Blocks of variables	130	130	Single variables	24 373	67633
Non zero elements	122 065	338 290	Discrete variables	4131	12 761

statistics. A similar design trend occurs as in the 5-house neighbourhood (Figure 5.10a) with an increasing number of house-available CHP units, microgrid-available CHP units and batteries with increasing importance of unavailability as design objective. Note that the most available point on the Pareto set ($\lambda_c = 0.0001$) has only nine microgrid-available CHP units in contrast with the expected 10 in each neighbourhood house (i.e. most available design). At $\lambda_c = 0$ this is, however, not reflected in the average system availability value. This availability value namely only considers 7 microgrid-available CHP units as this value dominates any value thereafter due to resolution limits in GAMS. A house that has a connection with a microgrid with $n_{chp} \in [0; n_h - 1]$ microgrid-available CHP units has a configuration unavailability.⁵ GAMS can only differentiate between values to 10^{-8} - 10^{-9} , hence no differentiation can be made between configurations with more than 7 microgrid-available CHP units. This resolution problem does, however, not affect design decision-making since an availability of ten nines (reached from $\lambda_c = 0.0800$) does not make practical sense from a cost perspective within a residential setting.⁶ Points beyond $\lambda_c = 0.0800$ only marginally improve system availability for the same number of nines but require a relative large cost increase. The latter points thus make no practical

⁵Configuration unavailabilities of $2.403341E-5$ (1 CHP), $9.809206E-7$ (2 CHP), $5.826789E-8$ (3 CHP), $2.133964E-8$ (4 CHP), $1.986162E-8$ (5 CHP), $1.980247E-8$ (6 CHP), $1.980010E-8$ (7 CHP), $1.980000E-8$ (8 CHP), $1.980000E-8$ (9 CHP).

⁶This might however be required in high reliability uninterrupted power supply facilities.

implementation sense. The ‘knee-point’ optimal configuration is namely around 4 nines and represents a design with one microgrid-available CHP unit in the neighbourhood ($\lambda_c = 0.2500$). Additionally, multiple designs are obtained, especially before $\lambda_c = 0.2500$ where cost still dominates outcomes, that only slightly differ in cost and unavailability ($\leq 3\%$) but have significant design differences. These differences include one or two house-available CHP units in the neighbourhood, different locations of CHP units and pipes, and existence of pipes. This is partly due to the adopted discrete capacity-availability intervals, and the non-existent relation between location and availability (see Section 5.7). Note also that CPU times vary drastically between model solutions with different weighting factors, from 679 s ($\lambda_c = 1.0000$) to 1306890 s ($\lambda_c = 0.2100$). Upscaling thus incurs some solution challenges (see Section 5.7).

5.6.2.2 Sensitivity analysis

Among the numerous input parameters of the model, deterministic renewable energy resource availability, here the sun, shows a high level of uncertainty. Sun (un)availability, part of the total PV (un)availability, is consequently analysed through percentage increases and decreases from about zero (unavsun-25 %) to about 100 % (unavsun+95 %) from the current level (unavsun, ref). Average house electrical system unavailability is then optimised with cost ($\lambda_e = 0$) at $\lambda_c = 0.2000$ for each sun availability level, see Figure 5.16. Table 5.6 summarises total installed DG unit capacities in the neighbourhood. Despite a reduction in sun availability, limited PV panels are still installed, complemented by 5 CHP units (4 microgrid-available). Neighbourhood design is thus relatively stable for the reference value (see Figure 5.10a) of sun availability plus and minus 25 %. The number of installed PV units increases with increasing sun availability. Each house has an available PV unit from (unavsun+30 %) but only 4 microgrid-available CHP units. Pipelines are never installed and microgrid sharing is always adopted.

TABLE 5.6: Total neighbourhood unit capacity [kW or kWh] for sun unavailability levels at $\lambda_c = 0.2000$ ($\lambda_e = 0$). CHP=combined heat and power unit, EST=battery, PV=photovoltaic unit, ref=reference value of Figure 5.10a.

	-25%	-20%	-10%	ref	+10%	+20%	+30%	+40%	+50%	+60%	+70%
PV	7.7	8.5	10.5	12.7	12.7	12.7	15.2	15.2	15.2	18.1	18.1
CHP	37.5	37.5	37.5	37.5	37.5	37.5	36.2	36.2	36.2	38.6	38.6
EST	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	7.0	7.0

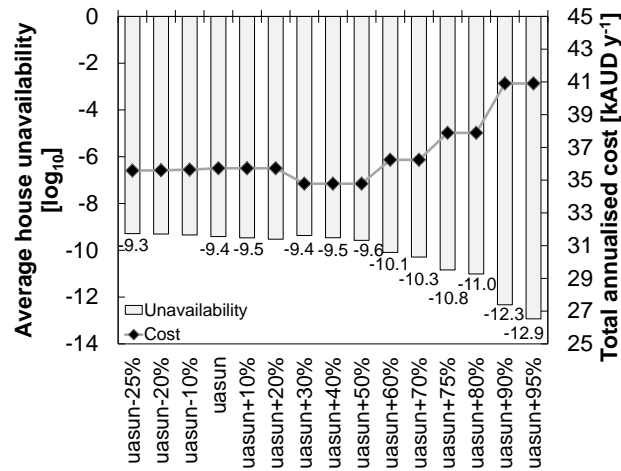


FIGURE 5.16: Unavailability-cost for in percentage varying solar resource availability.

5.6.2.3 Implementation aspects

Since switching to islanding, i.e. disconnecting from the grid, is not taken into account, comparing both on- and off-grid design unavailability-cost trade-offs ($\lambda_e = 0$) provides an illustration of the need for component redundancy in the transition from on-grid to islanding. To ensure supply availability in off-grid mode, the capacity thresholds for PV units and batteries are adapted (see Appendix I). Figure 5.17 compares both trade-offs. The dashed lines highlight the availability levels of the first two *on-grid* designs points. On-grid solutions dominate off-grid ones. The off-grid ‘knee-point’ is the second ($\lambda_c = 0.500$) point. This is a design change from two small CHP units available for accommodating houses ($\lambda_c = 1.000$) to a single larger microgrid-available CHP unit. To obtain a similar availability level in the off-grid model to the ‘best’

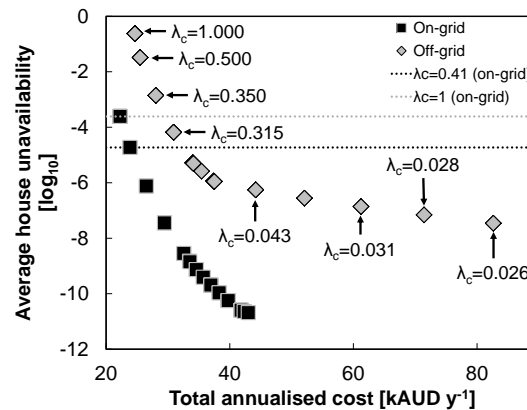


FIGURE 5.17: Pareto set of the trade-off between the average house electrical unavailability in the neighbourhood [\log_{10}] (nines) with total annualised cost [kAUD y^{-1}] for on- and off-grid modes of the neighbourhood ($\lambda_e = 0$).

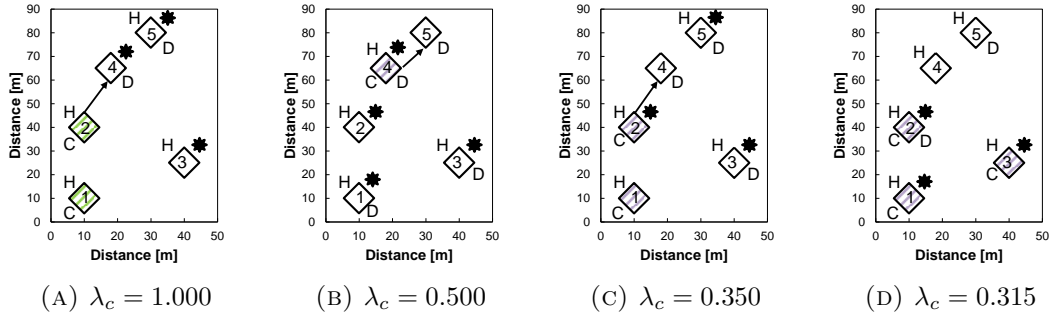


FIGURE 5.18: [colour] Major design changes for off-grid unavailability-cost trade-off ($\lambda_e = 0$). white diamonds=boiler and airco, grey hatched diamond (green)=available CHP for house and AC, dark grey hatched diamond (purple)=available CHP for MG and AC, sun=PV, triangle=battery, AC=absorption chiller, C=cold storage, CHP=combined heat and power, D=dumplload, H=heat storage, PV=photovoltaic.

on-grid configuration, i.e. an availability level around 4 nines (between the dashed lines in Figure 5.17), three microgrid-available CHP units would be required in the neighbourhood (off-grid: $\lambda_c = 0.315$), compared to one in the on-grid configuration. These additional units require a cost increase of about 30 % compared to on-grid to ensure component redundancy and system availability when allowing the system to island. Figure 5.18 illustrates the discussed off-grid designs and Table 5.7 summarises total installed neighbourhood capacities. Note that in the discussed points, cost still dominates, which makes it cheaper to dump excess electricity rather than invest in batteries. Additionally, there is a focus on dispatchable generation through CHP units. This leads to a heat generation surplus, which is mostly used for cooling generation with absorption chillers and limited heat transfer to other houses.

TABLE 5.7: Total neighbourhood unit capacity [kW] for off-grid designs at various λ_c levels for unavailability-cost trade-off ($\lambda_e = 0$). B=boiler, CHP=combined heat and power unit, D=dump load, HST=heat storage, PV=photovoltaic unit. No batteries are adopted and microgrid operation is always adopted.

	PV	CHP	AC	B	airco	HST	CST	D
$\lambda_c = 1.000$	6.6	5.2	3.6	20.5	7.4	31.3	8.4	4.1
$\lambda_c = 0.500$	7.8	8.0	2.3	24.3	8.1	32.0	4.9	4.3
$\lambda_c = 0.350$	6.4	16.1	3.5	20.5	7.4	31.6	7.8	3.9
$\lambda_c = 0.315$	5.4	24.1	5.6	14.6	5.1	30.2	16.9	5.2

5.7 Discussion and generalisation of approach

Several decisions, where alternatives exist, have been made throughout the optimisation process to highlight the framework capability. The model is, however, general and

flexible to be adapted to different requirements as detailed in Section 4.6. Table 5.8 summarises examples of specific adaptations that can be made at various modelling stages for the multi-objective approach, in particular the unavailability aspects.

TABLE 5.8: Adaptability and flexibility of the developed framework.

Stage	Adaptations & flexibility
Implementation	<ul style="list-style-type: none"> - capacity-availability and location-availability relation - different and more threshold capacity steps - boiler and CHP together allowed (smoother emissions-cost curve) - different objective quantification - thermal energy supply system availability - inclusion of small-scale wind turbines - different available technology combinations
Case-study	<ul style="list-style-type: none"> - availability data sensitivity analyses - threshold capacities sensitivity analyses - storage implementation
Optimisation	<ul style="list-style-type: none"> - stochastic optimisation including stochastic sun resource availability - dynamic Markov chain
Results	<ul style="list-style-type: none"> - role of technologies in trade-offs - impact of availability inputs on results - different levels of detail in result presentation

Different capacity-supply availability implementations can be considered, either a single discrete step as adopted in this Chapter (single step in Figure 5.20), more refined steps, or, a continuous relation. The current approach led to discrete jumps in solutions throughout the Pareto sets. In practice, the probability that an installed component with certain capacity cannot supply the load in each hour throughout the year (supply availability) comprises a more gradual relation with installed capacity. The shape of this curve can be determined by a load model for each house (house-level technologies) and for the neighbourhood (microgrid-available technologies), such as a load duration curve (LDC) of hourly demand profiles. A LDC represents each hour by its peak demand [kW] [55, 56, 282]. These hourly peak demands are then rearranged in descending order. Combining this load relation with a certain installed generation capacity enables to assess the number of hours throughout the year a certain demand level will exceed a generation capacity level, i.e. loss of load indices. Figure 5.19 illustrates both a more realistic and a simplified linearised LDC, adapted from [55, 56, 282]. For a certain installed generation unit capacity level (CL), the hourly load can exceed installed capacity for a certain number of hours (t). Dividing this number of hours of load loss throughout the year with the total number of hours in a year results in the probability that the unit cannot supply the load (supply unavailability) [282]. From the point where the installed capacity is able to meet the load at each time t (plus a potential reserve margin, RM),

the supply availability becomes 100 %. Figure 5.20 translates the simplified linearised LDC into a relation between supply availability and unit capacity level.

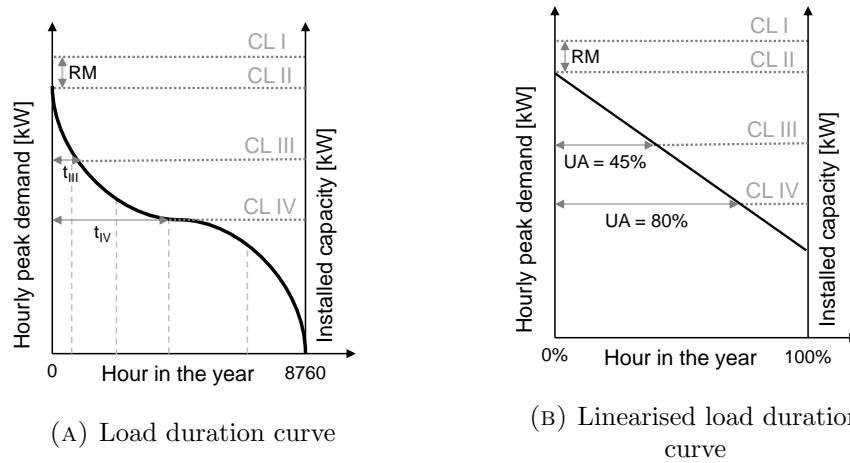


FIGURE 5.19: Load duration curves to determine the probability that a generation unit of capacity level (CL) cannot supply the load during a certain amount of hours throughout the year (Δt), adapted from [55, 56, 282]. RM=reserve margin.

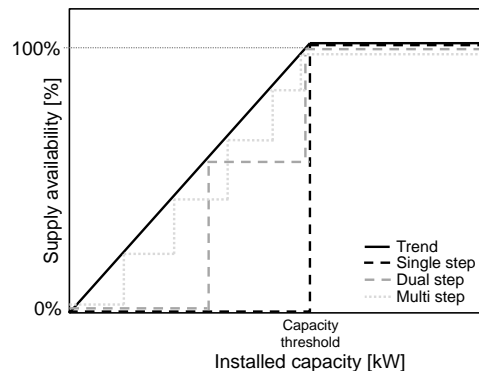


FIGURE 5.20: Illustration of capacity steps of the relation between installed capacity of technologies [kW] and electrical supply availability [%].

The adopted availability approach does not yet accommodate for fully optimised capacity values since each point (often through threshold capacities) on the Pareto set in Figure 5.10 represents the dominant point of a range of designs where the capacity of the installed units increases (more expensive) but has not reached the next capacity-availability threshold. For example, the last point on Figure 5.10a represents the situation where the maximum availability level is achieved. For $\lambda_c = 0$, however, cost is no longer an issue. The installed capacity of CHP units will therefore be maximised without an improvement in availability level. The last illustrated points on each set thus dominate any designs thereafter. Availability is currently also only related to the

type and size of units and not yet to their location in the neighbourhood. This could be included by incorporating energy network availability through cable length-dependent failure rates and their contribution to system configuration availability.

The obtained results present relative ordering of designs. When varying capacity thresholds (see Section 5.4.3.1), the obtained trends in Figure 5.10 remain the same. It is only the relative spreading of the points that will either reduce (less additional cost for the next availability step) or increase (more additional cost for the next availability step) with decreasing or increasing capacity thresholds, respectively. The current capacity thresholds are a first step towards the introduction of a more gradual relation between capacity and availability (and consequently emissions), similar to that which already exists between capacity and cost. A gradual relation is desired to obtain a continuous Pareto curve or a solution set with smaller gaps. Other jumps in the obtained Pareto sets in Figure 5.10 are due to design decisions and technology restrictions (see Table 4.6). Allowing, for example, a boiler to complement CHP units could avoid discrete emission and cost jumps where the smallest required CHP unit is replaced by a boiler.

Both security of supply and sustainability objectives could be quantified differently. For example, total neighbourhood unavailability or maximum neighbourhood unavailability, and primary resource utilisation or life cycle emissions, respectively, could be minimised. Furthermore, additional technologies and services can be included. Unavailability of the thermal energy supply system, for example, could be modelled similarly to the electrical system approach with unavailability of technical components and interactions. Alternative technologies and more or different system configurations could also be included through the consideration of, for example, wind turbines.

Currently, a limited number of electrical system configurations has been considered. Increasing (i) the number of technologies, and thus configurations, (ii) the number of neighbourhood houses, (iii) the number of potential technology combinations, and (iv) the number of threshold capacity intervals, all increase the degrees of freedom of the system. As already pointed out in Section 5.6.2.1, increasing complexity leads, however, to resolution problems. Additionally, increased computational efforts are incurred. This is due to (i) a binary-dominated logic-gate implementation, and (ii) the existence of many system designs that are equal in availability (due to the threshold being equal for each house) but only slightly vary in cost or location of units. Note that implementing

a gradual relationship between supply (total) availability and cost implies implementing supply (total) availability as a variable. This might introduce non-linearities in the model through variable multiplications between configuration variables ($B_{con,i}$) and configuration availability value variables ($ua_{con,i}$). These non-linear relations either need to be linearised, or, alternative implementation and solution techniques need to be considered to ensure efficient optimisation processes. Each system configuration is based on more than just a discrete combination of house technologies, i.e. neighbourhood level interactions and coupling between batteries and their charging sources. These internal interactions limit implementation possibilities within MILP environments. The binary logic-gate approach is able to handle this behaviour but at the cost of increased complexity with increasing degrees of freedom.

Selected sensitivity analyses have already been conducted with respect to upscaling and solar resource availability. Component availability data and threshold capacities can, however, experience uncertainty. Renewable energy resource availability is especially unpredictable. This could be incorporated through the inclusion of variability in the form of probability density functions of hourly available sunshine. Ultimately stochastic optimisation approaches could be employed to deal with this (see Section 2.2).

5.8 Summary and conclusion

A generic MILP approach for multi-objective residential energy system design has been developed. The base model of Chapter 4 was hereto extended to enable trading off three objectives in the design process. The included minimisation objectives are aligned with the energy system objectives of competition, security of supply and sustainability as total annualised cost, average house electrical system unavailability and annual CO₂ emissions, respectively. The model has been applied to various case-studies and analyses, highlighting its flexibility and capability. The tri-objective approach ensures DES applicability within central power systems. Apart from a multi-faced engineering design that ensures DES technical and economic viability within a wider policy framework, DES still require an adequate regulatory framework to ensure their lawfulness and their widespread adoption. Chapter 6 builds further on the developed base model, extending it to an interdisciplinary approach that facilitates DES regulatory framework analysis.

Chapter 6

Regulatory issues in residential distributed energy system design

A framework that considers regulatory aspects of distributed energy system (DES) design is developed (fourth research question). The Chapter 4 model is hereto extended to facilitate regulatory framework analysis throughout the design process by identifying quantifiable relations between design, organisation and regulation. Parts of the work in this Chapter have been disseminated into the following publications [2, 36, 89].

6.1 Introduction

6.1.1 Regulation as driver for decision-making

Distributed energy systems (DES) have various unique technological and organisational characteristics, which are not readily accommodated for in conventional power system structures and regulation [15, 317]. Hence DES design projects do not only require ‘optimal’ engineering system design, but also ‘optimal’ regulatory design to fit in with conventional power system topology and ensure their lawfulness [44, 49, 241]. Regulation is, however, lagging behind DES technological and economical developments. Regulatory framework aspects relate to system design but are not always readily quantifiable. The question then arises what the ‘best’ design is whilst taking into account regulatory aspects. This provides an opportunity to develop an optimisation based approach.

6.1.2 Chapter overview

This Chapter aims to develop an approach to quantitatively assess the interaction between engineering and regulatory DES aspects through optimisation based techniques as an important and determining driver for DES design decision-making. Section 6.2 summarises both conventional system regulation, and regulatory developments and barriers for DES to shape the research question. The problem and framework are described in Section 6.3. Section 6.4 details the model, building further on the base model of Chapter 4, which is applied to a case-study in Section 6.5. Section 6.6 illustrates results to end with a general discussion (Section 6.7) and conclusion (Section 6.8).

6.2 Background on regulatory frameworks

6.2.1 Regulatory frameworks of distributed energy systems

A regulatory framework encompasses laws, policies and rules to sustain and establish adequate operational structures [15]. Since DER and DES typically connect to low voltage distribution networks (see Section 1.1.2), their structure and interactions thus directly interfere with conventional agents at various levels [15, 89]: (i) introducing *generators* and bottom-up/bi-directional power flows at the low voltage distribution level (‘prosumers’), (ii) connecting to the *distribution network*, and (iii) participating consumers are served under *retail* agreements. DES thus fundamentally change the conventional structure of power systems, including the concept of consumers as passive receivers of energy services. An adequate DES regulatory framework and a restructuring of conventional power system regulation are thus required to accommodate their unique characteristics [39, 317]. Currently, only limited regulation exists applicable to distributed generation units (DG), such as PV units. The regulatory environment of DES is even less developed. The DES regulatory environment namely depends on various aspects that fall under three main themes [45, 318], see Figure 6.1. Consumer-agent interactions and lawfulness aspects are the focus of this work:

1. *The lawfulness of its entity*, i.e. who owns and operates the infrastructure and what requirements does it need to meet in order to be able to connect to the central network in terms of size (DG units and customer portfolio) and technologies?

2. *Interactions between DES, their consumers, and involved agents*, i.e. are the conventional service territories undermined and how do conventional power system agents fit in? How will tariffs and revenues be set for fair distribution of costs and benefits among agents? Who are the involved agents?
3. DES combine activities of multiple conventional power system agents. Some of which require regulatory oversight (networks) and others are competitive services (retail/generation). How does the *regulator need to intervene* herein? Does a DES provider qualify as a licensed retailer that must adhere to requirements of billing, supplier of last resort, dispute resolution and information transparency? What about DES *incentives* and revenue regulation for involved agents?

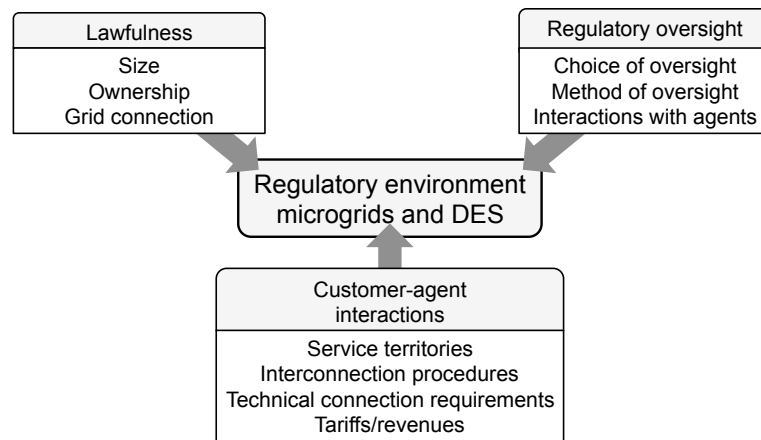


FIGURE 6.1: Schematic of regulatory environment of DES, adapted from King [45].

6.2.2 Regulatory environment of conventional power systems

To analyse DES regulatory frameworks, first current liberalised power system regulation has to be presented as it applies on residential consumers and DES. Examples of the National Electricity Market (NEM) in Australia serve to illustrate the framework of liberalised systems generally. Note that power system regulation refers to the regulation of the electrical supply system since thermal energy is generally adopted at the consumer level, with the exception of district thermal networks (see Sections 1.1.2 and 6.2.3).

Liberalised power systems have structurally and legally separated their power system activities (unbundling) (see Section 1.1.1), resulting in four independent power system agents: generators, transmission networks, distribution networks and retailers [1]. Transmission and distribution are natural monopoly services since network duplication is not

economically viable [1]. Networks are thus independent regulated monopolies that are prohibited from engaging in other activities and are subject to economic regulation.¹ Distribution networks, in particular, generally operate and connect consumers in designated service areas. Generation and retail, in contrast, are mostly fully competitive energy services [1]. Typically, full retail contestability is aimed for, i.e. the free choice for consumers to select and switch their energy provider (retailer) [13]. Power systems are governed by State-specific electricity acts and rules, often complemented by customer protection requirements [1, 13]. Residential consumers are here conventionally passive receivers of electricity through a top-down system.

Access and connection of generators to networks is conventionally regulated. Generally, non-discriminatory third party grid access is strived towards to facilitate competition and not instigate discrimination [1]. Additionally, all agents that make use of network services, such as generators and consumers, pay ‘use of system’ and network connection charges. Connections of generators to networks are subject to registration requirements with central energy markets, depending on their installed capacity, location and usage [319, 320]. Small-scale generation units with a capacity below about 5 MW (micro and mini in Table 1.1) are generally exempt from this requirement [47]. In the NEM, for example, exempt small-scale units can go into contractual agreements with a retailer or other consumer at the same connection point to sell their locally generated electricity at an agreed price through, for example, a feed-in tariff [321]. This bottom-up power injection, however, requires network upgrades. Distribution networks are thus often inclined to bound residential electricity export and charge for grid connections [1, 39].

Retailers are agents that engage in the business of purchasing electricity on the wholesale market and selling this to consumers through financial contracts [1, 322]. A retailer is an intermediary that operates through virtual/financial agreements, not through ‘physical’ energy exchanges. Under the National Energy Retail Law in the NEM, and within most liberalised power systems, retailers must be either authorised (licensed), or, be granted an exemption from the authorisation requirement to lawfully operate [1, 323]. An authorised retailer is obliged to comply with retail laws in terms of small consumer

¹*Economic regulation* frames services that not involve reasonable conditions for competition, i.e. networks. Regulation is required to restrict monopoly agents to maximise their profits in the short term by raising prices and to limit their infrastructural investments to below the optimum required (underinvestment). Economic regulation therefore imposes conditions on prices and revenues to align the objectives of the monopoly with global social welfare maximisation [1].

protection, dispute resolution, retailer of last resort and reporting obligations [1, 322, 323].² Exemptions can be allowed in cases where the retailer provides complementary services to consumers (i) that already purchase electricity from an authorised retailer, (ii) that is part of a bundled service where energy supply is an insignificant part of the contractual agreement, or, (iii) that are combined in a limited consumer group at, for example, a specific site (see Section 6.2.3) [322, 323].

6.2.3 Barriers and novel regulatory developments

Liberalised power systems are based on aspects that warrant competition, sustainability and security of supply. Several aspects, however, form a major barrier for the integration of DES. Table 6.1 provides a brief overview of conventional power system aspects, their barriers for DES and required regulatory developments. Increased consumer participation and awareness already initiated regulatory developments on several levels to enable novel technologies, smart network behaviour and consumer emancipation;

Interconnection requirements and standards for small-scale DG within distribution networks are being developed and adopted to ensure safe operation, adequate power quality, network stability, connection practices, protection schemes and metering [49, 64, 324]. The IEEE 1574.3 standard is the most established for DG and the IEEE 1574.4 for island microgrid operation [49, 64, 324]. Installed DG capacity, registration and disconnection requirements, and bi-directional power flows also have to be regulated. In most conventional power systems, any form of grid-connected DER is, namely, not allowed to island and has to be shut off in case of central system outages [49, 64].

Furthermore, alternative energy seller models are being established, driven by increasing energy prices, consumer awareness and the technological maturity of DER [325–328]. Alternative energy sellers are subject to case by case exemptions and do not necessarily allow for full retail contestability nor provide consumer protection, in contrast with authorised retailers. Two NEM models are *onselling* and *power purchase agreements* [322], see Figure 6.2. Onsellors purchase bulk energy from an authorised retailer to sell it on

²Small consumers are defined in the NEM as having a yearly electricity consumption less than 100 MWh [322]. Retailer of last resort schemes ensure continuity of energy supply to consumers in the event of retailer bankruptcy [323].

TABLE 6.1: Main regulatory practices in conventional liberalised power systems and DES barriers [2, 5, 15, 39, 44, 49, 89, 241, 329–334].

	Conventional liberalised power system	Barrier for DES adoption	Required regulatory aspects
Lawfulness and regulatory oversight	Competitive retail and generation service Unbundling of power system agents	Not always (full) retail contestability or competitive supply service DES is new power system agent that engages in generation, network and retail activities, combined with consumers in a single entity. DES thus have no clear separation of components and interactions, agents and ownership	Organisational framework Structural design
	Non-discriminatory third party access	Connection procedures to grid, lawfulness, structure, size and registration requirements needed	
	Environmental standards Integration of renewables	No local emission and efficiency standards Small-scale unit requirements, capacity and export bounds, lack of governmental support schemes and high upfront cost	
	Operational standards	Specific operational characteristics that lead to safety, voltage, bi-directional power and frequency challenges	
	Dependability standards Integration of new technologies restricted	Customisable dependability levels: how determined and who is responsible? Lawfulness in terms of size, ownership, organisation and registration requirements needed	
	Standardised responsibilities	Unique characteristics and structure tailored to specific requirements hindering standardisation	
	Consumer protection	No competitive retail environment (?), often independent exempt businesses	
	Operation and interactions	Networks	Potential interference with designated consumer areas and property rights of regulated monopoly networks. How will networks generate revenue from a connection with DES that has a large amount of self-generation and energy sharing but not much energy import? Upgrades, bi-directional power flows, islanding authorisation needed
Passive consumers		Internal and external DES energy sharing schemes, consumer protection requirements and consumers become active through engaging in other power system activities	
Generation		Inclusion of small-scale generation, often based on renewables, and storage plus requiring a back-up grid connection	New power system agent ‘prosumer’
Retailers		Retail protection, prosumer-based retail agreements, smart metering service schemes required and data protection needed	Novel energy selling frameworks

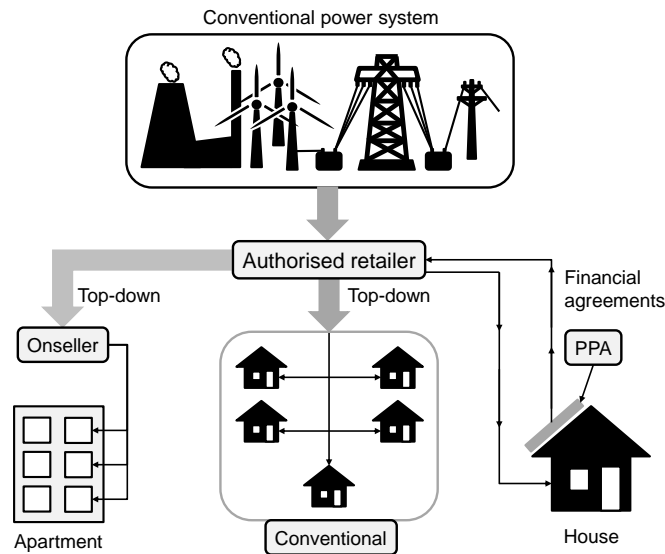


FIGURE 6.2: Alternative energy selling models in the NEM, adapted from [322].

to a defined cluster of consumers. Onselling is often adopted in multi-dwelling developments, such as apartments and commercial centres. Power purchase agreements, in contrast, are an ownership-lease agreement between a consumer and an alternative energy seller in which the energy seller takes on the upfront investment, installation and on-going operation and maintenance costs of a DG unit on the premise of the consumer. Energy generated by these units is, however, owned by the energy seller. The participating consumer can purchase this energy back at reduced tariffs. PV units are the most common DG unit under this model. Other practices include aggregator schemes, energy service companies or various other ownership and business models (see Section 6.2.4).

Increased DER uptake is challenging traditional retail models [322]. Consumers with DG units typically do not generate enough electricity to be fully self-sufficient, requiring additional contracts with authorised retailers. Lower energy volumes purchased, however, could make these agreements less profitable for authorised retailers. Opening up the retail market to alternative energy sellers increases consumer choice and variety but must be balanced with adequate consumer protection and retail contestability [323].

Other recent developments are governmental incentives to encourage small-scale (renewable) energy generation units [29], for example, feed-in tariffs for residential DG electricity export to the central grid, or, subsidies for DG investment. Some States have additionally adopted frameworks for the sharing of thermal energy in district heating

or cooling networks [241, 335]. Furthermore, residential cooperatives are being established where residential consumers can participate in purchasing a share in a central renewable energy generation unit, such as a wind farm, allowing them to virtually³ buy back the energy it generates at advantageous tariffs [336]. Lastly, there is a growing interest in sustainable communities that are powered through co- or tri-generation, supplying both thermal and electrical energy to its participating consumers. These new DES developments, however, still face major regulatory barriers [49, 89].

6.2.4 Regulation in distributed energy system design optimisation

DES regulatory design is a novel and emerging research area. The majority of the limited research is qualitatively focussed on electrical DES. Two main qualitative research streams are (i) *barrier-studies* and (ii) *framework and business model studies*. Quantitative research aspects are also limited.

6.2.4.1 Barrier-studies

Barrier studies assess conventional power systems to identify barriers and enablers for the uptake of DES. Some of the most common regulatory barriers were summarised in Table 6.1 [2, 5, 15, 49, 89, 241, 331–334]. The Berkeley Laboratory, for example, has conducted successive studies regarding the assessment of electrical DES at an international level under the IMAGINE reports [334]. The studies highlighted the underdeveloped regulatory aspects of electrical DES. Policy recommendations to establish demonstration programs were made based on lessons learned from researched sites. A specific DES barrier analysis of the Singaporean legislative framework was presented by Wouters [89]. Policy drivers for the integration of microgrids within regional electricity markets were demonstrated by Van Hende and Wouters [2]. Soshinskaya et al. [331], moreover, presented a study of common barriers to and success factors for widespread microgrid implementation based on the study of 13 microgrid case-studies.

³ *Virtual interactions* refer to monetary interactions rather than real physical flows of electricity.

6.2.4.2 Framework and business model studies

King [45, 337] performed the first major work to date regarding regulatory environments for DES. He surveyed State regulatory officials across the United States regarding DES regulatory requirements. The most important regulatory difference between electrical DES and conventional power system practices was identified as ownership and business models (money making) rather than technical installation and operational features [45, 337]. He presented hereto five ownership business models, see Table 6.2.

TABLE 6.2: DES ownership business practice models as presented by King [45, 337].

<i>utility model</i>	the local consumer network is owned and operated by the local distribution utility that enables consumer cost reduction and high reliability of supply
<i>landlord model</i>	the local network is installed and managed by a single third party, which provides consumers with electricity and/or heat through a contractual lease agreement
<i>co-op model</i>	the local network is cooperatively owned and operated by various consumers or third parties to meet their own local electricity and/or heating demands
<i>customer-generator model</i>	the local network is owned and operated by a single consumer or third party to meet the electricity and/or heating demands of itself and its neighbourhood
<i>district heating model</i>	the local network is owned and operated by an independent third party, which sells electricity and/or heat to consumers that can voluntarily join under a contractual agreement.

The work of King [45, 337] was conducted within the same research group as earlier work from Morgan and Zerriffi [338]. Morgan and Zerriffi [338] conducted an informal survey of utility commissioners regarding the regulatory environment of non-utility microgrids. A cooperative microgrid, established by consumers, was concluded to face less implementation barriers but the question remained as how to regulate these so-called ‘co-ops’. Tongsopit and Haddad [339], in their turn, looked into interconnection issues between microgrids and central infrastructure in the form of a property rights problem, i.e. conflicts in property and consumer allocation, and the need for institutional changes. Two emerging property right frameworks were analysed to potentially overcome connection issues: a community choice aggregation and public power cooperatives/municipalities. Bunning [340], finally, looked into the governance of low carbon urban systems by presenting barriers, enablers and business models to incorporate various governance models.

A particular research focus are ownership and business models for CHP systems with potential district heating, either through researching countries that have already adopted CHP systems, or, by developing theoretical models. Fuel-cell-based micro-CHP systems, for example, were studied by Schroeder et al. [341] within a European energy policy setting. The interdependency of European Union policy and CHP ownership structures

was analysed through three case-studies by looking at support schemes, investment risk and certain defined ownership arrangements. Pantaleo et al. [342], furthermore, provided a thorough analysis of energy service company (ESCO) business models, related ownership, investment models and service contracts, with a focus on biomass heating and CHP generation in Italy. CHP with district heating was studied by Kelly and Pollitt [241] focussing on the current United Kingdom framework and ESCO's. They defined an ESCO as '*any company that offers expertise or service for the supply or use of energy*'. ESCO's mostly combine several stakeholders to spread financial risks of projects.

6.2.4.3 Quantitative studies

Quantitative studies have been conducted in several areas, mainly with regard to economic viability and tariffs. Firestone et al. [99], for example, looked at electricity tariff structures and their impact on the widespread adoption of DG. Additionally, aggregators and virtual power plants have been researched, which are based on financial contracts. These structures virtually combine and manage geographically dispersed DG units or prosumers within a single entity through virtually purchasing energy they generate and either selling this energy to other prosumers within the same scheme or trading the aggregated energy in the central electricity market [330, 343, 344]. Studies regarding the profitability of commercial aggregators have been conducted through optimisation by, for example, Vatanparvar et al. [343]. The profitability of a rule-based commercial aggregator subject to tariffs was researched in a residential microgrid setting whilst trading off several costs. Faruque and Abdullah [330], furthermore, looked at profitability of residential aggregators as new market entities. Negotiating capabilities of aggregators were taken into account together with pricing rules. Operational optimisation of aggregator schemes has additionally been analysed by Nguyen and Le [344].

Energy management and operational research that includes policy and regulation was presented by, for example, Sáenz and Celik [345]. They researched multi-objective operational optimisation of technologies within microgrids under different operational and market policies: (i) the microgrid is solely used to serve local demand and it may only import electricity from the grid, and (ii) the microgrid is allowed to actively participate in the energy market by exporting electricity to the grid. Phillips [346], furthermore, presented an approach for microgrid control, operation and management. Several conditions

were analysed to aid decision-making for microgrid operational policy setting. Multi-agent control of microgrids, including market aspects, has been addressed by Dimeas and Hatziargyriou [347] and Hatziargyriou et al. [348]. Bidding strategies in community microgrid markets and aspects of community engagement models have additionally been introduced by Jalia et al. [349]. Furthermore, an agent-based market model for the commercialisation of small microgrids was proposed by Kim and Kinoshita [350]. Certain defined ownership schemes were here analysed. Lastly, an operational MILP model for fair cost distribution between participants in a smart building was presented by Zhang et al. [87] using the lexicographic minimax method.

The previous models focussed on market based aspects, such as bidding and aggregators, and operational optimisation, including energy management schemes. Sometimes certain established operational or ownership policies were analysed. No DES design aspects were, however, included. DES design optimisation including regulatory aspects is thus limited. Regulatory constraints have, however, been included in several forms throughout literature, see for example [95, 247]. Regulation namely influences energy tariffs, governmental support schemes (e.g. feed-in tariffs and subsidies), bounds on maximum DG capacity in residential settings, export allowances and emission taxes. Zachar et al. [190], for example, looked at the impact of policy decisions on optimal microgrid design at minimal energy supply cost through an MILP approach. Policy decisions regarding emission taxes, emission reduction targets and minimum system autonomy were researched through sensitivity and scenario analyses for a grid-connected heat-power system. Aki et al. [351], furthermore, focussed on fuel cells for domestic purposes in the Japanese market. The design of a regional hydrogen energy interchange network was optimised for a small cluster of 8 houses. Optimisation was employed to analyse the design trade-off between CO₂ emissions and costs. Several discrete ownership and management structures were qualitatively proposed: (i) units are owned and managed by accommodating houses, (ii) units are owned by accommodating houses and managed by an organisation, (iii) equipment is owned by houses while networks are owned and managed by an organisation, and (iv) units are owned and managed by an organisation. An ‘organisation’ was defined as an energy service provider or a gas utility. Lozano et al. [60], then, focussed on MILP cost-optimal design of a combined heating, cooling and power system under legal constraints. The considered constraints focussed on co-generation operational schemes in the Spanish market. The effect of established

schemes on system design was analysed for a cluster of 500 buildings. Zhang et al. [86], in their turn, researched the link between optimisation of microgrid design aspects (unit selection, siting and sizing), optimal electricity transfer tariffs and equal cost sharing between participants using Game Theory within an MI(N)LP model. Lastly, Hawkes et al. [352] presented a mixed-integer framework for the design and unit commitment of a CHP-based microgrid under various performance metrics, identified by commercial deployment pathways. These pathways focussed on investment decisions by stakeholders and were first introduced in qualitative studies by Watson [353] and Sauter and Watson [354] as: (i) plug-and-play, i.e. owners of premises independently invest in microgeneration, (ii) company control, i.e. consumers are more passive and will receive energy from a site governed by an ESCO or supplier, and (iii) community, i.e. a group of different stakeholders collectively owns and operates the units.

6.2.4.4 Research gaps

Regulatory DES research has been mostly qualitatively focussed, highlighting barriers and business models. Quantitative models, in contrast, focussed mostly on operational optimisation aspects under certain business models and policies, including aggregator profitability, tariff setting and internal market operation. Design optimisation whilst explicitly taking into account regulatory aspects is very limited and has been mainly touched upon for isolated aspects, such as certain defined ownership schemes of energy networks [351] or CHP systems [352]. Optimal design of DES including analysis of regulatory framework aspects has not been developed and will be tackled in this Chapter.

6.2.5 Summary and discussion

DES regulatory frameworks entail various aspects related to lawfulness, energy, and monetary interactions and oversight. Frameworks for DG units have already been developed within conventional power systems but major DES barriers remain due to their unique structural and operational characteristics. This Chapter aims to bridge the gap between engineering and regulatory aspects of residential DES design through a decision-making approach based on mathematical optimisation. DES regulatory frameworks are intertwined with and determined by their operational and structural organisation [241].

Regulatory frameworks can therefore be analysed using organisational aspects within a design optimisation model. Framework aspects are, however, not all readily quantifiable. Several more readily quantifiable key organisational framework features have, nevertheless, been analysed and discussed throughout the literature reviewed in Section 6.2; e.g., ownership schemes, business models, tariffs and remuneration, involved stakeholders, energy sharing agreements, consumer integration as well as physical (microgrid) and virtual (aggregator) interaction schemes. Based on the above features, six key organisational framework factors have been identified for incorporation in the developed model. The characteristics and barriers, presented in Figure 6.1 and Table 6.1, encompass structural, interaction and operational aspects related to DES regulatory requirements and frameworks: type (lawfulness), scale (connection and registration requirements, lawfulness), ownership (lawfulness and interactions), tariffs (remuneration of agents and interactions), choice (lawfulness and interactions) and objectives (stakeholder interests, central system objectives). The identified factors are detailed and summarised in Table 6.3.

6.3 Method

6.3.1 Problem description

Depending on the DES organisational structure, each regulatory aspect (see Section 6.2.1) will be defined differently, which in its turn determines the required DES regulatory framework [241], see Figure 6.3. DES can thus be organised in various configurations that are characterised by factors. The factors analysed in this work have been defined

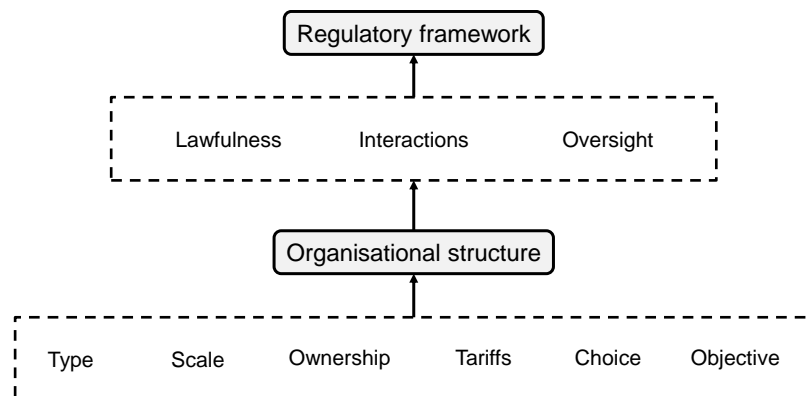


FIGURE 6.3: Factors and aspects that determine DES regulatory frameworks.

TABLE 6.3: Identified regulatory framework factors.

<i>Type</i>	DES can appear in two types based on the nature of energy interactions; (i) technical physical or (ii) commercial virtual; (i) A physical DES has infrastructure, such as a control unit, poles, wires and pipelines that facilitate energy flows. Participating consumers within a geographically clustered area can share generated energy and present themselves as a single entity to the central system through a point of common coupling. (ii) A virtual DES is based on contractual financial agreements. No physical infrastructure for local energy sharing is considered, but consumers can trade locally generated energy with, for example, a virtual aggregator. Participating consumers do not need to be geographically clustered in this arrangement.
<i>Scale - Degree of centralisation</i>	DER can be installed on several scales within DES; either individual houses can install units or a larger DES-based unit can be installed. These are referred to as a decentral household and central DES scale, respectively. Alternatively, combinations of both can be installed, i.e. hybrid scale.
<i>Ownership</i>	Ownership determines who bears the costs related to DES investment, operation and maintenance as well as who owns the locally generated energy. Ownership can be implemented based on discrete schemes or based on a share. Either consumers individually or jointly own and operate the system or a third party does. In case of third party ownership, consumers are served under contracts. Third party owners could be, for example, an ESCO, a distribution system operator or a retailer. Alternatively, hybrid ownership arrangements could also be installed between consumers and (a) third part(y)ies.
<i>Choice and flexibility</i>	Since liberalised power systems mostly require full retail contestability, DES could be assessed based on the flexibility and choice of individual consumers to opt in or out agreement without affecting its operation and design. Consumers may, namely, individually bear more cost to attain the cheapest overall DES design. This relates to less flexibility, choice or equal cost sharing of the latter consumers since their participation is key for DES viability. Furthermore the question arises whether and when households have the opportunity to opt in or out; at the end of a contractual agreement or with a change of inhabitants? What about the ownership of the house, i.e. rental or owned? Individual choice of consumers – although not readily quantifiable – presents an important assessment of optimal organisational structures.
<i>Tariffs</i>	Any form of DES energy interactions – between individual consumers or individual consumers and a third party, physical or virtual – has a related tariff. These can be central energy tariffs, local energy sharing tariffs or third party tariffs. DES internal sharing tariffs might lead to additional costs for individual consumers, or, potential incomes. Several tariff structures can be adopted from flat usage tariffs (\$/kWh) to capacity payments (\$/kWp) or even time of use tariffs [99].
<i>Objectives, i.e. stakeholder interests</i>	Participating stakeholders will affect the choice of implemented framework. Multiple – often conflicting – stakeholder interests will need to be balanced. Stakeholder interests might be financial, technical or environmental in nature and ideally ensure conventional power system objectives are met (see Section 1.1.3). A financial objective can be the DES design that leads to the lowest overall cost for participating consumers. Consumers might, however, be willing to pay more to ensure dependable energy supply or energy supply with reduced greenhouse gas emissions. Alternatively, network operators might favour DES development in a neighbourhood to ensure dependability standards instead of upgrading network infrastructure, to complement its system.

based on the literature analysis, the ease of quantification and their potential to impact DES design as: (i) type, (ii) scale, (iii) ownership, (iv) choice and flexibility, (v) tariffs, and (vi) objectives, see Figure 6.4. The six identified factors can take on several identities/configurations and can be measured differently within the model as summarised in Table 6.4.

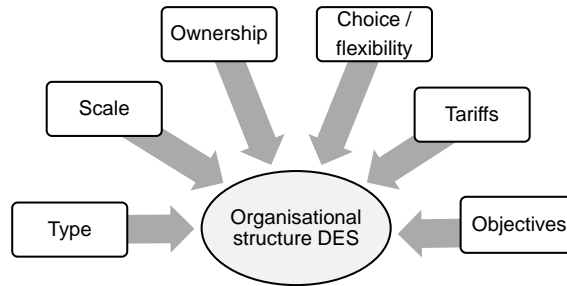


FIGURE 6.4: DES regulatory framework factors.

TABLE 6.4: Identities and model measures of regulatory framework factors.

Framework factors					
Type	Scale	Ownership	Choice	Tariffs	Objectives
Identities					
Virtual	Decentral	Neighbourhood	Equal cost sharing	Internal trading	Cost
Physical	Central	Third party	Retail choice	Central	Emissions
Hybrid	Hybrid	Hybrid	Flexibility	Feed-in	Availability
Model measure					
Structure	Structure	Structure/Input	Output/Objective	Input/Structure	Structure/Output

6.3.2 Optimisation framework and model requirements

The framework factors are integrated into the developed MILP model (see Chapter 4). In addition to the model requirements of Chapter 4 (see Section 4.2.2), regulatory aspect inputs are required that can help to determine regulatory outputs. In the first instance, the initial single cost objective is analysed to illustrate the methodology, i.e. *minimising total annual energy cost* of a neighbourhood to meet its yearly demands under various constraints. Figure 6.5 illustrates the adopted methodology. Framework factors are translated into quantified proxies⁴. These proxies can either provide new input parameters and allow for parameter sensitivity analyses, change aspects of the model structure by introducing new objectives or constraints, or, can use a model output to assess the relative gain in a factor depending on the optimised configuration, see Table 6.4. The

⁴A *proxy* is a figure, which is used to represent the value of or serve as a measure for something.

analysis of changing inputs and model structures on optimal residential DES design can facilitate decision-making to identify the ‘best’ regulatory framework aspects for a certain DES application.

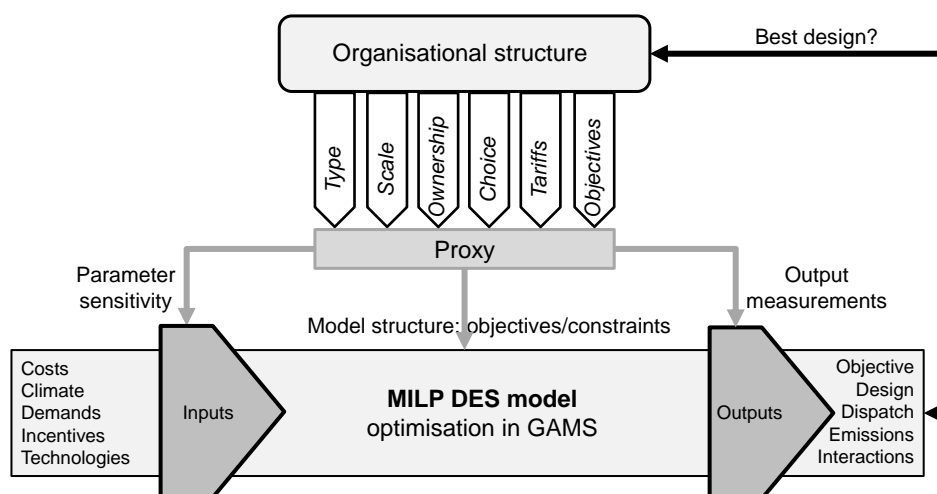


FIGURE 6.5: Regulatory framework factors implementation methodology.

6.3.3 Model assumptions and decisions

Modelling complex systems requires implementation decisions and assumptions to set boundaries on the system [82, 106, 107]. The developed model follows the same assumptions as the base model, see Section 4.2.3, complemented by:

- Residential DES can take on various forms based on the nature of their consumers [330]. Here a neighbourhood cluster is researched with consumers that own their houses and consider investing in a DES. Individual houses, or the DES as a whole, can engage in purchasing and selling energy, leading to costs or incomes for individual houses and the neighbourhood as a whole.
- Rather than looking at discrete ownership schemes, a continuous household ownership share parameter is adopted. This allows flexible decision-making in determining overall and optimal ownership of DES units and infrastructure.
- In the first instance, only physical energy integrated DES structures with several ownership and scale categories are analysed under cost minimisation.

Annualised operation and a yearly planning horizon are adopted for an average day (24 hours) in three seasons, i.e. summer, winter and mid-season (see Chapter 4). Furthermore, various choices have to be made regarding regulatory framework factor implementation, where alternatives exist. The adopted design choices are detailed in Section 6.4 together with the model implementation.

6.3.4 Contributions

The developed model of Chapter 4 is extended with new features and functionalities through the inclusion of regulatory framework analysis:

- implementing multiple regulatory framework factors explicitly in a DES design optimisation framework, rather than looking solely at regulatory constraints on operational schemes, emissions, discrete ownership shares or financial incentives,
- and researching the link between optimal engineering design and regulatory framework aspects through a decision-making optimisation-based approach.

6.4 Model implementation and design decisions

The model of Chapter 4 is adapted to decentral (Section 6.4.1: Eqs. 6.1-6.6, Appendix J: Eqs. J.1-J.2), central (Section 6.4.2: Eqs. 6.7-6.17, Appendix J: Eqs. J.3-J.16) and hybrid (Section 6.4.3: Eqs. 6.18-6.22, Appendix J: Eqs. J.17-J.19) scales as well as ownership variation (Section 6.4.4: Eq. 6.23). The model adaptations are summarised in the following Sections and detailed in Appendix J.

6.4.1 Decentral scale

The model already accommodates decentral scales. Some adaptations, however, need to be made to: (i) include overall neighbourhood electricity export at set tariffs, (ii) allow for household energy ‘trading’⁵, and (iii) include upscaling economies-of-scale relations.

⁵Note that this is not game-theoretic energy trading in a market environment with variable prices (see for example [86]) but rather the sharing of energy between houses at a set tariff.

6.4.1.1 Residential DG export

Electricity export tariffs need to be streamlined in order to facilitate potential DES participation in the central market. Hence, locally generated electricity by individual houses through PV units, small-scale wind turbines and CHP units is bundled, $\sum_{techDG} PE_{techDG,i,s,h}^{SAL}$ [kW], when a microgrid is installed. This bundled electricity can then be exported at a single tariff, T_{MG}^{SAL} [AUD kWh⁻¹]. Furthermore, the daily PV export limit is no longer applicable in this setting (see Section 4.4.1). Instead, this limit now refers to the total daily individual household export level from all its DG units.

6.4.1.2 House energy sharing

The base model assumed cost to be carried by the neighbourhood as a whole. Hence, no cost was associated with household energy sharing. Therefore, costs are now associated with ‘selling’ ($C_{SAL,energy}^{MG}$) and ‘purchasing’ ($C_{BUY,energy}^{MG}$) both electricity (*elec*) and thermal (*therm*) energy to and from individual houses. Associated tariffs are $T_{MGint,energy}^{BUY}$ for purchasing and $T_{MGint,energy}^{SAL}$ for selling. This implementation allows freedom to implement equal or different buy and sell tariffs, depending on the case-study. Electrical and thermal energy bought or received from the microgrid by a house ($PE_{MG,i,s,h}^{rec}$, $QH_{j,i,s,h}$, $QC_{j,i,s,h}$) and sold or circulated to the microgrid by a house ($PE_{techDG,i,s,h}^{CIRC}$, $QH_{i,j,s,h}$, $QC_{i,j,s,h}$) thus incur to respective internal trading costs:

$$C_{BUY,elec}^{MG} = \sum_{i,s,h} hr \cdot d_s \cdot T_{MGint,elec}^{BUY} \cdot PE_{MG,i,s,h}^{rec} \quad (6.1)$$

$$C_{SAL,elec}^{MG} = \sum_{i,s,h,DGtech} hr \cdot d_s \cdot T_{MGint,elec}^{SAL} \cdot PE_{techDG,i,s,h}^{CIRC} \quad (6.2)$$

$$C_{BUY,therm}^{MG} = \sum_{i,j,s,h} hr \cdot d_s \cdot T_{MGint,therm}^{BUY} \cdot (QH_{j,i,s,h} + QC_{j,i,s,h}) \quad \forall i \neq j \quad (6.3)$$

$$C_{SAL,therm}^{MG} = \sum_{i,j,s,h} hr \cdot d_s \cdot T_{MGint,therm}^{SAL} \cdot (QH_{i,j,s,h} + QC_{i,j,s,h}) \quad \forall i \neq j \quad (6.4)$$

6.4.1.3 Economies-of-scale

To allow for benefits of unit upscaling, an economies-of-scale cost relation is introduced. Initially, only CHP units are hereto considered since they are dispatchable, more readily

scaled up than renewable technologies, and allow for thermal as well as electrical energy integration. In the base model, CHP unit investment cost was a fixed incremental value per installed unit of electrical capacity. This approach, however, introduces uncertainty governing the adopted cost value and resulting designs. CHP units are namely important for DES economic viability [280]. Especially in the micro-range, this incremental cost per unit capacity decreases significantly with a small increase in capacity, i.e. a strong non-linear relation between total investment cost and installed capacity of the unit [244, 245]. Hence, recent research has been looking at linearising non-linear relations within LP and MILP environments [229, 244, 245, 352]. Non-linear economies-of-scale relations are typically introduced in linear models through piecewise linearisation [355]. The concept of piecewise linearising non-linear cost curves is not new [355], but the application to DES has only limitedly been touched upon. Piecewise linearisation involves approximating a non-convex continuous relation between two variables as a combination of consecutive separable linear functions, i.e. reducing a non-convex relation to a set of functions that each only depend on a single variable [107, 108, 355, 356]. Merkel et al. [244], for example, introduced economies-of-scale for CHP and storage units through piecewise linearisation in a small-scale heating network design MILP, minimising yearly CHP-related costs. A multi-objective MILP was presented by Rieder et al. [245] for a small district heating system considering CHPs and heating technologies. Linearised economies-of-scales were employed for boilers, thermal storage units and pipelines. Furthermore, linearisation of technology economies-of-scale in an MILP design optimisation of an ‘eco-town’ was presented by Weber and Shah [229].

Piecewise linearisation can be implemented either through binary variables and inequality constraints or through the introduction of Special-Ordered-Sets (SOS) [107, 108, 356]. The principle of Special-Ordered-Sets of type 2 was first introduced by Beale and Tomlin [357]. SOS are a type of positive variables that are ordered, where a specified number of successive variables in the set (type 1 or 2) can be different from zero. The SOS-2 approach is generally preferred over binary variables since it can be employed in MILP models, can be handled by most common solvers, such as CPLEX, and is more compact in formulation and solution tree [355]. Hence this approach is employed here. A non-linear economies-of-scale function $f(x)$, see Figure 6.6, can thus be reduced to a sum of linear functions through a set n of scaling points (SOS-2), a_1 to a_n . Only two consecutive scaling point variables can be non-zero [245]. An optimised cost ($f(x)$) - capacity

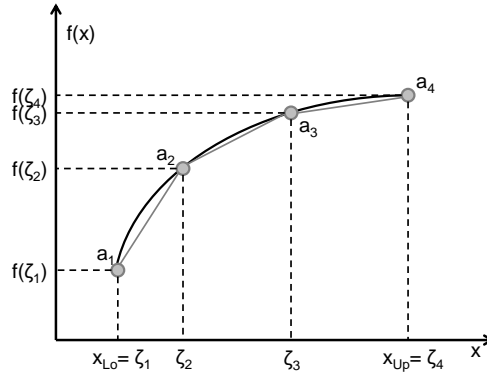


FIGURE 6.6: Piecewise linearisation of non-convex function, adapted from [108].

(x) relation is obtained through interpolation between two SOS-2 variables based on n sample points $(f_n(\zeta_n), \zeta_n)$. Sample points are typically selected in concave functions by taking more sample points in the steep incline and fewer sampling points the more gradual the function becomes. Optimised total investment cost ($C_{CHP,i}^{INV}$) and installed capacity ($DG_{CHP,i}^{MAX}$) [kW] of a CHP unit in house i is then found as [229, 244, 245]:

$$C_{CHP,i}^{INV} = \sum_{t=1}^n f(\zeta_t) \cdot a_t \quad \text{and} \quad DG_{CHP,i}^{MAX} = \sum_{t=1}^n \zeta_t \cdot a_t \quad \text{with} \quad \sum_{t=1}^n a_t = 1 \quad \forall i \quad (6.5)$$

6.4.1.4 Terms of the objective function

The objective function (see Equation 4.1) now additionally becomes a function of the costs and incomes related to internal DES energy ‘trading’:

$$\begin{aligned} \min C^{TOT} = & C^{INV} + C^{OM} + C^{FUEL} + C_{BUY}^{GRID} + C^{CT} - C_{SAL}^{GRID} \\ & + C_{MG,elec}^{BUY} - C_{MG,elec}^{SAL} + C_{MG,therm}^{BUY} - C_{MG,therm}^{SAL} \end{aligned} \quad (6.6)$$

6.4.2 Central scale

CHP units are the only considered units for upscaling to central scales, potentially combined with a central absorption chiller (see Section 6.4.1.3). In central DES, individual houses are assumed to no longer be allowed to install DG and storage units. Houses can, however, still install non-DG conventional thermal technologies: boilers, gas heaters and

air-conditioning units. These are design choices where alternatives exist. Furthermore, thermal pipeline and electricity sharing can be adopted from a central unit to individual houses, complementing energy sharing between houses.

6.4.2.1 Technology constraints

The potential central CHP unit (*chpct*) is modelled similar to the decentral units (see Appendix D) through an installed capacity, upper and lower capacity bounds and a binary variable, but now with an economies-of-scale cost relation (Equation 6.5). Electricity generated by the central CHP unit in each hour of each season can either be used for circulation to neighbourhood houses ($PE_{chpct,s,h}^{CIRC}$), for export to the central grid ($PE_{chpct,s,h}^{SAL}$) or for central absorption chiller fuelling ($PE_{chpct,s,h}^{AC}$). Absorption chillers namely require electricity per kW generated cooling, determined through their electricity to cooling ratio (*ECR*). Generated cooling is then transferred to houses *i* ($QC_{acct,i,s,h}$). Heat generated by the central CHP is determined by its total electricity generation ($PE_{chpct,s,h}^{TOT}$) and heat to electricity ratio (*HER*). This heat can be used for heating ($PH_{chpct,s,h}^{HEAT}$) or cooling purposes ($PH_{chpct,s,h}^{COOL}$) or can be dissipated ($PH_{chpct,s,h}^{DIS}$). Heat dissipation is allowed to balance excess heat and must be allowed due to the design choice that no decentral DG thermal storage is installed in central scales. Heat for heating purposes is distributed to individual houses *i* ($QH_{chpct,i,s,h}$):

$$PH_{chpct,s,h}^{HEAT} = \sum_i QH_{chpct,i,s,h} \quad \forall s, h \quad (6.7)$$

The central absorption chiller follows the behaviour of decentral absorption chillers, see Appendix D. Generated cooling is determined by CHP waste heat for cooling purposes, absorption chiller existence and the chiller cooling to heating coefficient, n_{AC}^{th} . Total generated cooling is distributed among different houses *i* ($QC_{acct,i,s,h}$):

$$PH_{chpct,s,h}^{COOL} \cdot n_{AC}^{th} = \sum_i QC_{acct,i,s,h} \quad \forall s, h \quad (6.8)$$

A central absorption chiller can, furthermore, only be installed together with a central CHP unit decided by binary variables B_{acct} and B_{chpct} , respectively:

$$B_{acct} \leq B_{chpct} \quad (6.9)$$

6.4.2.2 Central pipeline constraints

In order for heating to be transferred from the central unit to an individual house ($QH_{chpct,i,s,h}$), a pipeline with maximum utilisation rate U_{snd} must exist, expressed through binary variable $YP_{techct,i}$:

$$QH_{chpct,i,s,h} \leq U_{snd} \cdot YP_{techct,i} \quad \forall i, s, h \quad (6.10)$$

Heating received by a house from the central CHP unit can contribute to the house heat load in hour h , or, be transferred to other houses through an optimised pipeline network (see Section 4.3.2.3). The pipeline balance (Equation 4.7) then becomes:

$$\begin{aligned} \sum_j QH_{j,i,s,h} - QH_{i,s,h}^{LOSS} + QH_{chpct,i,s,h} - QH_{chpct,i,s,h}^{LOSS} \\ = QH_{i,s,h}^{LOAD} + \sum_j QH_{i,j,s,h} \quad \forall i, s, h \text{ with } i \neq j \end{aligned} \quad (6.11)$$

Central thermal transfer losses are obtained similarly to decentral transfer losses (see Equation 4.9). Random x and y coordinates for the location of the central unit are once generated, from which the transfer length to each house is determined. The location of the central unit is thus once arbitrarily determined (Sections 6.5.2 and 6.7). The central cooling pipeline network is modelled similarly to the heating network.

6.4.2.3 Grid interaction

The central CHP unit can only export electricity to the central grid ($X_{chpct,s,h}^{snd}$) if the neighbourhood as a whole exports, determined by a daily export level (U_{snd}) (similar to Section 4.3.3.2). A central CHP unit can also only be installed when a microgrid is installed in the neighbourhood (Z).

$$PE_{chpct,s,h}^{SAL} \leq U_{snd} \cdot X_{chpct,s,h}^{snd} \quad \forall s, h \quad (6.12)$$

$$X_{chpct,s,h}^{snd} + X_{i,s,h}^{rec} \leq 1 \quad \forall i, s, h \quad \text{and} \quad X_{chpct,s,h}^{snd} \leq Z \quad \forall s, h \quad (6.13)$$

6.4.2.4 Microgrid interactions

Central CHP electricity for microgrid circulation is modelled similarly to Section 4.3.3.2. Total microgrid transfer by the central and decentral units is appropriately bound. Central CHP electricity can be transferred to individual houses i ($PE_{chpct,i,s,h}^{snd}$). Electricity sent to each house from the central unit, minus transfer losses, equals the electricity the house receives ($PE_{chpct,i,s,h}^{rec}$). Electricity transfer losses are determined similarly to Chapter 4, Equation 4.17. The central unit microgrid balance then becomes:

$$\sum_i PE_{chpct,i,s,h}^{snd} - \sum_i PE_{chpct,i,s,h}^{LOSS} = \sum_i PE_{chpct,i,s,h}^{rec} \quad \forall s, h \quad (6.14)$$

6.4.2.5 Energy balances

The pipeline balances incorporate contributions from the central technologies (see Equation 6.11) so that the thermal balances are not affected (see Appendix D). Electricity balances, however, need to be adapted. Each house can now meet its electricity demand through the combination and consideration of grid import ($PE_{i,s,h}^{GRID}$) and/or central microgrid operation ($PE_{chpct,i,s,h}^{rec}$):

$$C_{ELEC_{tot},i,s,h}^{LOAD} = PE_{i,s,h}^{GRID} + PE_{chpct,i,s,h}^{rec} \quad \forall i, s, h \quad (6.15)$$

6.4.2.6 Terms of the objective function

The objective function now additionally includes household costs of purchasing both electric ($C_{techct,elec}^{BUY}$) and thermal ($C_{techct,therm}^{BUY}$) energy from a potential central unit:

$$C_{techct,elec}^{BUY} = \sum_{i,s,h} hr \cdot d_s \cdot T_{techct,elec}^{BUY} \cdot PE_{chpct,i,s,h}^{rec} \quad (6.16)$$

$$C_{techct,therm}^{BUY} = \sum_{i,s,h} hr \cdot d_s \cdot T_{techct,therm}^{BUY} \cdot (QH_{chpct,i,s,h} + QC_{acct,i,s,h}) \quad (6.17)$$

6.4.3 Hybrid scale and scale differentiation constraints

DES scale can be set up as either decentral, central or hybrid. To allow the model to implement one of three scales, additional binary variables are introduced. B^{DCtech}

becomes 1 if the neighbourhood has installed decentral DG and storage units (WT, PV, CHP, EST, HST or CST). B^{CT} becomes 1 if the neighbourhood *only* has a central unit (AND-NOT gate, see Section 5.4.3.2 and Appendix H):

$$B^{CT} = B_{chpct} \wedge \overline{B^{DC}} \quad (6.18)$$

Binary B^{DC} becomes 1 if the neighbourhood *only* has decentral units (AND-NOT):

$$B^{DC} = \overline{B_{chpct}} \wedge B^{DCtech} \quad (6.19)$$

Binary variables B^{CT} and B^{DC} are thus mutually exclusive but allow for hybrid DES scales through the following relations:

$$B^{CT} + B^{DC} \leq 1 \quad \text{and} \quad B_{chpct} + B^{DCtech} \leq (1 - B^{DC}) + (1 - B^{CT}) \quad (6.20)$$

Hybrid scales allow both central units, and decentral DG and storage units. Thermal storage units in each individual house within hybrid DES are assumed to also potentially be filled through pipeline transfer:

$$\begin{aligned} PH_{CHP,i,s,h}^{PIPE} + \sum_j QH_{j,i,s,h} - \sum_j QH_{j,i,s,h}^{LOSS} + QH_{chpct,i,s,h} - QH_{chpct,i,s,h}^{LOSS} \\ = QH_{i,s,h}^{LOAD} + QH_{i,s,h}^{STO} + \sum_j QH_{i,j,s,h} \quad \forall i \neq j \end{aligned} \quad (6.21)$$

Electricity balances need to be adapted. Each house can now meet its electricity demand through the combination and consideration of grid import ($PE_{i,s,h}^{GRID}$), self-generation ($PE_{techDG,i,s,h}^{SELF}$), battery discharge ($ES_{i,s,h}^{OUT}$), decentral microgrid operation ($PE_{MG,i,s,h}^{rec}$), and/or central microgrid operation ($PE_{chpct,i,s,h}^{rec}$), $\forall i, s, h$:

$$C_{ELECtot,i,s,h}^{LOAD} = PE_{i,s,h}^{GRID} + PE_{MG,i,s,h}^{rec} + PE_{chpct,i,s,h}^{rec} + \sum_{techDG} PE_{techDG,i,s,h}^{SELF} + ES_{i,s,h}^{OUT} \quad (6.22)$$

6.4.4 Ownership

Either the neighbourhood houses, a third party or a combination between both, i.e. hybrid, can own the DES (Equation 6.23). To formulate ownership Equation 6.23, first,

a classification of costs has to be made in order to determine what terms – as part of the total annualised cost – are related to and can change with ownership.

$$\begin{aligned}
\min C^{TOT} = & \sum_{tech} [\omega \cdot (C_{techDCT}^{INV} + C_{techST}^{INV} + C_{infDG}^{INV}) + C_{techCV}^{INV}] \\
& + \sum_{tech} [\omega \cdot (C_{techDCT}^{OM} + C_{techST}^{OM} + C_{infDG}^{OM}) + C_{techCV}^{OM}] \\
& + \sum_{tech} [\omega \cdot (C_{techDCT}^{FUEL} + C_{infDG}^{FUEL} + C_{techDCT}^{CT} + C_{infDG}^{CT}) + C_{techCV}^{FUEL} + C_{techCV}^{CT}] \\
& + \sum_i C_{BUY,i}^{GRID} - \omega \cdot \sum_i C_{SAL,i}^{GRID} + C_{BUY,elec}^{MG} + C_{BUY,therm}^{MG} - \omega \cdot C_{SAL,elec}^{MG} \\
& - \omega \cdot C_{SAL,therm}^{MG} + (1 - \omega) \cdot (C_{techct,elec}^{BUY} + C_{techct,therm}^{BUY}) \\
& + (1 - \omega) \cdot \sum_{tech,i,s,h} hr \cdot d_s \cdot (QH_{i,s,h}^{STO} + QC_{i,s,h}^{STO}) \\
& + (1 - \omega) \cdot \sum_{tech,i,s,h} hr \cdot d_s \cdot (PH_{techDG,i,s,h}^{Load} + PC_{techDG,i,s,h}^{Load}) \\
& + (1 - \omega) \cdot \sum_{tech,i,s,h} hr \cdot d_s \cdot T_{MGint,elec}^{BUY} \cdot (PE_{tech,i,s,h}^{SELF} + PE_{tech,i,s,h}^{STO}) \quad (6.23)
\end{aligned}$$

Costs proportional with ownership share, i.e. their contribution to the neighbourhood objective function decreases if ownership shifts from households to a third party, are:

- investment cost of decentral DG ($techDG$) and storage units ($techST$),
- investment cost related to the central CHP and absorption chiller,
- investment cost associated with DES infrastructure ($infDG$), i.e. microgrid central controller, dump loads, decentral and central pipelines,
- operation and maintenance, fuel and carbon tax costs of the first three points, and
- incomes from both grid export and household energy trading.

Additionally, some costs increase when ownership shifts from houses to a third party. When the DES is (partially) owned by a third party, this third party also (partially) owns the energy generated by its units. Houses are then served under contract. Hence, when household relative ownership decreases, houses will have to increasingly pay for self-generated and stored energy at set internal trading prices. This is valid for both thermal and electrical energy generated by both decentral or central units. Costs related to ($techCV$) boilers, gas heaters, air-condition units, grid import and the purchase of electricity, heating and cooling from decentral or central units remain at all times to

be carried by the neighbourhood houses. Ownership is in the first instance analysed by introducing a parameter weighting factor (ω) multiplied with each of the ownership-sensitive terms. This factor can take on any value between 1 (100 % household ownership) and 0 (100 % third party ownership).

6.5 Case-study: a small Adelaide based neighbourhood

Section 4.4 presented the researched case-study. Additional aspects are detailed below.

6.5.1 Energy tariffs and export limitations

DES environments require energy tariffs, which might be flat or varying with the time of day [322]. Since no time of use tariffs are established in the case-study location and the uncertainty of predicting them, flat set tariffs are adopted for all energy interactions. Apart from central electricity and gas tariffs, internal energy sharing tariffs and DES electricity export tariffs have to be set. Since a holistic neighbourhood view is taken in the model, buying and selling prices of energy are set the same. This could be different with a third party design view. Hence, internal DES energy sharing tariffs, between houses or from the central unit, are set to one third of the central energy tariffs (see Section 4.4.1) as illustration; 0.115 AUD kWh⁻¹ for electricity and 0.043 AUD kWh⁻¹ for thermal energy. This is a choice where other options are available. Furthermore, the feed-in tariff for residential solar electricity is extended to electricity export from all DG units. Each house in the neighbourhood, additionally, has a total electricity export limit of 45 kWh per day [275]. This includes export from its installed DG units as well as an equal share from the total electricity exported by the central CHP unit.

6.5.2 Economies-of-scale and central transfer distances

The employed economies-of-scale relation for small CHP units is adapted from Merkel et al. [244], see Appendix K. The power relation between total cost and total installed capacity is presented in Figure 6.7 together with the piecewise linearisation sample points. The transfer distances [m] between the central CHP unit and each house are

determined from the arbitrary central unit coordinates (58 m; 99 m) as $l_{ct,h_1}=101$ m, $l_{ct,h_2}=76$ m, $l_{ct,h_3}=66$ m, $l_{ct,h_4}=57$ m and $l_{ct,h_5}=35$ m.

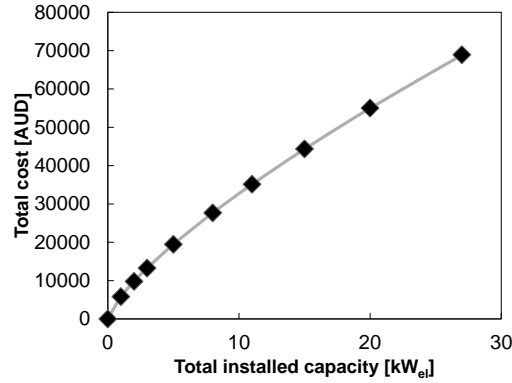


FIGURE 6.7: Economies-of-scale relation for small-scale CHP units, $C_{CHP}^{INV} = 5812.2 \cdot (DG_{CHP}^{tot})^{0.75}$, adapted from Merkel et al. [244].

6.5.3 Analysis and selected energy system scenarios

The model is solved for several scenarios to analyse the relation between framework aspects and design, and to demonstrate results and trade-offs that can be obtained and discussed. Note that conventional supply (Scenario I in Chapter 4) is included as reference. Table 6.5 indicates how each regulatory framework aspect is analysed.

Design of the three DES scales is optimised through fixing binary variables, for an ownership share ranging from 0 % (100 % third party ownership) to 100 % (100 % household ownership) with steps of 25 %. Results are first analysed for trends between regulatory

TABLE 6.5: Analysis and proxies of regulatory framework aspects.

Framework aspect	Analysis	Proxy	Model
Type	Physical	Optimal design	Structure
Scale	Decentral, central and hybrid designs	Fixing binary variables (B^{DC} , B^{DCtech} , B^{CT} , B_{chpct}) and obtaining optimal design	Structure/output
Ownership	Continuous ownership share	Optimal design for parameter variation $\omega \in [0\%; 100\%]$ with steps of 25%	Structure/input/output
Choice	Maximum cost difference between households as measure for equal cost sharing	ΔC_{max}	Output
Tariff	Sensitivity to set internal energy sharing tariffs	Optimal design for percentage variation of T^{int}	Input/output
Objective	Economic objective value, indirect objective CO ₂ emissions	$\min C^{TOT}$	Structure/output

framework measures of objective (total cost), indirect objective (total CO₂ emissions), ownership and cost sharing (ΔC_{max}) for various scales. The maximum cost difference between households, ΔC_{max} , is employed as proxy for flexibility of consumers to opt in or out an agreement. ΔC_{max} is namely a measure of fair cost sharing/distribution between houses and enables configuration comparison. Note that there is inherently a cost difference between houses based on the difference in energy demands (h_1 the lowest and h_5 the highest). Cost differences are complex outputs that arise through the interaction between demand differences, costs associated with units in particular houses, imports and energy sharing, and income differences due to export. Stakeholder interests, then, can be measured in several ways but are here measured through the optimisation objective, total annualised cost. The impact of other stakeholder interests or consumer choices can indirectly be measured through output data, annual neighbourhood CO₂ emissions and maximum household cost difference, for example. A comparison between scenarios is presented for neighbourhood energy interactions and design in Section 6.6.1.

Uncertainty regarding deterministic input data can affect results, hence the sensitivity of resulting designs with internal trading tariffs is analysed. Internal trading tariffs are namely uncertain and depend on specific contractual agreements. To illustrate the method, only hybrid scales are optimised for 100 % household ownership with in percentage varying internal trading tariffs, see Section 6.6.2.1. Additional features that increase model applicability and flexibility can also be analysed. The model is hereto adapted to a mixed-integer non-linear (MINLP) framework, including a non-linear economies-of-scale relation. This analyses the impact of linearisation. As a case-study, a hybrid scale is optimised for 100 % household ownership including the non-linear CHP cost-capacity relation in Section 6.6.2.2.

6.6 Results and analysis

6.6.1 Energy system design scenarios

Figure 6.8 presents annual cost, maximum cost difference and annual emissions for varying ownership shares for optimal decentral, central and hybrid designs. DES decrease total cost compared to conventional, due to low internal trading tariffs in a market

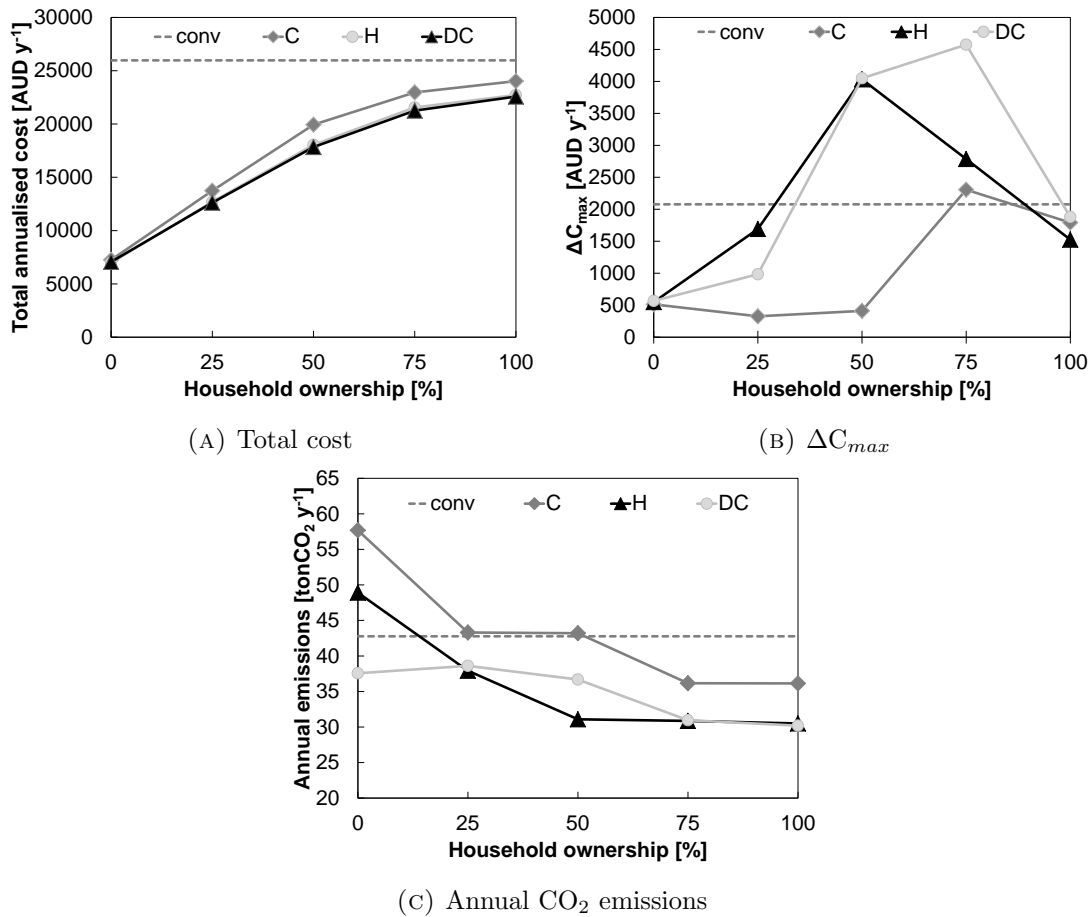


FIGURE 6.8: Relation of total cost (6.8a), maximum cost difference ΔC_{max} (6.8b), annual emissions (6.8c) and ownership for DES scales. C=central scale, conv=conventional operation results, DC=decentral scale, H=hybrid scale.

with high energy tariffs. Unit investment and fuel costs dominate annual neighbourhood cost, leading to total cost increase with increasing household ownership. 100 % household ownership namely requires all costs to be borne by consumers. Total cost flattens around 50-75 % ownership from where third party impact decreases. Decentral units (hybrid and decentral) reduce costs slightly due to slightly better balancing of demand and unit capacities. At 100 % third party ownership, scale costs are approximately equal. A third party bears here all the DG-related costs. System designs will thus focus on ‘free’ DG units from which houses can purchase energy at cheap internal trading tariffs. Note that central scales and increased third party ownership lead to unit over-dimensioning since costs are no longer carried by houses. In real projects, in contrast with this case-study with a single neighbourhood point of view, a third party will conduct a cost-benefit analysis to assess the ‘best’ system design (see Section 6.7).

Household ownership between 50 and 75 % increases ΔC_{max} . Here, cost contributions

from houses will start to dominate third party contributions. Decentral units (decentral and hybrid) lead to higher cost differences since a single house invests in an expensive unit that serves other houses at cheap internal trading tariffs. The decentral trend peaks around 75 % household ownership where only a single house has a CHP unit that shares energy with more than one house, compared to multiple house-CHP units at 50 % household ownership. The hybrid trend peaks around 50 % household ownership, which is the turning point from a large central CHP combined with larger decentral CHPs to a smaller (better balanced) single decentral and central CHP at 75 % household ownership. The central scale trend, lastly, peaks around 75 % ownership, which marks a drastic drop in central CHP capacity combined with more individual household conventional units. A larger central unit namely allows houses to purchase cheap energy at low internal tariffs whereas a smaller central unit requires houses to individually invest in complementary units, which increases ΔC_{max} . Also, the more decentral units and household ownership, the less emissions (decentral < hybrid < central) due to better balancing of demands, which minimises excess thermal and electrical energy. DES also mostly reduce annual emissions compared to conventional. A drop in emissions occurs between 25 and 75 % household ownership for all scales. Drops are related to a reduction of CHP capacity or of the number of decentral CHP units.

Figure 6.9 illustrates total installed neighbourhood units for different scales and ownerships. Neighbourhood designs are illustrated in Figures 6.10, 6.11 and 6.12 for decentral, hybrid and central scales, respectively. Note that 0 % household ownership is not always depicted to keep the capacity scale readable. 0 % household ownership (100 % third party) often leads to maximisation of unit capacities, either through operational boundaries (e.g. air-conditionings, boilers, CHP, PV) or capacity bounds (storage and absorption chillers), since costs are carried by a third party. Ownership impacts neighbourhood design, which facilitates design trade-offs. More stable designs occur below 50 and above 75 % household ownership with a trade-off interval between 50 and 75 %. The more third party ownership, the more expensive DG units (CHPs and absorption chillers) and the more energy sharing are adopted. The upfront investment costs are here namely majority born by the third party. The more household ownership, in contrast, the more conventional units are installed (boilers and air-conditioning units), at the expense of energy sharing. Large household thermal storage units are installed in houses that have a (large) CHP and absorption chiller in decentral configurations.

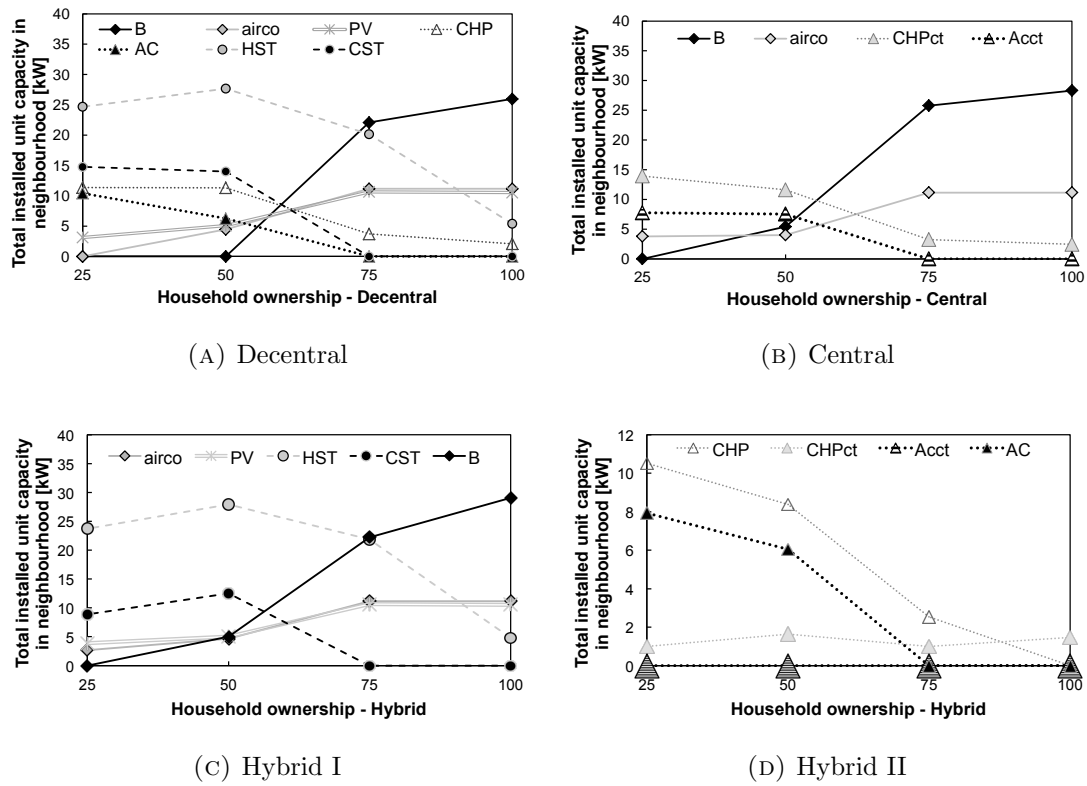


FIGURE 6.9: Total installed capacity of units in neighbourhood [kW] for different scales and ownerships. AC=absorption chiller, ACct=central AC, airco=air-conditioning, B=boiler, CHP=combined heat and power, CHPct=central CHP, CST=cold storage, HST=heat storage, PV=photovoltaic. No batteries adopted.

In hybrid configurations, larger storage units are installed in houses that have a direct pipeline connection with the central tri/co-generation unit. The received thermal energy is either used or stored by the receiving house or transferred to other houses.

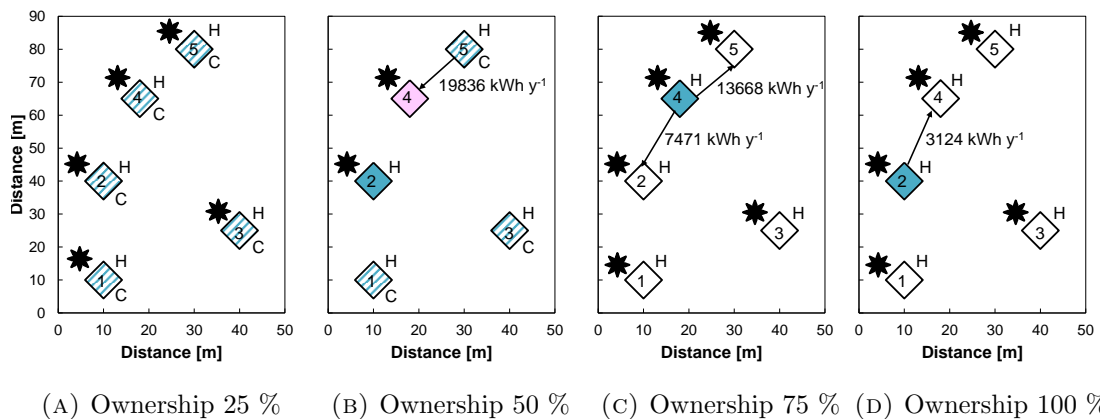


FIGURE 6.10: [colour] Decentral neighbourhood layout for varying ownership. sun=PV, H=HST, C=CST, dark grey diamond (blue)=CHP and airco, white diamond=boiler and airco, grey (blue) hatched diamond=CHP and AC, light grey diamond (pink)=only airco, black arrow=pipeline heat transfer [kWh y^{-1}].

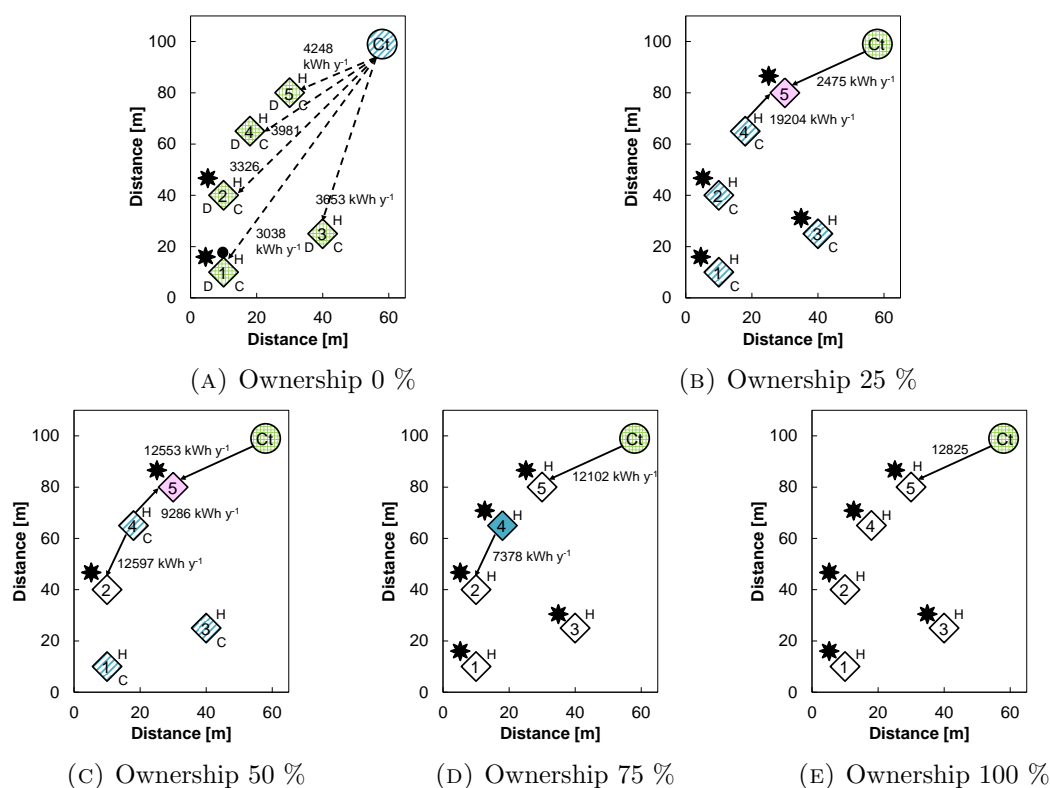


FIGURE 6.11: [colour] Hybrid neighbourhood layout for varying ownership. sun=PV, H=HST, C=CST, CT=central units, dark grey diamond (blue)=CHP and airco, white diamond=boiler and airco, grey (blue) hatched=CHP and AC, light grey diamond (pink)=only airco, grey (green) hatched=CHP only, black arrow=pipeline heat transfer, black dashed arrow=pipeline cooling transfer [kWh y^{-1}].

Ownership levels thus significantly affect optimal design. Third party ownership relieves responsibilities from individual houses, especially in case of central scales. Third party ownership also facilitates energy integration in terms of not only electricity but also heating and cooling but with the risk of over-dimensioning equipment, increasing yearly emissions. Household ownership and decentral scales, in contrast, balance local supply and demand better, reduce emissions most and allow for houses to opt into a cooperative share of a central unit. Central units, in contrast, facilitate cost levelling. Hybrid scales then, allow to combine small-scale DG renewables (PV) with a larger central heat, cooling and electricity generation unit, facilitating resource diversification.

Figures 6.13, 6.14 and 6.15 illustrate optimised yearly neighbourhood electricity interactions for different ownership levels at decentral, central and hybrid scales, respectively [kWh y^{-1}]. All axes are equally scaled with 45000 kWh y^{-1} . Total yearly electricity generated by the neighbourhood central CHP (ctCHP), decentral CHPs and PV units

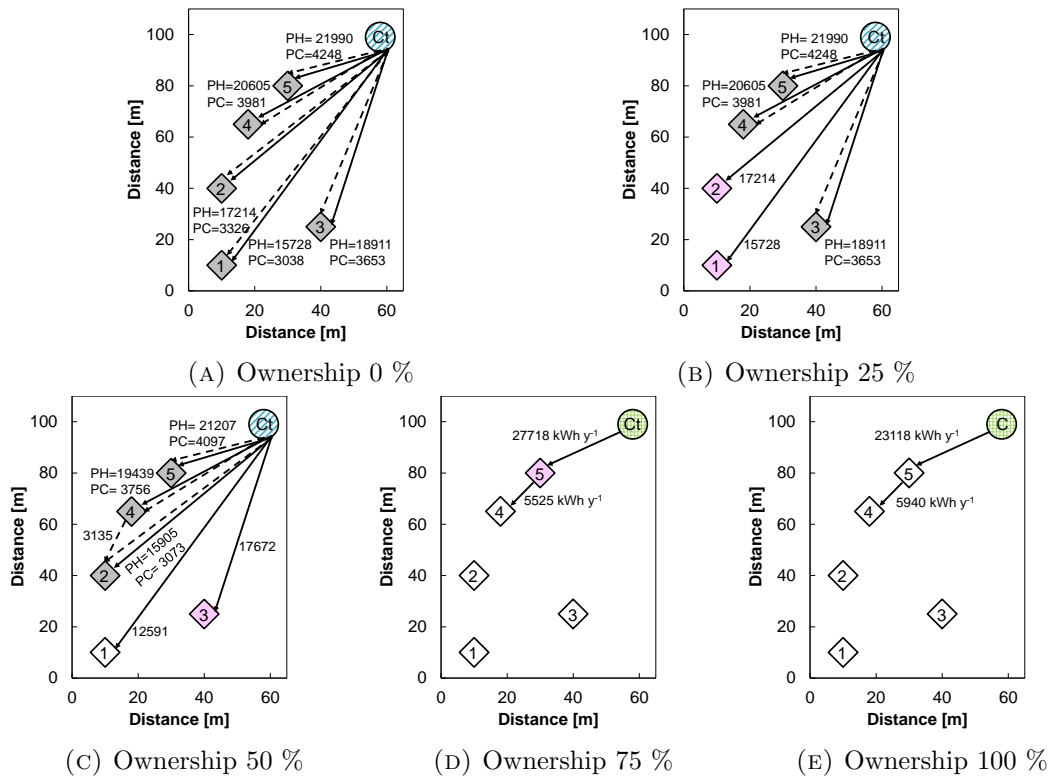


FIGURE 6.12: [colour] Central neighbourhood layout for varying ownership. sun=PV, H=HST, C=CST, CT=central units, white diamond=boiler and airco, grey (blue) hatched=CHP and AC, light grey diamond (pink)=only airco, grey (green) hatched=CHP only, grey diamond=no thermal units, black arrow=pipeline heat transfer (PH), black dashed arrow=pipeline cooling transfer (PC) [kWh y^{-1}].

can be used for export (SAL), for microgrid sharing (CIRC) and for self-use by the accommodating house of the decentral units. The zero level and the yearly neighbourhood electricity demand, including air-conditioning cooling (26644 kWh y^{-1}), scaled to about 40 % on the axes, are both included as references. Two trends can be distinguished in all three cases; (i) 100-75 % household ownership where DG generation is more balanced across total use, microgrid operation, import and export. Unit capacities are here also balanced with demand and not oversized since houses bear their costs. And, (ii) 50-0 % household ownership, which reduces cost contributions to the cost objective function and leads more to unit over-dimensioning, both central and decentral, with more electricity and heat generation as a result (see discussion in Section 6.7). Excess heat is either stored or dissipated, and excess electricity is exported to the grid. The latter leads to an income for houses or the third party, depending on ownership. Note that total electricity generated by CHPs relates to household heating demands due to heat-following CHP operation. CHP units should thus individually be able to meet house heat loads

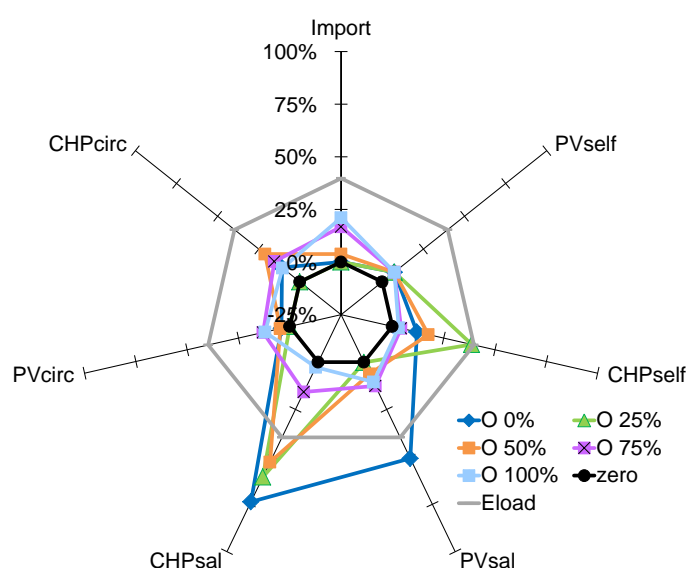


FIGURE 6.13: [colour] Yearly decentral neighbourhood electricity interactions [kWh y^{-1}] for household ownership shares [%]. CHP=combined heat and power, circ=microgrid sharing, Eload=yearly neighbourhood electricity load is reference, import=grid import, self=self-use by accommodating house, PV=photovoltaic, zero=zero values are expanded for clarity.

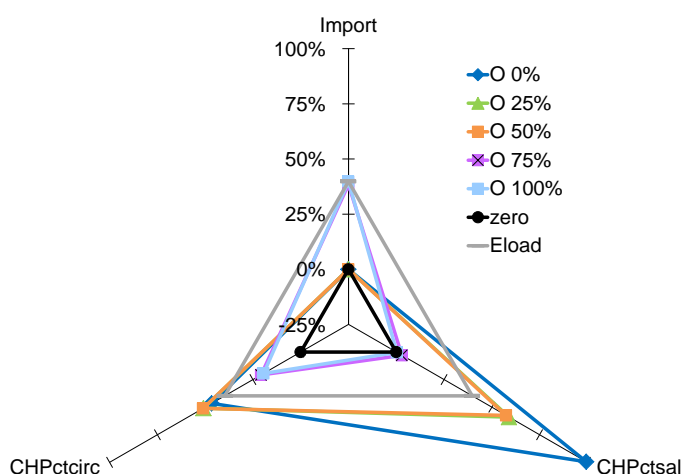


FIGURE 6.14: [colour] Yearly central neighbourhood electricity interactions [kWh y^{-1}] for household ownership shares [%]. CHPct=central CHP, circ=microgrid sharing, Eload=yearly neighbourhood electricity load is reference, import=grid import, self=self-use by accommodating house, zero=zero values are expanded for clarity.

as alternative to boilers (see Section 4.4.4). A certain heat requirement therefore results in a certain (excess) amount of electricity generated by the CHP (heat to electricity ratio). More DG electricity is generated with increasing third party ownership, which is partly used for microgrid operation at advantageous internal trading tariffs but is mostly exported. As a result and due to the high central energy prices as compared with the

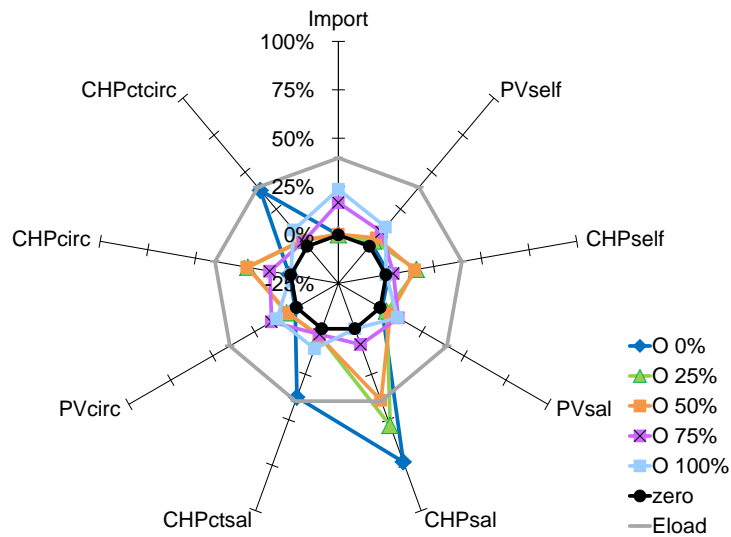


FIGURE 6.15: [colour] Yearly hybrid neighbourhood electricity interactions [kWh y^{-1}] for household ownership shares [%]. CHP=combined heat and power, CHPct=central CHP, circ=microgrid sharing, Eload=yearly neighbourhood electricity load is reference, import=grid import, self=self-use by accommodating house, PV=photovoltaic, zero=the zero values are expanded for clarity.

cheap internal tariffs, grid electricity import reduces then to (close to) zero. Overall, decentral units (decentral and hybrid) lead to better local energy balancing. Note that currently some interactions are maximised for 100 % third party ownership due to no neighbourhood cost restrictions (see Section 6.7).

6.6.2 Impact of decisions: model robustness

Model robustness is subsequently illustrated through sensitivity and linearity analysis.

6.6.2.1 Sensitivity with internal trading tariff

The set cheap internal trading tariffs favour internal energy sharing over import due to the high central energy tariffs in the Adelaide market. To assess the impact of the uncertain internal tariffs on design, neighbourhood design is optimised at constant 50 % household ownership for in percentage varying internal electricity and thermal energy trading tariffs from -50 % to +200 % of the set tariffs. The latter is equal to the central energy tariffs. Total neighbourhood unit capacities [kW] are given in Figure 6.16 for each tariff scenario. Table 6.6 illustrates the installed hot thermal pipeline connections.

Cold thermal pipelines are not adopted. Decentral scale is adopted in each scenario, but optimal design depends on tariff. Since PV electricity is mainly used for self-generation or export, PV capacity is relatively not much affected by tariffs. Changing tariffs, however, influence the relative importance of CHP units and absorption chillers. The lower the tariffs, the more CHP units are installed, the more cooling is generated by absorption chillers and the more thermal energy is stored. Higher internal trading tariffs will increase total boiler capacity and heat integration. A tariff trade-off between two design trends is thus required between 100 and 150 % tariff increases for this case study.

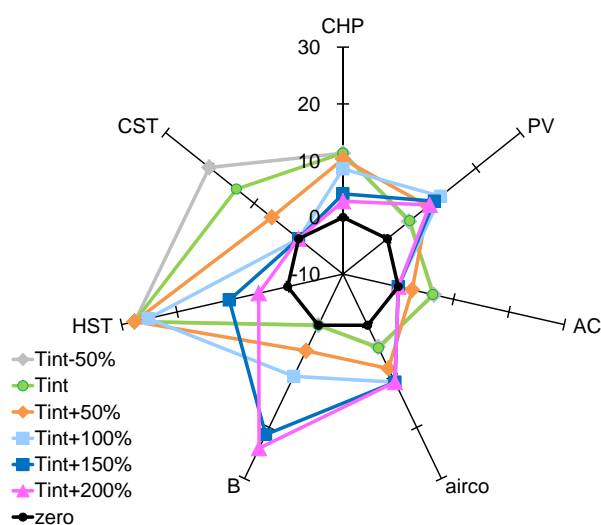


FIGURE 6.16: [colour] Total installed capacity of units [kW] with changing internal trading tariff (Tint). AC=absorption chiller, airco=air-conditioning, B=boiler, CHP=combined heat and power, CST=cold storage, HST=hot storage, PV=photovoltaic.

TABLE 6.6: Installed hot thermal pipelines in the neighbourhood with changing internal trading tariff (Tint).

Tariff	Tint-50 %	Tint	Tint+50 %	Tint+100 %	Tint+150 %	Tint+200 %
House pair	(5,4)	(5,4)	(5,4)	(4,2) and (4,5)	(4,2) and (4,5)	(5,4)

6.6.2.2 Non-linear economies-of-scale

In reality DES show non-linearities with respect to cost and operational behaviour (see Section 3.2.1). An attempt to explicitly deal with and analyse the impact of non-linearity is made through the explicit integration of a non-linear CHP economies-of-scale relation (see Section 6.5.2). Table 6.7 summarises optimal design results for a decentral scale DES with 100 % household ownership for various solvers. The MILP result (piecewise

linearisation/CPLEX) is included as reference. Microgrid sharing and limited pipes are adopted in all feasible results. The location and size of the CHP unit and pipeline, however, changes. Due to the size of the model, some solvers are no longer able to obtain solutions. Additionally, global optimality is not guaranteed with most MINLP solvers. The non-linear model is thus currently intractable for decision-making.

TABLE 6.7: Results of non-linear economies-of-scale relation in MINLP model for different solvers. *=result from MILP solver with linearised EOS. **=MILP result evaluated on the non-linear EOS function.

	Solution approach	CHP [kW]	Pipeline	Total cost [AUD y ⁻¹]	CPU [s]
CPLEX (MILP)	Branch and bound	2.077 (h ₂)	(2,4)	22577*/22597**	433
ALPHAECP (MINLP)	Extended cutting plane method	2.498 (h ₄)	(4,5)	22786	18730
CONOPT (MINLP)	nlp=conopt, mip=cplex, rminlp=conopt, minlp=dicopt	2.044 (h ₂)	(2,4)	22599	4487
SBB (MINLP)	Branch and bound	Solver failure (node limit)			
BARON (MINLP)	Branch and bound	Solver failure (insufficient memory)			

6.7 Discussion and generalisation of approach

The developed framework allows for flexible structure implementation and analysis of DES regulatory framework factors at various modelling stages, see Table 6.8. A physical DES scale was researched that included energy sharing between consumers. Other

TABLE 6.8: Adaptability and flexibility of the developed framework.

Stage	Adaptations & flexibility
Implementation	<ul style="list-style-type: none"> - more and different virtual and physical energy systems at different scales - varying (time of use) tariffs - different (discrete) ownership schemes - multiple ownership shares for equipment and infrastructure - multiple and different optimisation objectives - ownership as optimisation variable in MINLP environment - weighted objective function based on individual consumer preferences - multi-microgrid operation - 3P economic viability
Case-study	<ul style="list-style-type: none"> - hourly changing parameters, such as tariffs - different ownership and scale scenarios
Optimisation	<ul style="list-style-type: none"> - analysis of different energy system scenarios through pre-setting binary variables and ownership schemes
Results	<ul style="list-style-type: none"> - role of technologies in organisational scenario - impact of technology and interaction bounds on results - impact of regulation on results (CT, FIT, rebates, restrictions)

schemes could, however, be analysed through the same framework by, for example, eliminating physical energy flows (virtual) or by looking at houses with individual DER without energy sharing (power purchase agreements). Virtual DES allow consumers to connect with an authorised retailer, enabling retailer contestability. Virtual DES involve (third party) financial contracts and currently only focus on electricity supply. Virtual schemes could be implemented through: (i) no cost and installation of energy sharing infrastructure, and (ii) houses can individually install decentral units, co-invest in (a share of) a central unit or a hybrid combination of both. Physical DES, in contrast, typically only have a single on-site provider and combine aspects of distribution network infrastructure (poles, wires, protection schemes), generation, consumption and retailing. The strict ownership/activity division in liberalised power systems might need adjustment to facilitate physical DES. A new power system agent could be defined to get around strict unbundling and competition requirements. DES infrastructure could potentially fall under the responsibility of conventional distribution network operators.⁶ Alternatively, residential ‘gentailers’ or independent power producers could be established or privatisation of certain services might be adopted. Note that semi-physical types can also be implemented with, e.g. a central CHP unit and physical thermal integration through district networks but only contractual electricity sharing. The selected DES type thus determine interconnection requirements, costs and standards.

In the current model formulation, the central unit location was set arbitrarily as illustration. Since its location determines pipe lengths and energy transfers, this location determines cost and operation, and therefore also the structure of the network. The central unit location should thus ideally be optimised, constrained by pipeline network cost, minimum distances from residences and other requirements.

Ownership is a determining regulatory factor. DES can be structured in various ownership schemes and scales with multiple involved parties. The adopted continuous ownership share allowed for ownership flexibility. Ownership shares could be representative of the share that houses have within an Energy Service Company (ESCO), for example [241]. Other explicitly identified ownership structures could, however, easily be

⁶Ownership by distribution network operators (DNO) is often highlighted as a way for cost effective network expansion. Nevertheless, DNO-DG ownership is an area of extensive debate [358]. Distribution network operators (DNOs) within liberalised electricity markets, for example, cannot assume this ownership due to unbundling requirements of generation and distribution [358]. An example is the European Directive 2003/54/EC and the SA Electricity Law. Retailers, in contrast, can own and operate generation units as well as engage in retail businesses under so-called competitive ‘gentailer’ structures.

identified by adopting weighting factors to include or remove terms from the neighbourhood cost objective function. Nevertheless, full household ownership might not be practically feasible. DES could namely benefit from some third party or regulatory oversight in protecting consumers, legally framing the adopted scheme, taking on (part of) the infrastructural and unit costs, and facilitating monetary transfers. In turn, these third parties could gain ownership over the locally generated energy, which it can sell back to consumers. Increased third party ownership, however, makes compliance with competition requirements more difficult, since participating houses might have no choice of energy supplier. Several different ownership shares could also be included for particular technologies or infrastructure. This enables designing and analysing various discrete and more elaborate ownership schemes. Additionally, ownership could be included as optimisation variable, modifying the model structure to an MINLP approach, through multiplications of continuous ownership share variables with cost variables.

An important regulatory feature is the choice and flexibility of consumers to opt in or out of a DES agreement. Opting for DG installation will be mostly a decision of the home owner whereas the income generated through export is part of a retail contract and hence will mostly benefit the home maker. Opting to step into a DES scheme would require committing to the lifetime of the system for energy supply to counteract overdimensioning of equipment, and to achieve best balancing of local supply and demand. Physical DES thus do not provide much consumer flexibility. Physical DES, however, provide benefits in terms of exploiting and balancing locally available resources and co-generation, leading to increased efficiency and cost savings. Central or hybrid physical DES could provide more flexibility to consumers through a single central energy provision unit that serves individual consumers under contract. Decentral scales, in contrast, could require individual houses to install expensive units (CHPs, ACs) that provide energy for the neighbourhood as a whole. This is a large commitment and reduces flexibility for this house. Neighbourhood energy integration, moreover, requires infrastructure and house connections, which reduces flexibility and ties houses to the system.

DES are often implemented in remote neighbourhoods, which are often exempt from competition requirements. This makes the concept of ‘choice’ a philosophical one; is electricity supply a basic requirement or does this apply to a grid connection? Is electricity supply a basic requirement or is it a choice? The presented MILP approach has

not explicitly introduced factors to analyse choice and flexibility of consumers. This could, however, be analysed through various model adaptations: (i) a multi-microgrid option could be installed [247] where within one larger neighbourhood, houses could opt in or out of one or multiple DES, (ii) equal cost sharing could be optimised through minimisation of ΔC_{max} or a Game Theory based optimisation of fair cost sharing (see e.g. [86]), or, (iii) a weighted multi-objective function could be constructed where each household can set different weights for each objective in the overall objective. The latter could also balance interests of various stakeholders.

Design objectives are important factors in determining type and scale. In reality designs have to balance various stakeholder interests/design objectives. The question then arises as to how other objectives, such as the presented in Chapter 5, relate to regulatory framework factors. With regard to electrical system unavailability, the following could be proposed: physical electrical system availability is higher than from a virtual aggregator since the latter might not have customer support or availability requirements as compared with conventional power system agents. Alternatively, a larger, third party owned unit might have a better unit availability due to contractual service requirements [241].

Tariffs relate to energy interactions, policies and design. Tariffs thus have to be carefully designed. Low internal trading tariffs could be appropriate for majority household owned DES where a third party might be given infrastructural responsibilities. Feed-in tariffs, moreover, could help the integration of renewable and highly efficient generation units but also enable larger DES to contribute to the central electricity market. The presented framework allows for implementation and analysis of various tariffs (fixed and variable). This can be easily achieved through hourly and/or seasonal dependence of tariffs, $T_{s,h}$. Similarly, internal trading tariffs and feed-in tariffs can be adapted or optimised.

The developed approach takes the viewpoint of the neighbourhood in determining the most cost effective design. This results in over-dimensioning and over-investment of units close to their maximum bounds in case of predominant third party ownership, since costs are then no longer carried by the consumers. Hence, there is currently no bound on the investment borne by a third party. In reality, however, any third party that will consider installing and operating such a system will first conduct a thorough cost-benefit analysis [241, 330, 343, 344]. A third party ownership-dependent constraint could bound this unrealistic design behaviour. The constraint could be: *total annual costs of*

the third party \leq *total annual income of the third party*, i.e the absolute upper limit of investment where revenue is zero. A constraint of this type would increase accuracy of the optimised designs at small household ownership levels. There are, however, some issues with this constraint that limit its ready inclusion within the current model context; First, the model solely takes on the viewpoint of the neighbourhood as system box. From this viewpoint, designs for various ownership levels should ideally look as optimised. Since third party costs are transferred outside the box, this leads to over-investment. Adding a third party investment bound would, however, mix the two viewpoints (consumers and third party) and could potentially impact other existing equations. Also, the current case-study internal trading tariffs are quite low for a third party to recover cost (see point below). Adding this constraint under the given inputs could thus lead to no available or feasible DES design. These type of third party constraints, however, show that the model could be expanded beyond the current system box.

Second, costs due to over-investment at increased third party ownership should in reality be carried by the third party and recovered by its income [241, 330, 343, 344]. This income is, however, uncertain. It not only depends on (i) internal trading tariffs it receives from houses for energy delivery, but also on (ii) electricity export tariffs for which a third party might get special rates or a premium in the market, (iii) potential government subsidies for sustainable development, or even (iv) revenues from economic regulation [1] if the third party involves a network operator. As an illustration, third party incomes, costs and revenues are presented in Table 6.9 for the cases with varying internal trading tariffs of Section 6.6.2.1. This illustrates the current third party cost-income discrepancy and its reduction with increasing internal tariffs.

TABLE 6.9: Third party (3P) annual income, costs and resulting revenue with changing internal trading tariff.

Tariff	Tint-50 %	Tint	Tint+50 %	Tint+100 %	Tint+150 %	Tint+200 %
3P income	3091	5365	7382	9246	8592	8521
3P cost	15334	15477	14921	14158	9838	8292
3P revenue	-12243	-10112	-7539	-4913	-1246	228

In reality two things could thus happen in a DES development project to offset costs of third party owners; (i) the cost of the ideally optimised configuration is taken into account by the third party and the required tariffs (export, premiums, internal trading tariffs, etc.) for cost recovery are determined taking into account a potential revenue

margin, or, (ii) the tariffs are known, allowing for the constraint to be added on design. Determining the economic viability of third parties, such as aggregators, is, however, beyond the scope of this work (see Section 1.5).

The framework and results highlighted that various aspects impact both engineering and regulatory design, leading to useful discussions for decision-makers. Results and identified trade-offs allow to assess the ‘best’ design that ensures lawfulness of DES within conventional power systems and enables exploiting their potential. ‘Best’ design is here, however, no longer a strict optimisation result but rather a trade-off of the relative importance of structural and organisational factors within an energy system, the governing central power system and the relative preferences and incentives of stakeholders. A single framework that fits in with governing regulation facilitates a plug-and-play approach and standardisation. The question arises here whether DES regulatory frameworks require location-specific tailoring, similar to their engineering design.

6.8 Summary and conclusion

A mixed-integer programming approach was presented that enabled analysing regulatory framework aspects of residential DES. DES regulatory frameworks are based on their organisational structure, which in its turn is determined by various design factors, such as type, scale, ownership, consumer choice and flexibility, tariffs and design objective(s). The developed model provided examples of how DES regulatory factors can be analysed and adapted to accommodate for various case-study requirements and scenarios. Additionally, the discussion and analysis illustrated how the developed framework could be used for interdisciplinary decision-making.

Chapter 7

Conclusions and future work

Central power systems still predominantly consist of large generators that provide electricity to a broad consumer base through extensive networks. This conventional top-down supply to consumers is, however, being challenged by growing urbanisation levels, increasing demand, ageing infrastructure and climate change. Localised distributed energy systems (DES) are increasingly presented as solutions to these challenges. However, for DES to become viable, a novel cross-disciplinary design approach is required that encompasses multiple stakeholder interests. This thesis aimed to address this need through developing a flexible multi-objective decision-making framework for DES design, from an engineering and regulatory perspective, using mixed-integer linear programming. Contributions made through this thesis to the ongoing work in the field of DES design optimisation are summarised and discussed in Section 7.1. Suggestions for future research areas are presented in Section 7.2. Section 7.3, finally, concludes the thesis.

7.1 Contributions of the thesis

A comprehensive and flexible DES design decision-making tool has been developed, encompassing engineering, economic, environmental as well as regulatory aspects. The model was applied to a small South Australian neighbourhood to illustrate its capability for design analyses and decision-making within conventional power systems generally.

The framework is useful for decision-makers to (i) ensure DES applicability within conventional power systems, (ii) to assess the design impact of various stakeholder interests, and (iii) to ensure the relevance of design to governing energy regulation.

Chapter 1 framed the modern DES concept and demonstrated the need for a new design approach by looking at the evolution of power systems over time. Motivated by the current research and development status of DES, the research problem, aims, solution approach and scope of the thesis were identified. The aim was to develop an approach to design the energy system of a small residential neighbourhood through the selection, siting and sizing of potential DER technologies and interactions to meet the yearly neighbourhood energy demands in terms of electricity, space heating and space cooling. The problem was broken down into four research questions (see Section 1.4):

1. *What is the current status of DES design optimisation?*
2. *How can DES be techno-economically designed with cost as driving objective?*
3. *How can DES be designed whilst balancing multiple stakeholder interests?*
4. *How can DES regulatory aspects be integrated and assessed within design optimisation frameworks?*

DES design is a popular research topic as was highlighted throughout Chapter 2. A general background on mathematical modelling and optimisation was herein presented together with its application to DES (first research question). The current status of DES design optimisation research was identified, analysed and categorised to identify research gaps and shape the research questions addressed in the thesis.

Chapter 3 detailed the employed superstructure mixed-integer linear (MILP) optimisation methodology and the conceptual framework. The method was developed to enable most suitable design of small residential neighbourhood energy systems, framed by location specific parameters and subject to multiple objectives, whilst meeting total yearly neighbourhood energy demands.

Chapter 4 addressed the second research question of developing a generic approach for techno-economic DES design with cost as driving objective. An MILP approach was developed for the design of energy integrated residential DES while minimising total annualised energy cost (competition). ‘Optimal’ design was here obtained through the

selection and sizing of distributed energy resources (DER) and energy interactions, from a considered pool, and siting them across neighbourhood houses. Extensive analyses were conducted to highlight model applicability and flexibility (see Section 4.5). The case-study results showed that (i) optimal design can be obtained under various scenarios, (ii) design is sensitive to energy tariffs, (iii) thresholds for technology and operational characteristics can be found, (iv) design is fairly insensitivity to sun variability, and (v) technology combination constraints can be adapted. The approach facilitates decision-making to level the playing field for DES as competitive energy supply alternatives.

Chapter 5 answered the third research question of developing an approach to design DES whilst balancing multiple stakeholder interests. The MILP model of Chapter 4 was extended to a multi-objective framework, which enabled trading off three objectives in the design process. The three central energy system objectives of competition, security of supply and sustainability were translated into design minimisation objectives of total annualised cost, electrical system unavailability and annual CO₂ emissions, respectively. Design trade-offs between objectives could be obtained for a range of weighting factors, leading to the identification of ‘knee-point’ designs. Additionally, component redundancy for systems with islanding capabilities could be analysed through on- and off-grid unavailability-cost trade-offs. This design framework ensured DES applicability within the conventional system and their relevance to governing energy policy.

The model was extended in Chapter 6 to enable analysis of identified DES regulatory framework factors, i.e. type, scale, ownership, choice, tariffs and design objectives, addressing the fourth research question. Framework factors were translated into proxies, which either provided new input parameters and allowed for parameter sensitivity analyses, changed aspects of the model structure by introducing new objectives or constraints, or, used a model output to assess the relative gain in a factor depending on the optimised configuration. The model and results highlighted that various factors impact both engineering and regulatory aspects, leading to useful discussions for decision-makers to identify ‘best’ DES designs. ‘Best’ design is here no longer a strict optimisation result but rather a trade-off of the relative importance of structural and organisational factors within a neighbourhood energy system, the governing central power system and the relative preferences and incentives of stakeholders.

7.2 Future work

The developed framework is flexible in its current formulation, serving as a starting point for further research in the field of DES design optimisation as highlighted below.

7.2.1 System aspects

The current model formulation is set up in a flexible plug-and-play manner (modular black-box) to readily include direct system changes or extensions, such as other implementation and design decisions, technologies, sectors and features. These extensions would increase degrees of freedom for a neighbourhood energy system design. Also, general model flexibility and suitability to a wide range of case-studies and neighbourhood-specific characteristics is hereby increased. Design and implementation choices – where alternatives exist – have, however, to be made at all times.

First, other technologies could be considered. These technologies can either belong to a similar pool as already implemented technologies, e.g. electric boilers. Such technologies could be readily interconnected with existing interactions and available resources (central grid and gas supply, or, sun and wind). Alternatively, new technology approaches, such as electric vehicles, could be included. Implementation of new technologies, however, presents more thought. Electric vehicles would be coupled to the electrical system but, depending on their state of charge, the time of day and their location in the neighbourhood, they would serve as either storage or generators (see e.g. [359]). Time dependence of component availability is here an important feature. The concept of electrical vehicles, i.e. ‘moveable storage’, would add dynamic degrees of freedom to DES design.

Second, technologies fuelled by resources other than the already considered, e.g. biomass, could be considered to increase resource diversification and reduce the case-study design bias towards cheap natural gas fuelled technologies in a system with high retail electricity prices. These technologies might introduce additional neighbourhood interactions and add new terms to the energy balance equations. Currently only the energy services of electricity, space heating and space cooling were balanced. Different interactions between energy services could be considered, for example, facilitated through an electric heat pump that can convert electricity into heat [360, 361]. Other energy services, including

hot water for cooking and showering, could also be included. These additional energy services could be satisfied through the consideration of energy generated by existing units or newly implemented technologies. All considered energy services systems could then also be implemented within the minimisation of overall system unavailability, similar to the electrical system approach developed in Chapter 5.

Third, a flexible design approach was employed whereby different technology combinations, design decisions and interactions could easily be enabled or disabled through relations between their relevant binary decision variables (see Table 4.6). For example, individual houses could be allowed to install both a condensing boiler and CHP unit. This could allow for smoother trade-off curves. Other implementation choices, such as enabling storage units to be charged by and discharged to external feeds (microgrid and central grid), could be included through additional variables and interactions.

Fourth, currently, continuous technology capacity intervals were employed as to not pre-restrict ‘optimal’ behaviour. Such a continuous relation could also be applied to capacity-availability to increase model accuracy (see Section 5.7). In reality only certain discrete technology capacities are available in the market at set prices. Discrete capacities could therefore be implemented to reflect available technology models. Appendix F included an example of how discrete CHP capacities with different total costs could be included. Small-scale technologies, in particular, additionally experience strong non-linear economies-of-scale. This behaviour was already analysed in Chapter 6 for CHP units, but could be expanded to more technologies to assess its impact on design.

Last, DES design models are inherently complex. Hence, they require a trade-off between model accuracy and complexity [82, 92, 104, 240] (see Section 2.4.2). This trade-off is especially required in determining the spatial, temporal and detail scales of the model:

- The boundaries of the system, its layout and number and type of consumers, determine its spatial scale. Considering a larger neighbourhood, upstream services (e.g. natural gas networks) and larger central technologies of multiple types (e.g. wind turbines) increases model degrees of freedom and applicability but at the expense of increased complexity. The number of variables, namely, increases significantly with each additional house, leading to increased computational efforts. Additionally, the more degrees of freedom, the more neighbourhood energy system

designs are available within a close objective range from each other, slowing down the solution process. Section 5.6.2.1 already illustrated this behaviour for larger neighbourhoods. Alternative model formulations or optimisation approaches might here provide solutions (see Section 7.2.2).

- Currently, an hourly temporal scale was employed for a typical day in each season over a yearly planning horizon. Combining several hours into time periods (coarser time scales) reduces model complexity but also accuracy. These coarse scales could miss peak demand behaviour and renewable energy input or storage behaviour [104]. More detailed time scales, in contrast, could capture operational behaviour, but increase complexity with each smaller time interval. The choice of time step for the specific modelling goal is therefore important. The impact of varying time scales on results could here provide additional insight. Furthermore, time dependent parameters, such as tariffs, will increase model flexibility and ability to start incorporating dynamic behaviour (see Section 7.2.2).
- A superstructure high-level approach was employed, which implied simplifying and linearising detailed thermodynamic and electrical interactions and non-linear behaviour. More detail on each of these levels increases model accuracy but also complexity. System reality thus presents various practical implementation issues [130].

7.2.2 Model aspects

DES design problems involve not only multiple alternative configurations and design constraints but also uncertainties related to model design, analysis and interpretation of results [91]. DES design is therefore inherently a complex integrated cross-disciplinary and multi-objective problem. Optimising energy system designs involves determining the meaning of ‘optimality’ within this context and what most suitable designs for a researched consumer area would look like. As highlighted throughout the thesis and in Appendix F, optimised designs depend on the chosen optimality level. In the presented case-study there are a whole range of ‘acceptable designs’ that lie within 10 % of the optimal objective value, but might be more preferred by involved stakeholders. Looking for near-optimal solutions through cut-set based techniques, as already instigated by Voll et al. [90, 228], provides opportunities to expand the developed framework with the option of comparing multiple ‘equivalent’ designs.

Deterministic optimisation approaches were employed throughout the thesis. DES experience in reality, however, non-linear behaviour (see Section 3.2.1), issues with data and output availability, uncertainty and prediction, and have to take into account multiple stakeholder interests, which introduces complexity;

First, the employed superstructure approach puts scale boundaries on the researched system, requiring simplification and linearisation of real system behaviour. Explicitly taking into account non-linear behaviour allows to analyse the impact of employed assumptions on results but makes the model non-linear (e.g. MINLP, see Section 6.6.2.2), requiring non-linear optimisation techniques.

Second, deterministic approaches do not account for unpredictability of input parameters. Renewable energy resources, especially, can exhibit significant uncertainty. This uncertainty can be analysed either through thorough parameter sensitivity analyses in deterministic models or through stochastic modelling approaches [104]. Energy demands also experience uncertainty with regard to peaks and volatility. Each household behaves differently and, depending on the weather, extreme peak demand events can occur, which are not accounted for through hourly average demands. Either more refined time scales need to be employed – especially when looking more into the operational or control side – or stochastic optimisation approaches.

Last, three different objectives have already been taken into account. Each of the already employed objectives could be formulated differently (see Section 5.7). Additionally, other social, technical and sustainable objectives could be added. More than three objectives would, however, require a reconsideration of the employed optimisation tool, where NSGA-II or SPEA2 could be more suitable. Moreover, DES encompass dynamic operational behaviour, such as demand side management and real-time control, that allows data forecasting and enables implementing flexibility at generation and demand levels. Integrating this behaviour would, however, require dynamic modelling approaches.

7.2.3 Future directions

DES optimisation has experienced a strong focus on specific techno-economic issues. DES integration into the wider energy system and the inclusion of social aspects are to date still under-represented. The latter are, however, important to ensure adequate

DES design that fits into the broader energy system. In addition to cross-disciplinary DES design decision-making approaches subject to several objectives (as presented in this thesis), other research is still required to enable DES viability;

First, without social acceptance and willingness of consumers to adopt DES technologies or take up agreements with their neighbours, DES will not be adopted. Additionally, home ownership (rental or owned property), consumer flexibility, regulatory barriers and local government play an important role to initiate this acceptance.

Second, DES interact with different sectors beyond the energy services they provide. These include, transportation, resource supply chains and manufacturing of technologies. Uncertainty, underdevelopment and interruptions in these areas will influence DES design and uptake. Note here that DES are put forward as energy entities with high energy efficiency levels and low local emissions. Their components (e.g. PV units), however, experience a whole life cycle with potential environmental impacts. Life cycle assessment is therefore an important upcoming area of research (e.g. [185]).

Third, DES dynamic interactions are in reality not blindly followed by participating consumers as each consumer has specific personal interests. To facilitate DES operation, research is still required regarding internal DES energy markets, including game theory and pricing (e.g. [86, 87]), interactions between DES and the central market (e.g. multi-DES [70]), and cost-benefit analyses of investors and participating consumers.

Fourth, localised energy systems require communication technology in order to optimise their behaviour [40, 41]. Apart from technological development challenges of complex communication and data networks, large amounts of real-time consumer data needs to be collected for control and forecasting. This data could be valuable for various commercial purposes. Issues arise here with the collection, storage and protection of data and consumer privacy, which could be alleviated through standardised protocols.

Last, national and regional energy systems require transitions to deal with the challenges they experience (see Section 1.1.1). These transitions involve long-term planning and forecasting. Two research streams are here being considered. Larger, more interconnected electricity systems are being proposed that include large renewable energy units interconnected and balanced across a broad (even continental) region through electricity highways [362]. At the same time, more energy integrated localised systems are being

proposed [363]. Also combining electricity with thermal energy provision within distributed or district energy systems is being investigated. The question then arises how these two trends could be integrated, and who will pay for central system upgrades when consumers will become more concentrated and self-sufficient in small localised systems. The consensus is that an energy system transition will and has to happen. The direction of this transition and the required technological, economic, regulatory and social developments still present exciting and topical fields of future research.

7.3 Conclusion

Localised distributed energy systems (DES) are increasingly presented as solutions to conventional power system challenges. However, for DES to become viable, a novel cross-disciplinary design approach is required that encompasses multiple stakeholder interests. This thesis addressed this need through developing a flexible multi-objective decision-making framework for DES design, from an engineering and regulatory perspective, using mixed-integer linear programming techniques. The following main contributions to the work in the field of DES design optimisation have been made:

- an MILP model for cost-optimal residential energy system design was developed;
- the developed MILP model was extended to a multi-objective approach reflecting three central energy system objectives, and
- regulatory framework factors were included in the developed model, enabling analyses of relations between engineering and regulatory DES design aspects.

The model has been applied to a small South Australian neighbourhood to illustrate DES design decision-making within conventional power systems generally.

List of Communications

This Section summarises a list of publications and presentations that arose from the work in this thesis.

Peer-reviewed journal papers

C. Wouters, E.S. Fraga, A.M. James, 2016. ‘A multi-objective framework for cost-unavailability optimisation of residential distributed energy system design’. (Under review)

C. Wouters, E.S. Fraga, A.M. James, 2015. ‘An energy integrated, multi-microgrid, MILP (mixed-integer linear programming) approach for residential distributed energy system planning – A South Australian case-study’, *Energy* 85(1):30-44.

C. Wouters, 2015. ‘Towards a regulatory framework for microgrids—The Singapore experience’, *Sustainable Cities and Society*, 15:22-32.

K. B. H. Van Hende and **C. Wouters**, 2014. ‘The Regulation of Microgrids in Liberalized Electricity Markets in the EU and East Asia’, *European Networks Law and Regulation Quarterly*, 3:190-204.

Peer-reviewed conference proceedings

C. Wouters, E.S. Fraga, A.M. James, 2016. ‘Residential microgrid design optimisation under uncertain μ CHP characteristics’, *Computer Aided Chemical Engineering*, Vol. 38, pp.1491-1496. ESCAPE, Portorož, Slovenia.

C. Wouters, E.S. Fraga, A.M. James, 2015. ‘MILP approach for the design of residential microgrids with energy interaction restrictions’, *Computer Aided Chemical Engineering*, Vol. 37, pp.2357-2362. ESCAPE/PSE, Copenhagen, Denmark.

C. Wouters, E.S. Fraga, E.M. Polykarpou, A.M. James, 2014. ‘Mixed-integer optimisation based approach for design and operation of distributed energy systems’, *In transactions of: Australasian Universities Power Engineering Conference (AUPEC)*, September 28 - October 1, Perth, Australia, IEEE.

Other publications

C. Wouters and K. Van Hende, 2015. ‘The role of microgrids within future regional electricity markets’, ICER Distinguished Scholarly Award.

C. Wouters, C. Vigar and K. Van Hende, 2015. ‘Increasing consumer choice – The potential impact of prosumers on electricity market regulation’, *ICER Chronicle*, March 2015, Edition 3.

Conference presentations

C. Wouters, E.S. Fraga, A.M. James, 2017. ‘A policy-based multi-objective optimisation framework for residential distributed energy system design’, World Renewable Energy Congress XVI 2017, February 5-9, Perth, Australia. (Accepted)

C. Wouters, E.S. Fraga, A.M. James, 2016. ‘Regulatory frameworks for prosumer-based energy systems’, Energy Networks Conference 2016, May 18-20, Adelaide, Australia.

C. Wouters and K. Van Hende, 2015. ‘The integration of microgrids in future regional electricity markets’, World Forum on Energy Regulation (WFER) 2015, May 25-28, Istanbul, Turkey.

C. Wouters, E.M. Polykarpou, E.S. Fraga, 2013. ‘Optimal design of a microgrid: A case study in South Australia’, All-Energy Australia 2013, October 8-10, Melbourne, Australia.

Appendix A

Details of literature review

This Appendix details how the extensive literature review of previous DES design optimisation research has been conducted in support of Figure 1.4, Chapter 1 and Section 2.3, Chapter 2. In the first instance, a targeted literature search has been conducted in the Scopus database search engine¹ in support of Chapter 2. The search in Scopus was conducted with the following search term logic condition code:

*TITLE-ABS-KEY(("district energy system" OR "multi*generation" OR "multi*energy" OR "poly*generation" OR "poly*energy" OR "integrated energy system" OR "distributed energy system" OR "distributed generation system" OR "micro*grid" OR "energy hub" OR "tri*generation" OR "co*generation" OR "distributed energy resource*" OR CHPC OR CCHP OR CHCP OR CHP OR "hybrid energy system" OR "renewable energy system" OR "sustainable energy system" OR "Distributed energy center" OR "sustainable energy planning" OR "distributed*generation facilities" OR "district energy planning" OR "distributed energy planning") AND ("micro*grid" OR district OR community OR city OR "*town" OR residential OR urban OR neighbourhood OR area OR domestic OR village OR building OR "small*scale" OR "house*" OR "dwelling") AND (planning OR plan OR sizing OR siting OR design OR architecture OR topology OR selection OR allocation OR mix OR retrofit OR configuration OR combination OR synthesis) AND ("optim*" OR programming) AND NOT ("Voltage rise" OR "Test bus" OR "Reactive power" OR "Hierarchical control" OR "Frequency control" OR "Frequency management" OR "Feeder" OR "Circuit" OR "Power quality" OR Inverter OR converter OR Enthalpy OR exergy OR propulsion OR simulation OR "fluid dynam*" OR axis OR convection OR "steel*" OR furnace OR "super*critical" OR polymer OR rankine OR*

¹<http://scopus.com/>

*ventilation OR mill OR laser OR "*dish" OR desalination OR kinetic OR glazing OR insulation OR insulator OR shading OR "power cycle" OR "superheat*" OR expander OR vane OR piston OR "heat flux" OR "mass transfer" OR "heat resistance" OR IEEE OR inverter))*

This keyword combination focussed on design optimisation whilst eliminating detailed electrical or thermodynamic analysis not related to (superstructure) design optimisation. On 14 July 2016 this search gave 1155 hits among which 1033 written in the English language. This English-based set included: articles (570), conference papers (371), review papers (29), articles in press (29), conference reviews (18), books (4) and book chapters (9). The search for Chapter 2 was narrowed down to only include peer-reviewed academic journal articles and articles in press (599). This latter set was then manually and iteratively reviewed based on scope and categorised based on the themes set out in Section 2.3, Chapter 2. The literature results of this search have been complemented throughout the thesis with other found research works from more targeted searches in the field of DES design optimisation.

Figure 1.4 in Chapter 1 was constructed based on the search term combination without specifying optimisation aspects: *TITLE-ABS-KEY(("district energy system" OR "multi*generation" OR "multi*energy" OR "poly*generation" OR "poly*energy" OR "integrated energy system" OR "distributed energy system" OR "distributed generation system" OR "micro*grid" OR "energy hub" OR "tri*generation" OR "co*generation" OR "distributed energy resource*" OR CHPC OR CCHP OR CHCP OR CHP OR "hybrid energy system" OR "renewable energy system" OR "sustainable energy system" OR "Distributed energy center") AND (district OR community OR city OR "*town" OR residential OR urban OR neighbourhood OR area OR domestic OR village OR building OR "small*scale" OR "house*" OR "dwelling" Or "industr*")) AND NOT (health OR mirror OR "immun*" OR "community health plan*" OR "charcoal hemoperfusion" OR projection OR "neuro*" OR "anion" OR "ion" OR "electron" OR "proton"))*

On 14 July 2016 this search gave 14050 hits among which 12822 written in the English language. This English-based set included: articles (5814), conference papers (5552), review papers (440), articles in press (139), conference reviews (288), books (57) and book chapters (175). For Figure 1.4 this was limited to peer-reviewed academic journal/conference articles/reviews and articles in press, i.e. 12233 hits.

Appendix B

Distributed energy technologies

This Appendix details and summarises the energy conversion behaviour of the technologies considered within the design model.

B.1 Absorption chiller

The general energy conversion principle of absorption chillers is similar to vapour compression chillers, but the mechanical compressor (pump) is here replaced by a ‘thermochemical compressor’, i.e. heat, to increase the pressure of the refrigerant [364, 365]. An absorption chiller has a refrigerant (e.g. water) and an absorbent (e.g. lithium-bromide solution) with a high affinity for each other. First, through boiling/evaporating the refrigerant in a low pressure environment by taking away the heat of the circulating working fluid for cooling (e.g. water at ambient temperature), the cooling effect is provided. This cooled working fluid (water) could be used in a pipeline network for space cooling. Since the refrigerant is evaporated in a low pressure environment, its boiling point is low. Second, the evaporated refrigerant (gaseous) will be mixed with an absorbent liquid. A pump will subsequently increase the pressure of the mixture and feed it to a generator. Third, the refrigerant-saturated liquid is heated (by low grade waste heat by CHPs), causing the refrigerant to evaporate out. This process separates out the absorbent ready for the next cycle. The refrigerant is subsequently condensed to repeat the cycle. The number of times heating is used within the cycle determines the type of process; single-, double- or triple-effect. Single-effect is the most simple and therefore most employed design [364].

B.2 Air-conditioning unit

Air-conditioning units are electrical compression chillers, which use chemicals to convert fluids between phases [364]. Three main components are installed as part of the system, i.e. a compressor, a condenser and an evaporator [366]. An airco has an outside unit that consist of a condenser and compressor, and an inside unit that is used for evaporation. A chemical working fluid interacts with the in- and outside components to extract heat from the inside air and release this to the outside air. The electrically driven compressor increases the pressure and temperature of the gaseous chemical. The chemical is then transferred to a condenser (radiator fins) leaving the condenser as a high pressure cooler chemical. The liquid chemical is then fed into the evaporator through a tube with a big drop in diameter, reducing the pressure of the chemical. The latter will instigate evaporation of the chemical into a gaseous form. Evaporation requires heat, which is extracted from the inside air, cooling the air inside. A fan circulates the cooled air in the room that requires cooling. After the evaporation stage, the chemical has a cool gaseous low pressure form and is returned to the compressor.

B.3 Cold thermal storage

Cold thermal storage systems are thermally insulated tanks that can come in various forms, including based on chilled water or ice as working fluid [367]. These systems receive a cold working fluid from a chiller (e.g. absorption chiller), which is stored in a storage tank from where the fluid can be retrieved for cooling purposes. In chilled water based systems, water is typically stored in vertically stratified layers at 4 to 6 degrees Celsius. The layers makes sure the coldest water is at the top of the tank and the bottom has a slightly higher temperature. Discharging the tank will take out water at the bottom of the tank for cooling use. The temperature difference across the tank determines the cooling capacity of the system. Ice storage systems also employ water as working fluid but take advantage of a phase change to ice to obtain higher storage capacities. (i.e. latent heat is removed by transforming liquid water to ice).

B.4 Combined heat and power unit

Various types of small-scale CHP units exist, e.g. micro-turbines, fuel cells or Stirling engines [364, 365]. CHP units generate electricity and waste heat simultaneously. Micro-(gas)turbines are smaller scale types of combustion engines, typically fuelled by natural gas (Brayton cycle). Gas is compressed and heated up by going through a compressor (isentropic compression). This compressed gas is then combusted in the combustion chamber (isobaric combustion) and then expanded within a turbine (isentropic expansion). The gas expansion will move the blades of a turbine leading to electricity generation through rotation within a generator (changing magnetic field induces an electric current). Waste heat (hot exhaust gas) from the process is recovered for heating purposes. A Stirling engine can be fuelled by various energy resources, such as natural gas, and is based on an piston engine where a medium (e.g. helium or hydrogen) is cycled. A fixed amount of gas of which the pressure is changed through an ignition, causes a piston to expand and contract which leads to a rotation of a shaft used for electricity generation. Several types of Stirling engines exists based on the number of pistons. Fuel cells, in contrast, have no moving parts but generate electricity and heat through a chemical reaction of hydrogen and oxygen.

B.5 Condensing gas boiler

A boiler is fuelled by natural gas, received from a natural gas main [368]. Gas is burned in the boiler. Hot gas will heat up water (flows through copper pipes) through a heat exchanger. Hot water is then pumped around a house through radiators. Radiators consist of multiple bended loops to maximise transfer heat from the hot water inside the pipes to the outside air.

B.6 Electrical battery storage

Batteries have three main components, i.e. an anode, a cathode and an electrolyte, that enable them to convert chemical energy into electrical energy [369]. The anode and cathode are made from different metallic materials and are connected by a conducting wire to form an electrical circuit that can drive appliances. The anode and cathode are also interconnected by a chemical electrolyte that facilitates flows of electrons between

cathode and anode. By discharging the battery, a chemical reaction occurs whereby the anode releases electrons that are attracted by the cathode (oxidation reaction). This introduces a charge difference between anode and cathode, causing a current in the conducting wire between anode and cathode. Charging a battery will reverse the flow of electrons, resetting the anode and cathode to enable another discharging process.

B.7 Gas heater

Gas heaters work similarly to gas condensing boilers but heat generated by combustion of natural gas is now used to heat up air through a radiator/heat exchanger rather than heating up a working fluid, such as water, in a central heating system [370].

B.8 Hot thermal storage

Hot thermal water storage tanks are similar to cold thermal water storage tanks. These systems receive a hot working fluid from a heater (e.g. waste heat from co-generation unit is used to heat up water), which is stored in a storage tank between 25 and 90 degrees Celsius (mostly around 60 degrees Celsius) from where the fluid can be retrieved for heating purposes [371]. In heated water based systems, water is typically stored in vertically stratified layers. The latter makes sure the hottest water is at the top of the tank and the bottom has a slightly lower temperature. Discharging the tank will take out water at the bottom. The temperature difference across the tank determines the heating capacity of the system.

B.9 Microgrid central control unit

Within a microgrid, each electricity generation unit has a power electronic interface [40, 41]. Power electronics, such as found in converters and inverters, are electronic circuits that consist of switches that can control the flow of electricity. Power electronics can ensure local balancing of supply and demand through a system architecture that has three main components (i) controllers of the DG units, (ii) a system optimiser, and (iii) protection schemes. Each feeder, within the microgrid electrical networks, has circuit breakers and power flow controllers for safety and balancing. A power flow controller

can regulate the the flow of power through the various cables to a level specified by the operator or manager of the system. Several types of DG controllers exist, e.g. basic control of real and reactive power, voltage regulation through droop, and frequency droop for power sharing. Controllers respond to requirements within milliseconds, using information of current and required system states, to control generation units at all times. Here, communication between generation units is required to exchange data to enable control actions. Typical DG controller inputs in this case are steady-state power output and local bus voltages. A local system manager ensures system optimisation through information of local demands, power and voltage requirements, costs, etc. to determine power flows between consumers and the amount of electricity imported or exported from and to the distribution grid.

B.10 Photovoltaic panel

Photovoltaic panels (PV) convert sunlight to electricity [372]. PV panels are made up of (semi-conductor) materials that have the photoelectric effect. The latter enables materials to release electrons by absorbing sunlight photons. Capturing of these electrons enables an electric current. PV panels consist of solar cells that are made of semi-conductor materials (e.g. silicon). These semi-conducting materials are made into very thin wafers that are treated to be charged differently on either side. Conducting wires attached to the semi-conductors will then enable a current when sunlight releases electrons from the semiconductor atoms. The current thus directly depends on the solar irradiation that reaches the cell. A PV module consists of a number of these solar cells combined in a module. A solar array combines a certain number of PV modules. PV units generate DC electricity, which can be converted into AC through an inverter.

B.11 Thermal pipelines

Pipeline networks receive hot or cold thermal energy in the form of water as working fluid [373]. Its system is similar to central heating for individual houses but on a larger scale. Hot water is generated by, for example, co-generation units. This water is transferred through a large network to individual consumer premises. Due to the large

size, storage and pumps are required within the network to maintain pressure and temperature. Hot water used for central heating in premises is then returned to the return pipeline network, which is fed back to the heat generator for reheating and recirculation.

B.12 Wind turbine

Wind turbines convert the mechanical energy of the wind in electricity [374]. The blades of a turbine will turn with the wind speed. Blades are connected to a shaft, which will turn with the speed of the turbine blades. The shaft is connected to a generator, which generates electricity based on the principles of electro-magnetism (a changing magnetic field induces an electric current.)

Appendix C

CPLEX solver

This Appendix details and summarises the solution approach of the CPLEX solver. The CPLEX solver employs a branch and bound approach for problems with integer variables, as detailed by IBM [246]. The explanation by IBM [246] is summarised here. The feasible solution space is divided into hierarchically, continually restricted, sub-problems (*branching*) referred to as nodes of a *search tree*, see Figure C.1. Objective bounds are obtained for each sub-model (*bounding*). Each search tree sub-problem node is analysed through its obtained bounds, which are used to remove sub-problems (nodes) from the solution space (*fathoming*). Bounds are obtained through *relaxation* of the analysed sub-problem.

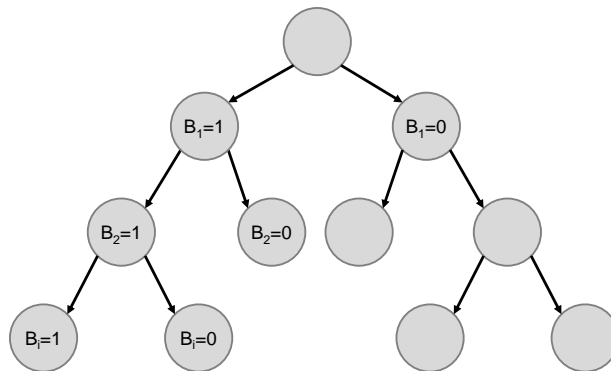


FIGURE C.1: Branch and bound search tree method, adapted from IBM [246].
 B_i =binary variable.

The process starts at the top/root node of the tree. This top node has the relaxed integer program as associated sub-problem. Its solution is either an optimal integer solution, but more commonly, a solution with some fractional-valued integer variables. The solution to the latter is obtained through additional constraints that tighten the

feasible region, *cutting planes* or heuristic algorithms. One fractional-valued integer variable is then chosen to form two new sub-problems through *branching*. A binary branching variable will create a sub-problem for each of its values, 1 or 0, leading to two new child nodes. The branching process continues if these sub-problems also lead to fractional-valued integer variables, creating a solution tree. The branching process is stopped if the sub-problem of a node either has:

- no fractional-valued integer variables, i.e. a feasible solution to the original problem. If the obtained optimal solution is superior to any previously obtained feasible solution, it is used as new reference point for future solutions, or,
- no feasible solution or an optimal solution that is inferior to a certain reference value. Child sub-problems of this node would be even more inferior than the reference or also infeasible, resulting in fathoming of the node and its sub-problems.

Sub-problems become more constrained at each branching step, leading to increased possibility of fathoming. The search tree will remain contained in size as long as the branching process is not much faster than the fathoming process. The process finishes if no active nodes are left, returning the proven optimal solution that results from the reference objective values set throughout the process.

Appendix D

Additional model equations of Chapter 4

This Appendix details and summarises model equations in support of the developed cost-optimal DES design model of Chapter 4. The model consists of an objective function bound by design and operational constraints of the available technologies, energy interaction constraints, and energy balances. First, the terms of the objective function are detailed, followed by additional technology design and operational behaviour as well as energy interactions. The developed cost minimisation model builds further on efforts by Mehleri et al. [95, 96], as was detailed in Section 4.2.4. The work in this Appendix has been included in publications [247–250, 281].

D.1 Terms of the objective function

The neighbourhood investment cost, C^{INV} [AUD y^{-1}], sums the annualised investment costs of the selected and installed technologies. Technology (*tech*) investment cost consists of a capital cost, C_{tech}^C , multiplied with either a pre-set installed capacity parameter and a binary selection variable ($B_{tech,i}$) for each house i (for units with discrete capacity), or, an optimised capacity variable $DG_{tech,i}^{MAX}$ (for units with a capacity range). In case of PV units, the optimised capacity is determined through an optimised surface area A_i^{PV} [m^2] multiplied with a rated capacity PV_{rat} [$kW_{peak} m^{-2}$]. A unit-specific capital recovery factor, CRF_{tech} annualises costs. The considered technologies are CHP units (*CHP*), PV units (*PV*), small-scale wind turbines (*WT*), thermal and electrical storage (*techST*), thermal technologies (*techTH*), i.e. the condensing boilers, gas heaters,

air-conditioning units and absorption chillers, hot and cold thermal pipelines (p), a microgrid central control unit ($MGCC$) and potential electrical dump loads ($dump$):

$$\begin{aligned}
C^{INV} = & \sum_i CRF_{CHP} \cdot C_{CHP}^C \cdot DG_{CHP,i}^{MAX} + \sum_i CRF_{PV} \cdot C_{PV}^C \cdot A_i^{PV} \cdot PV_{rat} \\
& + \sum_i CRF_{WT} \cdot C_{WT}^C \cdot B_{WT,i} \cdot WT_{rat} + \sum_{techST} \sum_i CRF_{techST} \cdot C_{techST}^C \cdot DG_{techST,i}^{MAX} \\
& + \sum_{techTH} \sum_i CRF_{techTH} \cdot C_{techTH}^C \cdot DG_{techTH,i}^{MAX} + \sum_{i \neq j} \sum_j CRF_p \cdot C_p^C \cdot YP_{i,j} \cdot l_{i,j} \\
& + CRF_{MGCC} \cdot C_{MGCC}^C \cdot Z + CRF_{dump} \cdot C_{dump}^C \cdot Pdl_i^{MAX} \tag{D.1}
\end{aligned}$$

The yearly operation and maintenance cost, C^{OM} [AUD y^{-1}], includes fixed (C_{tech}^{omf}) and variable (C_{tech}^{omv}) contributions of the selected and implemented technologies. The fixed contribution is based on installed capacity and only applies to certain technologies, for example, annual cleaning and maintenance of PV units. The variable contribution relates to regular maintenance based on yearly usage. The variable cost of the operation of all technologies is included as well as the fixed cost of the PV units, wind turbines, batteries (EST) and pipelines (p). d_s represents the number of days in each season s . Note that the capacity unit for batteries is kWh.

$$\begin{aligned}
C^{OM} = & \sum_{tech} \sum_i \sum_s \sum_h hr \cdot d_s \cdot C_{tech}^{omv} \cdot PE_{tech,i,s,h}^{TOT} + \sum_i C_{PV}^{omf} \cdot PV_{rat} \cdot A_i^{PV} \\
& + \sum_i C_{WT}^{omf} \cdot WT_{rat} \cdot B_{WT,i} + \sum_i C_{EST}^{omf} \cdot DG_{EST,i}^{MAX} + \sum_{i \neq j} \sum_j l_{i,j} \cdot C_p^{omf} \cdot YP_{i,j} \tag{D.2}
\end{aligned}$$

Natural gas fuels both the heat generating technologies ($techH$), i.e. boilers and gas heaters, as well as CHP units. Operating these technologies thus attracts a yearly fuel cost, C^{FUEL} [AUD y^{-1}], at the prevailing gas tariff (T^{gas}). For thermal technologies, the fuel cost is associated with heat generated throughout the year ($PH_{techH,i,s,h}^{TOT}$) and their thermal efficiency (n_{techH}^{th}). For CHP units the fuel cost is associated with electricity generated throughout the year ($PE_{CHP,i,s,h}^{TOT}$) and their electrical efficiency (n_{CHP}^{elec}).

$$C^{FUEL} = \sum_{techH} \sum_i \sum_s \sum_h hr \cdot d_s \cdot [PH_{techH,i,s,h}^{TOT} \cdot \frac{T^{gas}}{n_{techH}^{th}} + PE_{CHP,i,s,h}^{TOT} \cdot \frac{T^{gas}}{n_{CHP}^{elec}}] \tag{D.3}$$

Each house can purchase electricity from the central grid to complement local generation. The annual electricity import cost, C_{BUY}^{GRID} [AUD y^{-1}], depends on the prevailing

electricity tariff (T^{elc}) and the electricity purchased throughout the year ($PE_{i,s,h}^{GRID}$):

$$C_{BUY}^{GRID} = \sum_i \sum_s \sum_h hr \cdot d_s \cdot T^{elc} \cdot PE_{i,s,h}^{GRID} \quad (D.4)$$

A carbon tax, C^{CT} [AUD y^{-1}], can be directly imposed on the neighbourhood on an annual basis. The tax depends on the prevailing tariff (T^{ct}), the imported electricity as well as the natural gas consumed on-site by the boilers (B), gas heaters (G) and CHP units. The carbon intensities of the grid (CI_{elc}) and natural gas (CI_{gas}) are included.

$$C^{CT} = \sum_i \sum_s \sum_h T^{ct} \cdot hr \cdot d_s \cdot [CI_{elc} \cdot PE_{i,s,h}^{GRID} + CI_{gas} \cdot \sum_{techH} \frac{PH_{techH,i,s,h}^{TOT}}{n_{techH}^{th}} + CI_{gas} \cdot \frac{PE_{CHP,i,s,h}^{TOT}}{n_{CHP}^{elec}}] \quad (D.5)$$

In addition, locally generated DG ($techDG$) electricity can be exported ($PE_{techDG,i,s,h}^{SAL}$) at the prevailing feed-in tariffs in the market (T_{techDG}^{SAL}), leading to an annual income, C_{SAL}^{GRID} , for the neighbourhood:

$$C_{SAL}^{GRID} = \sum_{techDG} \sum_i \sum_s \sum_h hr \cdot d_s \cdot T_{techDG}^{SAL} \cdot PE_{techDG,i,s,h}^{SAL} \quad (D.6)$$

D.2 Technology design and operational constraints

Several pools of technologies are implemented as detailed below.

D.2.1 Thermal energy technologies

Thermal technology ($techTH$) capacities, i.e. boilers, gas heaters, air-conditioning units and absorption chillers, are bound. Each technology also has a dedicated binary selection variable to decide on the installation of a unit in a house ($B_{techTH,i}$). Thermal technologies generate either heat (H and $techH$), $PH_{techH,i,s,h}^{TOT}$ [kW], or cooling (C and $techC$), $PC_{techC,i,s,h}^{TOT}$ [kW]. The generated thermal power is bound by upper (U_{techTH}) and lower bounds (L_{techTH}) on the installed capacity ($DG_{techTH,i}^{MAX}$) of the unit:

$$L_{techTH} \cdot B_{techTH,i} \leq DG_{techTH,i}^{MAX} \leq U_{techTH} \cdot B_{techTH,i} \quad \forall techTH, i \quad (D.7)$$

$$PH/C_{techTH,i,s,h}^{TOT} \leq DG_{techTH,i}^{MAX} \quad \forall techTH, i, s, h \quad (D.8)$$

Heat generated by boilers, $PH_{B,i,s,h}^{TOT}$, and cooling generated by absorption chillers, $PC_{AC,i,s,h}^{TOT}$, can be divided in a part for self use (*SELF/Load*) by the accommodating house and a part for thermal storage (*STO*). The absorption chiller can also provide cooling for cold thermal pipeline transfer to other houses (*Pipe*).

$$PH_{B,i,s,h}^{TOT} = PH_{B,i,s,h}^{Load} + PH_{B,i,s,h}^{STO} \quad \forall i, s, h \quad (D.9)$$

$$PC_{AC,i,s,h}^{TOT} = PC_{AC,i,s,h}^{Load} + PC_{AC,i,s,h}^{STO} + PC_{AC,i,s,h}^{Pipe} \quad \forall i, s, h \quad (D.10)$$

D.2.2 Distributed generation technologies

PV unit operation, $PE_{PV,i,s,h}^{TOT}$, is bound by available average solar irradiation on a tilted surface in each hour ($It_{s,h}$ [kW m⁻²]), a rated capacity (PV_{rat} [kW_{peak} m⁻²]) and an electrical efficiency (n_{PV}^{elec}). Country specific regulation can place upper bounds on the maximum allowed installed capacity (U_{PV}) as well as daily electricity export ($PE_{PV,i,s,h}^{SAL}$) limits (U_{PV}^{export}) of residential PV units.

$$PE_{PV,i,s,h}^{TOT} \leq \min(A_i^{PV} \cdot PV_{rat}; A_i^{PV} \cdot It_{s,h} \cdot n_{PV}^{elec}) \quad \forall i, s, h \quad (D.11)$$

$$A_i^{PV} \leq U_{PV} \quad \text{and} \quad \sum_h hr \cdot PE_{PV,i,s,h}^{SAL} \leq U_{PV}^{export} \quad \forall i, s \quad (D.12)$$

Wind turbine electricity, $PE_{WT,i,s,h}^{TOT}$, is bound by the available wind speed in each hour ($V_{s,h}$ [m s⁻¹]), a rated capacity (WT_{rat} [kW]) and a binary variable ($B_{WT,i}$). Turbines are characterised by a cut-in (V_{CI}), a rated (V_R) and a cut-out (V_{CO}) wind speed [m s⁻¹] [251, 375, 376]. Furthermore, their power output is modelled following a Weibull distribution with a shape parameter, kw (see Appendix E) [251, 252]:

For $V_{CI} \leq V_{s,h} < V_R$:

$$PE_{WT,i,s,h}^{TOT} = WT_{rat} \cdot B_{WT,i} \cdot \frac{V^{kw} - V_{CI}^{kw}}{V_R^{kw} - V_{CI}^{kw}} \quad \forall i, s, h \quad (D.13)$$

For $V_R \leq V_{s,h} < V_{CO}$:

$$PE_{WT,i,s,h}^{TOT} = WT_{rat} \cdot B_{WT,i} \quad \forall i, s, h \quad (D.14)$$

For $V_{CO} \leq V_{s,h} < V_{CI}$:

$$PE_{WT,i,s,h}^{TOT} = 0 \quad \forall i, s, h \quad (D.15)$$

and

$$PE_{WT,i,s,h}^{TOT} \leq WT_{rat} \cdot B_{WT,i} \quad \forall i, s \quad (D.16)$$

Electricity generated by CHP units, $PE_{CHP,i,s,h}^{TOT}$ [kW], is bound by upper (U_{CHP}) and lower levels (L_{CHP}) on its capacity ($DG_{CHP,i}^{MAX}$) and a binary variable ($B_{CHP,i}$):

$$L_{CHP} \cdot B_{CHP,i} \leq DG_{CHP,i}^{MAX} \leq U_{CHP} \cdot B_{CHP,i} \quad \forall i \quad (D.17)$$

$$PE_{CHP,i,s,h}^{TOT} \leq DG_{CHP,i}^{MAX} \quad \forall i, s, h \quad (D.18)$$

Waste heat recovered from CHP electricity generation, based on a heat to electricity ratio (HER), can be used for space heating purposes ($PH_{CHP,i,s,h}^{HEAT}$) or fuel a heat driven cooling generation unit for space cooling purposes ($PH_{CHP,i,s,h}^{COOL}$):

$$PE_{CHP,i,s,h}^{TOT} \cdot HER = PH_{CHP,i,s,h}^{HEAT} + PH_{CHP,i,s,h}^{COOL} \quad \forall i, s, h \quad (D.19)$$

The portion used for heating ($PH_{CHP,i,s,h}^{HEAT}$) can meet the space heating load of the accommodating house ($Load$), can be stored in a hot water tank of the accommodating house (STO) or can be transferred through the hot thermal pipeline network to meet the space heating demands of other houses ($Pipe$):

$$PH_{CHP,i,s,h}^{HEAT} = PH_{CHP,i,s,h}^{Load} + PH_{CHP,i,s,h}^{STO} + PH_{CHP,i,s,h}^{Pipe} \quad \forall i, s, h \quad (D.20)$$

The heat generated for cooling purposes ($PH_{CHP,i,s,h}^{COOL}$) fuels the absorption chiller, which generates cooling ($PC_{AC,i,s,h}^{TOT}$) related to its coefficient of performance (n_{AC}^{th}):

$$PH_{CHP,i,s,h}^{COOL} \cdot n_{AC}^{th} = PC_{AC,i,s,h}^{TOT} \quad \forall i, s, h \quad (D.21)$$

Electricity generated by DG units, $PE_{techDG,i,s,h}^{TOT}$ [kW], can be used to meet the electricity load of their accommodating house ($SELF$), to export to the grid (SAL), to circulate through the microgrid to meet part of the electricity demand of other neighbourhood houses ($CIRC$) or to store in the battery of their accommodating house (STO):

$$PE_{techDG,i,s,h}^{TOT} = PE_{techDG,i,s,h}^{SELF} + PE_{techDG,i,s,h}^{SAL} + PE_{techDG,i,s,h}^{CIRC} + PE_{techDG,i,s,h}^{STO} \quad \forall techDG, i, s, h \quad (D.22)$$

Additionally, self-generated electricity by DG units can be dumped, $Pdl_{i,s,h}$, in a dump load installed in a house, bound by an upper level (U_{dump} [kW]):

$$Pdl_{i,s,h} \leq U_{dump} \quad \forall i, s, h \quad (D.23)$$

D.2.3 Storage units

Storage units are modelled based on a daily roll-over including seasonal independence. Thermal heating or cooling power stored in respective storage tanks, $PS_{i,s,h}^{STO}$ [kW], is a function of the power stored in the previous hour minus a static loss percentage (ζ) plus an inflow ($PS_{i,s,h}^{IN}$) minus an outflow ($PS_{i,s,h}^{OUT}$), based on a daily roll-over:

$$PS_{i,s,h}^{STO} = (1 - \zeta) \cdot PS_{i,s,h-1}^{STO} + PS_{i,s,h}^{IN} - PS_{i,s,h}^{OUT} \quad \forall i, s, h \text{ and } h > 1 \quad (D.24)$$

$$PS_{i,s,h_1}^{STO} = (1 - \zeta) \cdot PS_{i,s,h_{24}}^{STO} + PS_{i,s,h_1}^{IN} - PS_{i,s,h_1}^{OUT} \quad \forall i, s, h \text{ and } h = 1 \quad (D.25)$$

Power inflow can be supplied by either the CHP unit and boiler, or, absorption chiller in the accommodating house for hot or cold storage inflow, respectively. Note that the following equations are similar for the first hour of the day, based on daily roll-over:

$$PS_{i,s,h}^{IN} = (PH_{B,i,s,h}^{STO} + PH_{CHP,i,s,h}^{STO}) \text{ or } PC_{AC,i,s,h}^{STO} \quad \forall i, s, h \quad (D.26)$$

The storage tank can additionally not be loaded over its maximum capacity, $DG_{STO,i}^{MAX}$:

$$(1 - \zeta) \cdot PS_{i,s,h-1}^{STO} + PS_{i,s,h}^{IN} \leq DG_{STO,i}^{MAX} \quad \forall i, s, h \text{ and } h > 1 \quad (D.27)$$

The hourly outflow cannot exceed the thermal power stored in the previous hour:

$$PS_{i,s,h}^{OUT} \leq (1 - \zeta) \cdot PS_{i,s,h-1}^{STO} \quad \forall i, s, h \text{ and } h > 1 \quad (D.28)$$

Furthermore, the units are bound by upper (U_{STO}) and lower (L_{STO}) capacity levels through a binary decision variable ($B_{STO,i}$):

$$L_{STO} \cdot B_{STO,i} \leq DG_{STO,i}^{MAX} \leq U_{STO} \cdot B_{STO,i} \quad \forall i, s, h \quad (D.29)$$

$$PS_{i,s,h}^{STO} \leq DG_{STO,i}^{MAX} \quad \forall i, s, h \quad (D.30)$$

Batteries are modelled similarly to thermal storage units with additional charge (χ) and discharge ($\delta\chi$) rates, maximum charge ($max\chi$) and discharge rates ($max\delta\chi$), upper (U_{EST}) and lower (L_{EST}) limits on the state of charge, a depth of charge (DOC) and a binary decision variable, $B_{EST,i}$:

$$ES_{i,s,h}^{STO} = (1 - \eta) \cdot ES_{i,s,h-1}^{STO} + hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h}^{IN} - hr \cdot \frac{PS_{EST,i,s,h}^{OUT}}{(1 - \delta\chi)} \quad \forall i, s, h \text{ and } h > 1 \quad (D.31)$$

$$ES_{i,s,h_1}^{STO} = (1 - \eta) \cdot ES_{i,s,h_{24}}^{STO} + hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h_1}^{IN} - hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1 - \delta\chi)} \quad \forall i, s, h \text{ and } h = 1 \quad (D.32)$$

The in- and output electrical energy of batteries can not exceed installed capacity ($DG_{EST,i}^{MAX}$) and stored energy in the previous hour, respectively. Note that the following equations are similar for the first hour of the day, based on daily roll over.

$$(1 - \eta) \cdot ES_{i,s,h-1}^{STO} + hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h}^{IN} \leq DG_{EST,i}^{MAX} \quad \forall i, s, h \quad (D.33)$$

$$hr \cdot \frac{PS_{EST,i,s,h}^{OUT}}{(1 - \delta\chi)} \leq (1 - \eta) \cdot ES_{i,s,h-1}^{STO} \quad \forall i, s, h \quad (D.34)$$

The in- and output energy is restricted by maximum charge and discharge rates in function of the installed capacity:

$$hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h}^{IN} \leq max\chi \cdot DG_{EST,i}^{MAX} \quad \forall i, s, h \quad (D.35)$$

$$hr \cdot \frac{PS_{EST,i,s,h}^{OUT}}{(1 - \delta\chi)} \leq max\delta\chi \cdot DG_{EST,i}^{MAX} \quad \forall i, s, h \quad (D.36)$$

The battery can be charged through contributions of the DG units, i.e. PV units, CHP units and small-scale wind turbines installed in the accommodating house:

$$PS_{EST,i,s,h}^{IN} = \sum_{techDG} PE_{techDG,i,s,h}^{STO} \quad \forall i, s, h \quad (D.37)$$

The stored energy ($ES_{i,s,h}^{STO}$ [kWh]) cannot go below a level specified through the depth of charge of the battery (DOC) (see Figure D.1), and the installed capacity is bound by upper (U_{EST}) and lower (L_{EST}) levels through binary variable $B_{EST,i}$:

$$L_{EST} \cdot B_{EST,i} \leq DG_{EST,i}^{MAX} \leq U_{EST} \cdot B_{EST,i} \quad \forall i \quad (D.38)$$

$$(1 - DOC) \cdot DG_{EST,i}^{MAX} \leq ES_{i,s,h}^{STO} \quad \forall i, s, h \quad (D.39)$$

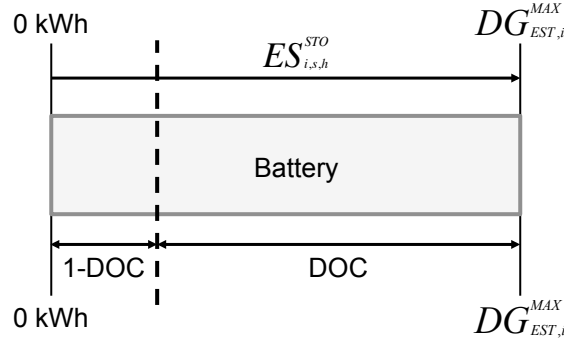


FIGURE D.1: Schematic of the battery depth of charge. A battery can not be discharged more than its depth of charge (DOC). In other words, there will always be a minimum charge level equal to $(1 - DOC)$.

D.2.4 Pipelines

The additional pipeline constraints are as follows. Heat send to the pipeline network ($PH_{CHP,i,s,h}^{Pipe}$) and from the network to a house ($QH_{i,s,h}^{Load}$) is bound by a maximum pipe utilisation rate, U_{snd} , and the total heat load of the house, $C_{HEAT,i,s,h}^{LOAD}$, respectively.

$$PH_{CHP,i,s,h}^{PIPE} \leq U_{snd} \cdot Y_{i,s,h}^{snd} \quad \forall i, s, h \quad (D.40)$$

$$QH_{i,s,h}^{LOAD} \leq C_{HEAT,i,s,h}^{LOAD} \cdot Y_{i,s,h}^{rec} \quad \forall i, s, h \quad (D.41)$$

D.3 Energy interaction constraints

Several energy interactions occur in the neighbourhood to (i) meet the energy balances, (ii) interact with the central grid, and (iii) share local electricity through the microgrid.

D.3.1 Energy balances

The electricity load of each house, $C_{ELEC,i,s,h}^{LOAD}$ [kW], together with a potential dump load ($Pdl_{i,s,h}$) and electricity for the operation of the absorption chillers and air-conditioning units (characterised by respective electricity to cooling ratios, ECR and n_{airco}^{th}), should be satisfied through the consideration and combined use of grid import ($PE_{i,s,h}^{GRID}$), electricity received through microgrid sharing ($PE_{rec,i,s,h}^{MG}$), self-generated electricity by DG units in the house ($PE_{techDG,i,s,h}^{SELF}$) and battery out-flow ($PS_{EST,i,s,h}^{OUT}$):

$$\begin{aligned} & C_{ELEC,i,s,h}^{LOAD} + Pdl_{i,s,h} + PC_{AC,i,s,h}^{GEN} \cdot ECR + \frac{PC_{airco,i,s,h}^{GEN}}{n_{airco}^{th}} \\ &= PE_{i,s,h}^{GRID} + PE_{rec,i,s,h}^{MG} + \sum_{techDG} PE_{techDG,i,s,h}^{SELF} + PS_{EST,i,s,h}^{OUT} \quad \forall i, s, h \end{aligned} \quad (D.42)$$

Heating, $C_{HEAT,i,s,h}^{LOAD}$, and cooling loads, $C_{COOL,i,s,h}^{LOAD}$, are met by gas heaters ($PH_{G,i,s,h}^{TOT}$), boilers ($PH_{B,i,s,h}^{SELF}$) or CHP units ($PH_{CHP,i,s,h}^{Load}$), or, air-conditioning units ($PC_{airco,i,s,h}^{TOT}$) or absorption chillers ($PC_{AC,i,s,h}^{Load}$) installed in the house, combined with hot or cold thermal pipeline transfer ($QH/C_{i,s,h}^{Load}$) and hot or cold thermal storage out-flow ($PS_{STO,i,s,h}^{OUT}$), $\forall i, s, h$:

$$C_{HEAT,i,s,h}^{LOAD} = PH_{G,i,s,h}^{TOT} + PH_{B,i,s,h}^{Load} + PH_{CHP,i,s,h}^{Load} + QH_{i,s,h}^{Load} + PS_{HST,i,s,h}^{OUT} \quad (D.43)$$

$$C_{COOL,i,s,h}^{LOAD} = PC_{airco,i,s,h}^{TOT} + PC_{AC,i,s,h}^{Load} + QC_{i,s,h}^{Load} + PS_{CST,i,s,h}^{OUT} \quad (D.44)$$

D.3.2 Grid interactions

Each house can in each hour either import, $PE_{i,s,h}^{GRID}$, or export, $PE_{techDG,i,s,h}^{SAL}$, electricity from and to the central grid up to a maximum ($U_{rec/snd}$). Alternatively, a house can also not interact with the central grid in an hour. The binary decision variables $X_{i,s,h}^{rec}$ and $X_{i,s,h}^{snd}$ decide whether a house receives or sends, respectively.

$$\sum_{techDG} PE_{techDG,i,s,h}^{SAL} \leq U_{snd} \cdot X_{i,s,h}^{snd} \quad \forall i, s, h \quad (D.45)$$

$$PE_{i,s,h}^{GRID} \leq U_{rec} \cdot X_{i,s,h}^{rec} \quad \forall i, s, h \quad (D.46)$$

$$X_{i,s,h}^{snd} + X_{i,s,h}^{rec} \leq 1 \quad \forall i, s, h \quad (D.47)$$

D.3.3 Microgrid operation

Electricity send to, $PE_{techDG,i,s,h}^{CIRC}$, or received from, $PE_{rec,i,s,h}^{MG}$, the microgrid by a house can be divided into house pair interactions, $PE_{i,j,s,h}^{snd}$ and $PE_{i,j,s,h}^{rec}$, that are bound by an upper level U_{MGC} :

$$\sum_{techDG} PE_{techDG,i,s,h}^{CIRC} = \sum_j PE_{i,j,s,h}^{snd} \quad \forall i, s, h \text{ and } i \neq j \quad (D.48)$$

$$PE_{rec,i,s,h}^{MG} = \sum_j PE_{i,j,s,h}^{rec} \quad \forall i, s, h \text{ and } i \neq j \quad (D.49)$$

$$PE_{i,j,s,h}^{snd/rec} \leq U_{MGC} \cdot MGC_{i,j,s,h} \quad \forall i, j, s, h \text{ and } i \neq j \quad (D.50)$$

The electricity balance of the microgrid should be respected in each hour for each house as well as for the neighbourhood as a whole:

$$PE_{i,j,s,h}^{snd} - PE_{i,j,s,h}^{LOSS} = PE_{i,j,s,h}^{rec} \quad \forall i, j, s, h \text{ and } i \neq j \quad (D.51)$$

$$\sum_{techDG} \sum_i PE_{techDG,i,s,h}^{CIRC} - \sum_i \sum_j PE_{i,j,s,h}^{LOSS} = \sum_i PE_{rec,i,s,h}^{MG} \quad \forall s, h \text{ and } i \neq j \quad (D.52)$$

Lastly, the total generated electricity by DG units for microgrid sharing is bound by both an upper level U_{MGC} and the existence of microgrid infrastructure (Z):

$$\sum_{techDG} \sum_i \sum_s \sum_h PE_{techDG,i,s,h}^{CIRC} \leq U_{MGC} \cdot Z \quad (D.53)$$

Appendix E

Input parameters of Chapter 4

This Appendix details and summarises input parameters for the developed cost-optimal DES design model of Chapter 4. Neighbourhood layout details are provided together with the derivation of the household thermal demands through the Degree Day method, up-scaled neighbourhood demands and the derivation of solar and wind data.

E.1 Neighbourhood layout

The distance between the different house pairs are explicitly included in Table E.1 for the 5-house neighbourhood, together with the yearly energy demands of each house. The distances between different house pairs for the 10- and 20-house neighbourhoods are included in Tables E.2 and E.3, respectively.

TABLE E.1: Distance [m] between each pair of houses (adapted from [95, 96]) as well as the yearly energy demands of each house in terms of electricity (E), heating (H) and cooling (C) [kWh y⁻¹]. Each row presents from one house the distance to the other houses in the neighbourhood as well as its yearly energy demands.

house	Distances					Yearly demands		
	h ₁	h ₂	h ₃	h ₄	h ₅	E	H	C
h ₁	0	30	40	50	70	3353	14138	2731
h ₂	30	0	30	20	40	3772	15905	3073
h ₃	40	30	0	50	70	4191	17672	3414
h ₄	50	20	50	0	20	4610	19439	3756
h ₅	70	40	70	20	0	5029	21207	4097

TABLE E.2: Distance [m] between each pair of houses for the 10-house neighbourhood, adapted from [96]. Each row presents from one house the distance to the other houses.

house	h ₁	h ₂	h ₃	h ₄	h ₅	h ₆	h ₇	h ₈	h ₉	h ₁₀
h ₁	0	55	30	20	60	30	60	70	20	45
h ₂	55	0	30	40	60	50	40	25	60	25
h ₃	30	30	0	30	65	40	50	55	45	30
h ₄	20	40	30	0	40	15	30	50	20	20
h ₅	60	60	65	40	0	30	15	45	45	30
h ₆	30	50	40	15	30	0	25	55	15	25
h ₇	60	40	50	30	15	25	0	35	40	20
h ₈	70	25	55	50	45	55	35	0	70	30
h ₉	20	60	45	20	45	15	40	70	0	35
h ₁₀	45	25	30	20	30	25	20	30	35	0

E.2 Thermal demand derivation (Degree-Day method)

The daily profiles of hourly average thermal energy demands for an average day in each season of a representative house, h₃, in the 5-house neighbourhood are obtained through a combination of the Degree Day method [258, 259] and the received data from the South Australian distribution system operator [257], as detailed below.

E.2.1 Thermal energy demand profiles for heating and cooling

Heating and cooling profiles of a house can be determined through a combination of temperature profiles and climate, acceptable human comfort levels and the energy performance of the house in the considered area [258, 259]. Heating and cooling demands in each hour for a house can be calculated through Equation E.1 and Equation E.2, respectively [258, 259]. $C_{HEAT,h}^{LOAD}$ and $C_{COOL,h}^{LOAD}$ are here the space heating and space cooling demands in each hour [kW], respectively, U_{tot} is the total heat loss coefficient of the house [$W K^{-1}$], T^{base} is the pre-set human comfort inside temperature level [K] and T_h^{out} is the outside temperature during the hour [K]:

$$C_{HEAT,h}^{LOAD} = U_{tot} \cdot \max(0, T^{base} - T_h^{out})/1000 \quad (E.1)$$

$$C_{COOL,h}^{LOAD} = U_{tot} \cdot \max(0, T_h^{out} - T^{base})/1000 \quad (E.2)$$

U_{tot} is the total heat loss coefficient of the house [$W K^{-1}$] and $U_{tot}^{-1} = R_{tot}$. The latter is the total thermal resistance of the house [$K W^{-1}$].

TABLE E.3: Distance [m] between each pair of houses for the 20-house neighbourhood, adapted from [96]. Each row presents from one house the distance to the other houses.

house	h ₁	h ₂	h ₃	h ₄	h ₅	h ₆	h ₇	h ₈	h ₉	h ₁₀
h ₁	0	60	40	25	30	60	50	110	65	55
h ₂	60	0	25	40	70	70	45	35	70	30
h ₃	40	25	0	20	50	65	40	55	105	30
h ₄	25	40	20	0	30	80	25	90	60	30
h ₅	30	70	50	30	0	35	30	70	35	50
h ₆	60	70	65	80	35	0	20	50	25	40
h ₇	50	45	40	25	30	20	0	40	45	20
h ₈	110	35	55	90	70	50	40	0	80	25
h ₉	65	70	105	60	35	25	45	80	0	65
h ₁₀	55	30	30	30	50	40	20	25	65	0
h ₁₁	100	40	70	80	105	90	75	40	120	55
h ₁₂	95	75	85	75	75	40	45	40	65	50
h ₁₃	120	75	90	95	110	65	75	40	105	65
h ₁₄	20	90	105	106	110	80	80	50	105	75
h ₁₅	80	25	50	60	80	70	50	20	90	35
h ₁₆	105	65	85	80	90	60	60	30	25	55
h ₁₇	45	95	90	75	65	30	50	65	35	65
h ₁₈	105	100	100	85	85	45	60	60	60	70
h ₁₉	220	95	105	95	100	65	75	55	85	75
h ₂₀	70	60	60	50	55	25	25	30	50	30
house	h ₁₁	h ₁₂	h ₁₃	h ₁₄	h ₁₅	h ₁₆	h ₁₇	h ₁₈	h ₁₉	h ₂₀
h ₁	100	95	120	20	80	105	45	105	220	70
h ₂	40	75	75	90	25	65	95	100	95	60
h ₃	70	85	90	105	50	85	90	100	105	60
h ₄	80	75	95	106	60	80	75	85	95	50
h ₅	105	75	110	110	80	90	65	85	100	55
h ₆	90	40	65	80	70	60	30	45	65	25
h ₇	75	45	75	80	50	60	50	60	75	25
h ₈	40	40	40	50	20	30	65	60	55	30
h ₉	120	65	105	105	90	25	35	60	85	50
h ₁₀	55	50	65	75	35	55	65	70	75	30
h ₁₁	0	70	45	65	25	55	110	95	80	70
h ₁₂	70	0	40	40	55	20	35	20	25	25
h ₁₃	45	40	0	25	45	20	25	60	40	55
h ₁₄	65	40	25	0	65	25	75	50	25	60
h ₁₅	25	55	45	65	0	45	85	80	70	45
h ₁₆	55	20	20	25	45	0	60	45	25	40
h ₁₇	110	35	25	75	85	60	0	25	50	40
h ₁₈	95	20	60	50	80	45	25	0	30	40
h ₁₉	80	25	40	25	70	25	50	30	0	50
h ₂₀	70	25	55	60	45	40	40	40	50	0

E.2.2 Temperature profiles and human comfort levels

First, the temperature profiles for the considered area, Adelaide in South Australia, need to be determined. Adelaide is located in Climate Zone 5 according to the Building Code of Australia [377]. This implies a climate and weather type of warm temperature. The mean high, low and average temperatures for each month in Adelaide for 2012 are presented in Figure E.1 [260, 378]. The trend line is approximated through a 6th order polynomial. Note that since Adelaide is located in the Southern hemisphere, the

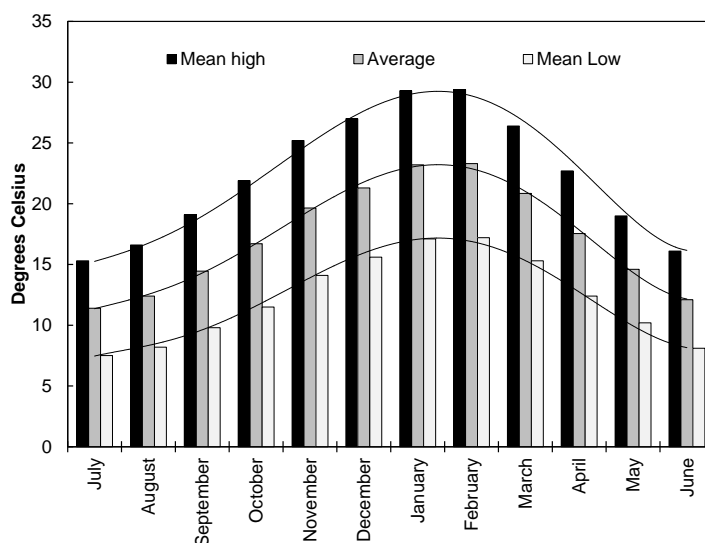


FIGURE E.1: Mean high, low and average temperatures for each month throughout a year in Adelaide, South Australia [260, 378].

summer months are set to January, February, November and December, and the winter months to May, June, July and August. The Degree Hour method should be performed on hourly temperature profiles for a day in each month. In order to determine the hours in each day with heating or cooling requirements, human comfort temperature levels are determined [258, 379]. These levels indicate temperatures where no heating or cooling is required to maintain a comfortable set base temperature inside the house. The base temperature is set at two different levels for heating and cooling respectively and for two time intervals, day and night. Table E.4 summarises the base indoor temperature for both heating and cooling within each time interval. Note that in winter (May through to August) and summer (November through to February) no space cooling and heating demand is assumed, respectively. Average hourly temperature profiles for an average day in each month for Adelaide, based on 2012 data, are given in Figure E.2 for heating and cooling months, respectively, together with the respective base comfort temperatures.

TABLE E.4: Human comfort temperature levels [°C] for a standard home based in Adelaide, South Australia [380–382].

	Heating	Cooling	unit
Day-time [7am-22pm]	20	23	[°C]
Night-time [23pm-6am]	18	21	[°C]

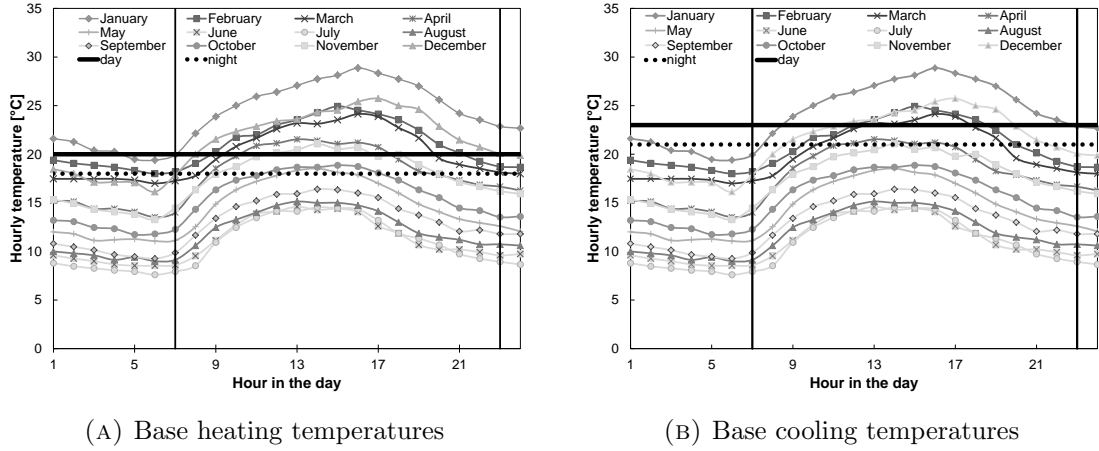


FIGURE E.2: Mean hourly temperature profiles for an average day in each month for Adelaide, Australia, with base temperature levels indicated for night and day as well as heating and cooling regions. Black vertical lines=day and night, black horizontal line=day base temperature, black horizontal dashed line=night base temperature.

E.2.3 Degree Hour method

The Degree Hour method determines the number of degrees of heating or cooling necessary in each hour by taking the positive difference between the set base temperature and the outside temperature [258, 379]. Equation E.3 determines the heating degrees for each hour and Equation E.4 determines the cooling degrees for each hour:

$$\text{HDH} = \max(0, T^{base} - T_h^{out}) \quad (\text{E.3})$$

$$\text{CDH} = \max(0, T_h^{out} - T^{base}) \quad (\text{E.4})$$

E.2.4 Degree Hours of heating and cooling

With the aforementioned base-temperatures and average hourly outdoor temperatures for an average day in each month, the total heating and cooling degree hours for each month in Adelaide are found, see Figure E.3. Note that the overall heating requirement is larger than the cooling requirement, but the former is more evenly spread out over the winter and mid-season months whereas the cooling requirement is spiky with a sudden peak in January. Sudden peak demand exerts most pressure on the central NEM system due to volatile summer peaking behaviour through electrically driven cooling.

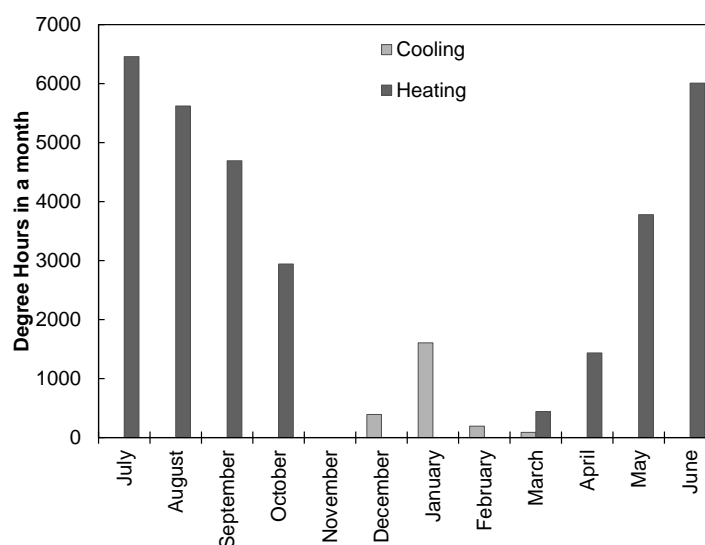


FIGURE E.3: Total heating and cooling Degree Hours for each month throughout a year in Adelaide, South Australia.

E.2.5 Thermal losses of residential houses

The thermal energy performance of a house can be determined through several methods: analytical, computational and experimental [380, 383]. With the experimental method, thermal heat losses, thermal isolation of the building materials and in- and outside temperatures are experimentally measured through calibrated equipment to determine the heat loss factor of a house. The computational method utilises fixed climatic conditions and standard building material characteristics to simulate the thermal performance of walls of houses. Some widely used commercial software packages are NatHERS, developed by CISRO in Australia, NABERS and AccuRate [380]. An analytical and theoretical model is in this Section adopted to estimate the thermal losses of a standard residential house based in Adelaide. The results obtained are estimates based on knowledge about thermal properties of the used building materials, and climate and temperature conditions of the region [380]. The estimated results can differ from the results determined through experiments. The reasons for the difference is mainly due to the non-linearity of thermal behaviour of the building materials, the internal energy generation in a house and consumption patterns of occupants [380].

The thermal heat loss coefficient of a house, U_{tot} , is required. This coefficient is the inverse of the total thermal resistance factor. The minimum acceptable value for the thermal resistance factor of new South Australian houses is predetermined through obligatory compliance with the South Australian building energy efficiency requirements that

include minimum insulation levels for walls, floors and roofs of new houses [256]. Building energy efficiency is measured through an energy star rating. The higher the rating, the lower the thermal losses of the building and the higher the insulation level and thermal energy performance of the building. The house considered in this study is based in Adelaide (34.9S; 138.6E [384]), South Australia. As per the *Development Act* 1993 of September 2010, all new homes and extensions built in South Australia need to achieve a 6-star level of energy efficiency through minimum insulation requirements [255]. The minimum measures of resistance to heat transfer of building materials are given in Table E.5. The house under investigation is a standard detached single story house with brick veneer walls and single glazing. This choice is motivated by the percentage of houses in Adelaide that have single or double glazing [385], i.e 95.1% and 4.9% respectively. Furthermore, most Australian houses are built either with weatherboard wall systems or with brick veneer. The latter is more widely used [380]. The house dimensions are in accordance with average floor areas and standard roof dimensions in South Australia [254, 380]:

- *The floor area* is set to 200 m² [254] with a length and a width of respectively 20 and 10 m, made out of a H class concrete slab with a depth of 100 mm [380, 386].
- *Total house height* is set to 4.5 m [380] with walls of 2.5 m and a roof of 2 m high.
- *Walls* are made of brick veneer with five layers: brick, air gap, timber frame, insulation foil and plaster (Gypsum) [380]. The wall to window ratio in Adelaide is on average 18% and the wall area is less than 25% of the floor area [385, 387]. Furthermore, two solid wooden doors between in- and outside are adopted with a width and height of 1.2 m and 1.5 m, respectively.
- *The roof* is 2 m high with a 20 degree tilt and made of timber with terracotta/concrete tiles [380].

The total house thermal loss coefficient, U_{tot} , consists of loss terms based on convection, conduction, radiation and ventilation [258, 259, 380]. Following the methodology explained in Durmayaz et al. [258] and Agioutantis and Bekas [259], the total thermal

TABLE E.5: Recommended R-values [Km² W⁻¹] and U-values [W(Km²)⁻¹] for new houses in Adelaide, South Australia [380, 384].

	R-value	unit	U-value	unit
Ceiling/roof	3.2	[Km ² W ⁻¹]	0.31	[W(Km ²) ⁻¹]
Walls	1.9	[Km ² W ⁻¹]	0.53	[W(Km ²) ⁻¹]
Floor	3.2	[Km ² W ⁻¹]	0.31	[W(Km ²) ⁻¹]
Openings	0.19	[Km ² W ⁻¹]	5.23	[W(Km ²) ⁻¹]

loss is calculated through the sum of the conduction and radiation losses, determined through Equations E.5 and E.6, respectively:

$$Q_{cond} = A \cdot U_{tot} \cdot (T^{in} - T^{out}) \quad (\text{E.5})$$

$$Q_{rad} = 0.8 \cdot V \cdot C_{p_{air}} \cdot \rho_{air} \cdot (T^{in} - T^{out}) \quad (\text{E.6})$$

Q_{cond} is the total house heat loss through conduction [W], A the surface of the house [m^2], U_{tot} the total house thermal loss factor and T^{in} the indoor temperature or base temperature [K]. The difference between the in- and outdoor temperature is equal to the Degree Cooling or Heating required in each hour. Q_{rad} is the total house heat loss through radiation [W], V the total volume of the house [m^3], $C_{p_{air}}$ the specific heat capacity of air [$\text{W}(\text{kg}^\circ\text{C})^{-1}$] and ρ_{air} the density of atmospheric air [kg m^{-3}].

E.2.6 Thermal loss factor of a typical residential house

The total thermal loss through conduction (Equation E.5) requires surface areas, material heat loss coefficients and the calculation of the total conductive house heat loss coefficient as given in Table E.6. The total thermal loss through radiation (Equation E.6) requires air parameters and the calculation of the total radiation house heat loss coefficient as given in Table E.7. The total house heat loss is then found by multiplying the total conduction and radiation coefficients with the temperature difference in each hour and subsequently summing both resulting losses, leading to the heating and cooling demands in each hour for the considered house.

TABLE E.6: Total conductive heat loss coefficient of an Adelaide house [W K^{-1}].

	Area [m^2]	U [$\text{W}(\text{K m}^2)^{-1}$]	AU [W K^{-1}]
Roof	212.80	0.31	66.50
Walls	88.80	0.53	46.73
Windows	27.75	0.65	18.04
Doors	33.45	0.16	5.35
Floor	200	0.31	62.50
Openings	47.80	5.23	250.190
AU_{tot} [W K^{-1}]			449.32

TABLE E.7: Total radiation heat loss coefficient of an Adelaide house [W/K].

	Value	Unit
V	700	$[\text{m}^3]$
$C_{p_{air}}$	0.24	$[\text{W}(\text{kg } ^\circ\text{C})^{-1}]$
ρ_{air}	1.2	$[\text{kg m}^{-3}]$
Total	161.28	$[\text{W K}^{-1}]$

E.2.7 Thermal profiles

The heating and cooling demand profiles for an average day in each month are calculated based on the information provided in the previous Section: (i) a model of a standard house based in Adelaide, (ii) the prevailing climate and temperature profiles, and (iii) the pre-set human comfort levels. Figure E.4 gives the heat demands for an average day in each heating month and Figure E.5 gives the cooling demands for an average day in each cooling month.

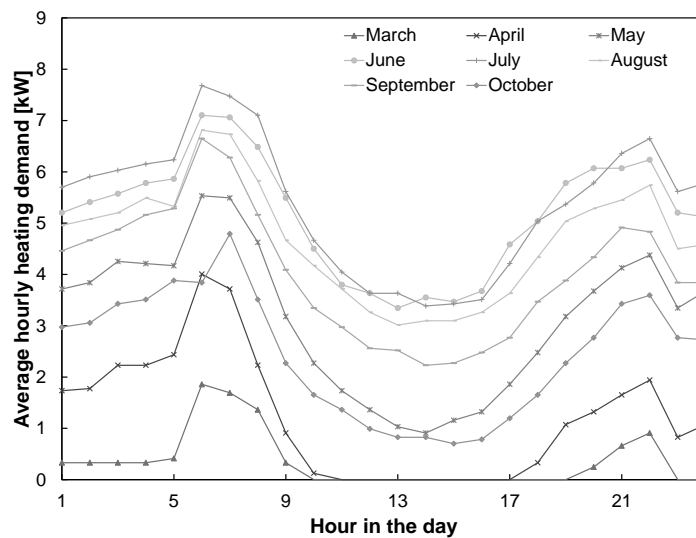


FIGURE E.4: Hourly heating demand profiles for a typical day in each month throughout a year in Adelaide, South Australia [kW].

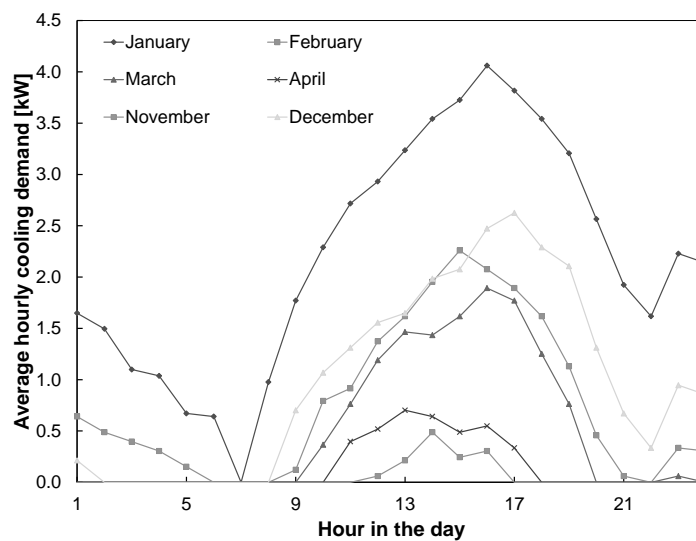


FIGURE E.5: Hourly cooling demand profiles for a typical day in each month throughout a year in Adelaide, South Australia [kW].

E.3 Neighbourhood energy demands

The demands of the 5-house neighbourhood are given in Tables E.10, E.11, E.12, and E.13 for winter, summer and mid-season, respectively. House h_3 is the representative house. Its electricity demands are obtained from averaged aggregated data received from the South Australian Distribution Network Operator. The thermal demands of h_3 are obtained through averaging the different monthly profiles in each season, obtained in Figures E.4 and E.5. The other house demands are varied with a percentage increase or decrease with respect to h_3 ; $h_1 = h_3 - 10\%$, $h_2 = h_3 - 20\%$, $h_4 = h_3 + 10\%$, and $h_5 = h_3 + 20\%$. The energy demands of the houses in the up-scaled neighbourhoods are related to the house demands in the 5-house neighbourhood as indicated in Tables E.8 and E.9 for the 10- and 20-house neighbourhoods, respectively.

TABLE E.8: Relation between the demands of the houses in the 10-house neighbourhood and the demands of the houses in the 5-house neighbourhood.

houses		h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}
demand	5-house	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
neighbourhood											

TABLE E.9: Relation between the demands of the houses in the 20-house neighbourhood and the demands of the houses in the 5-house neighbourhood.

houses		h_1	h_2	h_3	h_4	h_5	h_6	h_7	h_8	h_9	h_{10}
demand	5-house	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
neighbourhood											
houses		h_{11}	h_{12}	h_{13}	h_{14}	h_{15}	h_{16}	h_{17}	h_{18}	h_{19}	h_{20}
demand	5-house	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
neighbourhood											

E.4 Derivation of solar irradiation on a tilted surface

This Section summarises the derivation of the global solar irradiance on a tilted plane, e.g. a PV panel. First, some terminology is clarified to then derive the three components of the tilted global solar irradiance; direct tilted irradiance, tilted albedo and tilted diffuse irradiance. Last, the resulting hourly average tilted global solar irradiance for a typical day in each season for Adelaide, South Australia, is presented.

TABLE E.10: The hourly average electricity and heating demands [kW] for each house (h_i) in the 5-house neighbourhood for winter.

hr	electricity					heating				
	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
h1	0.207	0.233	0.258	0.284	0.310	3.915	4.404	4.893	5.383	5.872
h2	0.207	0.233	0.258	0.284	0.310	4.047	4.553	5.059	5.564	6.070
h3	0.216	0.243	0.270	0.297	0.324	4.212	4.739	5.265	5.792	6.318
h4	0.233	0.262	0.291	0.321	0.350	4.328	4.869	5.410	5.951	6.492
h5	0.228	0.256	0.285	0.313	0.341	4.319	4.859	5.399	5.939	6.479
h6	0.239	0.268	0.298	0.328	0.358	5.426	6.104	6.783	7.461	8.139
h7	0.282	0.318	0.353	0.388	0.423	5.352	6.021	6.690	7.359	8.028
h8	0.369	0.416	0.462	0.508	0.554	4.807	5.408	6.008	6.609	7.210
h9	0.420	0.473	0.526	0.578	0.631	3.791	4.265	4.739	5.212	5.686
h10	0.425	0.478	0.531	0.584	0.637	3.122	3.512	3.902	4.293	4.683
h11	0.416	0.468	0.520	0.572	0.624	2.659	2.992	3.324	3.657	3.989
h12	0.404	0.454	0.505	0.555	0.606	2.379	2.676	2.973	3.271	3.568
h13	0.398	0.448	0.498	0.547	0.597	2.205	2.481	2.756	3.032	3.308
h14	0.384	0.432	0.479	0.527	0.575	2.189	2.462	2.736	3.009	3.283
h15	0.385	0.433	0.481	0.529	0.577	2.230	2.509	2.787	3.066	3.345
h16	0.376	0.423	0.470	0.517	0.564	2.354	2.648	2.942	3.236	3.531
h17	0.408	0.459	0.510	0.561	0.612	2.858	3.215	3.572	3.929	4.286
h18	0.508	0.572	0.636	0.699	0.763	3.378	3.800	4.222	4.645	5.067
h19	0.662	0.744	0.827	0.910	0.993	3.873	4.358	4.842	5.326	5.810
h20	0.692	0.779	0.866	0.952	1.039	4.163	4.683	5.203	5.723	6.244
h21	0.640	0.720	0.800	0.880	0.960	4.402	4.952	5.503	6.053	6.603
h22	0.530	0.597	0.663	0.729	0.796	4.600	5.175	5.750	6.325	6.900
h23	0.310	0.349	0.388	0.426	0.465	3.733	4.200	4.666	5.133	5.600
h24	0.207	0.233	0.258	0.284	0.310	3.832	4.311	4.790	5.269	5.748

TABLE E.11: The hourly average electricity and cooling demands [kW] for each house (h_i) in the 5-house neighbourhood for summer.

hr	electricity					cooling				
	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
h1	0.216	0.243	0.270	0.297	0.324	0.501	0.564	0.626	0.689	0.751
h2	0.268	0.302	0.335	0.369	0.402	0.397	0.447	0.496	0.546	0.596
h3	0.267	0.301	0.334	0.368	0.401	0.299	0.337	0.374	0.412	0.449
h4	0.261	0.294	0.327	0.359	0.392	0.269	0.302	0.336	0.370	0.403
h5	0.269	0.302	0.336	0.370	0.403	0.165	0.186	0.206	0.227	0.247
h6	0.333	0.374	0.416	0.457	0.499	0.000	0.000	0.000	0.000	0.000
h7	0.397	0.447	0.497	0.546	0.596	0.000	0.000	0.000	0.000	0.000
h8	0.394	0.444	0.493	0.542	0.592	0.195	0.220	0.244	0.269	0.293
h9	0.419	0.472	0.524	0.577	0.629	0.519	0.584	0.649	0.714	0.779
h10	0.422	0.475	0.528	0.581	0.633	0.831	0.935	1.038	1.142	1.246
h11	0.418	0.470	0.522	0.574	0.626	0.990	1.113	1.237	1.361	1.484
h12	0.444	0.500	0.555	0.611	0.666	1.185	1.333	1.481	1.629	1.778
h13	0.434	0.488	0.543	0.597	0.651	1.344	1.512	1.680	1.848	2.016
h14	0.441	0.496	0.551	0.606	0.661	1.594	1.794	1.993	2.192	2.391
h15	0.455	0.512	0.569	0.626	0.682	1.662	1.869	2.077	2.285	2.492
h16	0.496	0.558	0.620	0.682	0.744	1.784	2.007	2.230	2.453	2.676
h17	0.550	0.619	0.688	0.757	0.825	1.668	1.876	2.085	2.293	2.501
h18	0.555	0.624	0.693	0.763	0.832	1.490	1.677	1.863	2.049	2.236
h19	0.541	0.609	0.677	0.744	0.812	1.289	1.450	1.611	1.772	1.933
h20	0.523	0.588	0.654	0.719	0.785	0.867	0.976	1.084	1.193	1.301
h21	0.421	0.474	0.526	0.579	0.631	0.531	0.598	0.664	0.731	0.797
h22	0.268	0.302	0.335	0.369	0.402	0.531	0.598	0.664	0.731	0.797
h23	0.216	0.243	0.270	0.297	0.324	0.702	0.790	0.878	0.966	1.054
h24	0.216	0.243	0.270	0.297	0.324	0.660	0.742	0.825	0.907	0.990

TABLE E.12: The hourly average heating and cooling demands [kW] for each house (h_i) in the 5-house neighbourhood for mid-season.

hr	heating					cooling				
	h_1	h_2	h_3	h_4	h_5	h_1	h_2	h_3	h_4	h_5
h1	1.890	2.126	2.363	2.599	2.835	0.000	0.000	0.000	0.000	0.000
h2	1.956	2.200	2.445	2.689	2.933	0.000	0.000	0.000	0.000	0.000
h3	2.161	2.431	2.701	2.972	3.242	0.000	0.000	0.000	0.000	0.000
h4	2.235	2.514	2.793	3.073	3.352	0.000	0.000	0.000	0.000	0.000
h5	2.392	2.691	2.990	3.289	3.588	0.000	0.000	0.000	0.000	0.000
h6	3.254	3.661	4.068	4.475	4.881	0.000	0.000	0.000	0.000	0.000
h7	3.284	3.694	4.105	4.515	4.926	0.000	0.000	0.000	0.000	0.000
h8	2.445	2.750	3.056	3.361	3.667	0.000	0.000	0.000	0.000	0.000
h9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
h10	0.000	0.000	0.000	0.000	0.000	0.073	0.082	0.092	0.101	0.110
h11	0.000	0.000	0.000	0.000	0.000	0.232	0.261	0.290	0.319	0.348
h12	0.000	0.000	0.000	0.000	0.000	0.342	0.385	0.428	0.470	0.513
h13	0.000	0.000	0.000	0.000	0.000	0.434	0.488	0.542	0.596	0.651
h14	0.000	0.000	0.000	0.000	0.000	0.415	0.467	0.519	0.571	0.623
h15	0.000	0.000	0.000	0.000	0.000	0.421	0.474	0.527	0.580	0.632
h16	0.000	0.000	0.000	0.000	0.000	0.489	0.550	0.611	0.672	0.733
h17	0.000	0.000	0.000	0.000	0.000	0.421	0.474	0.527	0.580	0.632
h18	0.000	0.000	0.000	0.000	0.000	0.250	0.282	0.313	0.344	0.376
h19	0.000	0.000	0.000	0.000	0.000	0.153	0.172	0.191	0.210	0.229
h20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
h21	2.123	2.388	2.653	2.919	3.184	0.000	0.000	0.000	0.000	0.000
h22	2.247	2.528	2.809	3.090	3.371	0.000	0.000	0.000	0.000	0.000
h23	1.480	1.665	1.850	2.036	2.221	0.000	0.000	0.000	0.000	0.000
h24	1.521	1.711	1.901	2.091	2.281	0.000	0.000	0.000	0.000	0.000

TABLE E.13: The hourly average electricity demands [kW] for each house (h_i) in the 5-house neighbourhood for mid-season.

hr	h_1	h_2	h_3	h_4	h_5
h1	0.212	0.238	0.264	0.291	0.317
h2	0.238	0.268	0.298	0.327	0.357
h3	0.242	0.272	0.302	0.333	0.363
h4	0.247	0.278	0.309	0.340	0.371
h5	0.249	0.280	0.311	0.342	0.373
h6	0.286	0.322	0.358	0.394	0.429
h7	0.341	0.383	0.426	0.468	0.511
h8	0.382	0.430	0.478	0.525	0.573
h9	0.420	0.472	0.525	0.577	0.630
h10	0.423	0.476	0.529	0.582	0.635
h11	0.417	0.469	0.521	0.573	0.625
h12	0.424	0.477	0.531	0.584	0.637
h13	0.416	0.468	0.520	0.572	0.624
h14	0.413	0.464	0.516	0.568	0.619
h15	0.420	0.473	0.525	0.578	0.630
h16	0.437	0.491	0.546	0.601	0.655
h17	0.480	0.540	0.600	0.660	0.720
h18	0.532	0.598	0.665	0.731	0.798
h19	0.601	0.676	0.751	0.826	0.901
h20	0.606	0.682	0.758	0.834	0.910
h21	0.529	0.595	0.661	0.727	0.793
h22	0.397	0.447	0.496	0.546	0.596
h23	0.262	0.295	0.328	0.361	0.394
h24	0.212	0.238	0.264	0.291	0.317

E.4.1 Definitions and rules of thumb

The radiation of the sun that reaches the ground is the global irradiance. Solar irradiation needed for PV output calculation is the global irradiance on a tilted surface [kW m^{-2}]. The global horizontal irradiance is the global irradiance measured on a horizontal surface and the global tilted irradiance is the global irradiance measured on a tilted surface. Global irradiance consists of three components; the beam or direct irradiance, the diffuse irradiance and the ground reflected irradiance or ground albedo, which can all be measured horizontally or tilted, see Figure E.6 [262, 388–391]. The beam irradiance reaches the surface directly, B^t [kW m^{-2}]. The diffuse irradiance reaches the surface after being scattered by the atmosphere and the influence of other sky conditions, D^t [kW m^{-2}]. The ground albedo reaches the surface after being reflected from the ground, A^t [kW m^{-2}]. The global irradiance on a tilted surface, G^t [kW m^{-2}], can then be found as the sum of its three tilted components [262, 388, 389, 392–394]:

$$G^t = B^t + A^t + D^t \quad (\text{E.7})$$

The beam and ground reflected components are obtained through goniometric and isotropic relations [262, 389, 392, 396] (see following Sections). The diffuse component, in contrast, is not as easily determined. PV panels can be installed in different configurations based on rules of thumb [262]. The fixed tilt panel is the cheapest configuration, in contrast with panels that track the sun throughout the day [262]. The tilt angle of a fixed panel should thus be optimised for annual sun harvest, which is, as a rule of thumb, a tilt angle equal to the latitude of the location [262]. Additionally, the orientation of the PV unit needs to be decided upon. The PV unit produces most power if directly facing the sun un-shaded [397]. For the Southern hemisphere, this orientation should be

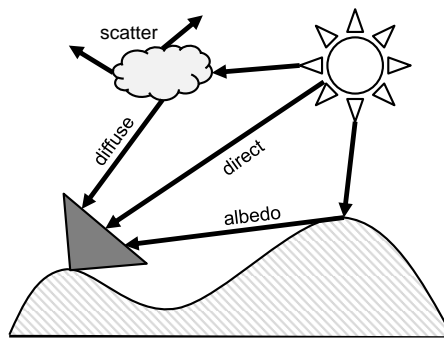


FIGURE E.6: Components of global solar irradiance on a tilted surface, adapted from [395].

due north [397, 398]. The maximum PV output is obtained for a tilt angle between 30 and 40 degrees due north for Adelaide, South Australia (34.95° S) [397].

E.4.2 Calculation of direct tilted irradiance

The tilted beam irradiance, B^t , can be found as the product of the direct irradiance on a horizontal surface (B^h) [kW m^{-2}] and the incidence angle ratio (R_b) [262, 388, 389, 392–394]:

$$B^t = B^h \cdot R_b \quad (\text{E.8})$$

The incidence angle ratio is the ratio of the cosines of the solar incidence angle on a tilted plane, θ_i [degrees], and the solar zenith angle, θ_z [degrees] (see Figure E.7):

$$R_b = \frac{\cos \theta_i}{\cos \theta_z} \quad (\text{E.9})$$

The cosine of the incidence and zenith angles can be obtained through:

$$\begin{aligned} \cos \theta_i = & \sin \delta \cdot \sin \phi \cdot \cos \beta - \sin \delta \cdot \cos \phi \cdot \sin \beta \cdot \cos \gamma \\ & + \cos \delta \cdot \cos \phi \cdot \cos \beta \cdot \cos \omega + \cos \delta \cdot \sin \phi \cdot \sin \beta \cdot \cos \gamma \cdot \cos \omega \\ & + \cos \delta \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega \end{aligned} \quad (\text{E.10})$$

$$\cos \theta_z = \sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos \omega \quad (\text{E.11})$$

- ϕ is the latitude of the location [degrees], positive for either hemisphere.
- δ is the solar declination: $\delta = 23.45 \cdot \sin(2\pi \cdot (284 + n) \cdot (365)^{-1})$, with n the day of the year starting from the 1st of January and going from 1 to 365 for non-leap years [399, 400]. The solar declination is the angle between the plane of the equator and the plane of the orbit of the earth (see Figure E.7). The solar declination angle changes with the movement of the earth along its orbit throughout the year [262]. The solar declination angle goes from 0 to +90 degrees [401].
- β is the tilt angle [degrees], measured from the horizontal from which the plane is tilted (see Figure E.7).
- ω ($\omega = 15^\circ \cdot (12 - LST)$) is the solar hour angle. ω represents the angular [degrees] displacement between the incidence location meridian and the meridian of the plane containing the sun (see Figure E.7) [402]. The solar hour angle is zero at solar noon and varies by 15 degrees per hour from noon [403]. At solar noon, the sun is due north in the Southern hemisphere. 12 is here the hour at local

noon and LST the Local Solar Time or apparent solar time [hours], which can be found as $LST = LT + TC \cdot 60^{-1}$. LT is the Local Time at the location and TC the Time Correlation factor. The TC is found as: $TC = 4^\circ(\lambda - LSTM) + EoT$. The Local Standard Time Meridian ($LSTM = 15^\circ \cdot \Delta T_{GMT}$), the longitude at the exact location of the measurements (λ) and the hour difference with the Greenwich meridian (ΔT_{GMT}) are required. The factor of 4 is introduced because the earth rotates 1° every four minutes [403]. The Equation of Time (EoT) is found as: $EoT = 9.87 \cdot \sin(2B) - 7.53 \cdot \cos B - 1.5 \cdot \sin B$ [403] (see Figure E.7). B [degrees] includes the number of days (d) since the start of the year: $B = 360^\circ \cdot 365^{-1} \cdot (d - 81)$.

- γ is the azimuth angle, defined as the local angle between the direction of the surface (due north for Southern hemisphere) and the surface of the perpendicular projection of the sun on the horizontal line, measured clockwise (see Figure E.7). The solar azimuth angle is measured away from north in the Southern hemisphere: $\cos \gamma = (\sin \delta \cdot \cos \phi - \cos \delta \cdot \cos \omega \cdot \sin \phi) \cdot (\cos \alpha)^{-1}$. The equation is only valid in the solar morning, in case of: (i) azimuth = γ for LST smaller than 12, which is equivalent to a solar hour angle smaller than zero, and (ii) azimuth = $360^\circ - \gamma$ for LST greater than 12, which is equivalent to a solar hour angle greater than zero.
- α is the solar angle [degrees], defined as: $\alpha = 90^\circ + (\phi - \delta)$ (Southern hemisphere).

For Adelaide, South Australia, based in the Southern Hemisphere, east of the meridian, the above angles are:

- $\phi = \beta = 34.95^\circ$,
- $\delta = -23.45 \cdot \sin(2\pi \cdot (284 + n) \cdot 365^{-1})$,
- $\alpha = 90 + (34.95^\circ - \delta)$,
- ω requires a longitude of 138.35° , an $LSTM$ of 138.52° and a ΔT_{GMT} of $+9.5$ hours and $+10.5$ hours during daylight saving time,

E.4.3 Calculation of albedo tilted irradiance

The ground reflected tilted irradiance can be found through isotropic and anisotropic relations. Research of comparison studies showed that using anisotropic methods does not add to the accuracy of the simple isotropic relation, such as [388, 389, 404, 405]:

$$A^t = G^h \cdot r_g \cdot R_r \quad (\text{E.12})$$

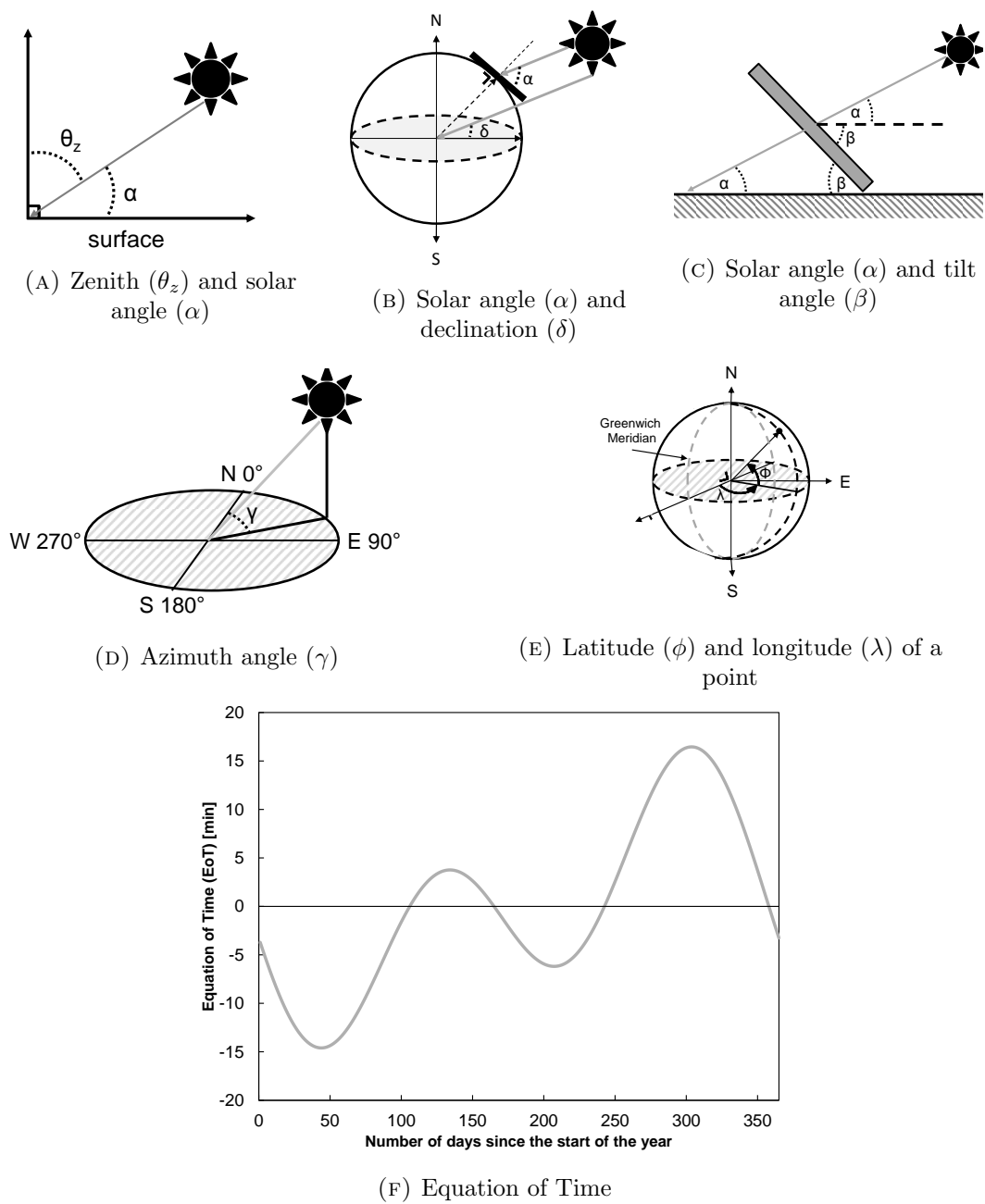


FIGURE E.7: Solar angles and Equation of Time.

G^h is here the global horizontal irradiance [kW m^{-2}], r_g is the ground reflectivity (0.2 for standard lawn and outdoor surface [262, 406]), and R_r the incidence angle ratio for the ground reflection, found as $R_r = (1 - \cos \beta) \cdot 2^{-1}$.

E.4.4 Calculation of diffuse tilted irradiance

The diffuse tilted irradiance is not as straightforward to obtain compared to the previous components due to its anisotropic behaviour under the sky dome [406]. Throughout literature different isotropic and anisotropic methods have been proposed. The diffuse tilted irradiance depends on the weather, sky conditions, soil and climate. Depending on the researched location, certain models will provide the best fit. The general expression to obtain the diffuse tilted irradiance is [388, 392, 404]:

$$D^t = D^h \cdot R_d \quad (\text{E.13})$$

D^h is here the diffuse horizontal irradiance [W m^{-2}] and R_d the incidence angle ratio for the diffuse solar irradiance. R_d can be determined based on isotropic or anisotropic methods. The difference between isotropic and anisotropic methods lies in the incorporation of sky radiation [388, 404].

E.4.4.1 Isotropic methods

The intensity of diffuse sky radiation is taken to be uniform over the sky dome for isotropic methods. This is a simplification of reality and will therefore sometimes lead to an overestimation of the tilted diffuse solar irradiation [388, 404]. The most common isotropic relations are summarised in Table E.14 with β the surface tilt angle [degrees] [388, 392, 404].

TABLE E.14: Most common isotropic methods to obtain the incidence angle ratio of the diffuse solar irradiation on a tilted surface [388, 392, 404].

R_d	Model	Comment
$\frac{1+\cos \beta}{2}$	Liu-Jordan model [407]	Most commonly accepted method [262, 405]
$\frac{(2+\cos \beta)}{3}$	Koronakis model [408]	Adaptation of the Liu-Jordan model
$\frac{(3+\cos(2\beta))}{4}$	Badescue model [409]	Pseudo-anisotropic model
$1 - \frac{\beta}{180}$	Tian model [410]	Isotropic model

E.4.4.2 Anisotropic methods

Anisotropic methods take into account both the isotropic diffuse tilted radiation as well as a measure for the anisotropy of the diffuse radiation in the circumsolar region [388, 404]. The circumsolar region is the region of the sky near the solar disk. Anisotropic methods refine the approach taken by isotropic methods with factors that incorporate a circumsolar, a horizon brightening and a sky condition correction. Hence, they are more accurate representations of reality [262]. A large variety of models exist, suitable to various locations [389, 390, 392, 396]. Table E.15 summarises the most common anisotropic methods found in literature with B^h the direct horizontal solar irradiance [W m^{-2}], D^h the diffuse horizontal solar irradiance [W m^{-2}], G^h the global horizontal solar irradiance [W m^{-2}], and r_b the beam radiation conversion factor. The tilted diffuse solar irradiance can be split up in a uniform irradiance of the sky dome (isotropic diffuse component), a circumsolar diffuse component and a horizon brightening component. Depending on the model, only the circumsolar or both the circumsolar and the horizon brightening corrections are added to the isotropic model.

E.4.4.3 Choice of method

The value of the tilted solar irradiance will be influenced by both the calculation method and by the climatological conditions of the location. Depending on the sky conditions, each method will potentially result in an over or under estimation of the diffused tilted solar irradiance component. Sky conditions, cloud cover, tilt angle and facing of the panel will all result in a different best-approach calculation method for the diffuse component. To assess the quality of results, each method requires a fitting and comparison with real data [388–390, 392, 405]. Generally, literature agrees that anisotropic methods deliver the best quality results, but the best anisotropic method depends highly on the conditions and location. Isotropic methods, in contrast, lead to acceptable results, which closely approximate the best anisotropic results. Moreover, the range of over- and under-estimation is small, if even existent. As the scope of this work is not to comparatively assess the results of different models to obtain the ‘best’ fit, but rather to get satisfactory approximate solar irradiation values to illustrate the capabilities of the developed modelling framework, the simple Liu-Jordan isotropic model is employed to obtain the diffuse tilted irradiance.

TABLE E.15: Most common anisotropic methods to obtain the incidence angle ratio of the diffuse solar irradiation on a tilted surface. CIRC=circumsolar correction, HB=horizon brightening correction, ISO=isotropic.

R_d	Symbols	Model	Comment	Type
$F_{Hay} \cdot r_b + (1 - F_{Hay}) \cdot \frac{1 + \cos \beta}{2}$	$F_{Hay} = B^h \cdot G_{ext}^{-1} \cdot G_{ext}$ is the extraterrestrial solar irradiance [W m^{-2}]	Hay model [411]	Reduces to the Liu-Jordan model for $F_{Hay} = 0$	ISO + CIRC
$F_{Hay} \cdot r_b + Z \cdot \cos \beta - S(\omega, \Omega_i) + (1 - F_{Hay} - Z) \cdot \frac{1 + \cos \beta}{2}$	$Z = \max(0.3 - 3 \cdot F_{Hay}, 0)$, $S(\omega, \Omega_i)$ takes into account the effect of obstacles obscuring the horizon and blocking a part of the diffuse radiation incident on a tilted plane	Skartveit-Olseth model [395]	Reduces to Hay model if $F_{Hay} \geq 0.15$ then $Z = 0$ [392]	ISO + CIRC
$\frac{1 + \cos \beta}{2} \cdot [1 + f_K \cdot \cos^3(\frac{\beta}{2})] \cdot [1 + f_K \cdot \cos^2 \theta_i \cdot \cos^3 \theta_z]$	$f_K = 1 - (D^h)^2 (G^h)^{-2}$ determines the degree of cloud cover through function	Klucher model [412]	Reduces to Liu-Jordan and Temps-Coulson [413] when $f_K = 0$ (i.e. $D/G = 1$) and $f_K = 1$ (i.e. $D/G = 0$)	ISO + CIRC and HB
$F_1 \cdot \frac{a}{b} + (1 - F_1) \cdot \frac{1 + \cos \beta}{2} + F_2 \cdot \sin \beta$	$F_1 = F_{11}(\epsilon) + F_{12}(\epsilon) \cdot \Delta + F_{13}(\epsilon) \cdot \theta_z$ is the sky brightness coefficient for the circumsolar region, $F_2 = F_{21}(\epsilon) + F_{22}(\epsilon) \cdot \Delta + F_{23}(\epsilon) \cdot \theta_z$ is the sky brightness coefficient for the region above the horizon line with $F_{i,j}$ the Perez coefficients function of the sky clearness parameter ϵ and the sky brightness parameter Δ	Perez model [414]	Gives a more detailed analysis in radians. Reduces to Liu-Jordan with $F_1 = F_2 = 0$. Many sets of $F_{i,j}$ have been determined in different studies [414]	ISO + CIRC and HB
$F_{hay} \cdot r_b + (1 - F_{Hay}) \cdot \frac{1 + \cos \beta}{2} \cdot (1 + f_R \cdot \sin^3 \frac{\beta}{2})$	$f_R = \sqrt{\frac{B^h}{G^h}}$ is the function that modulates the intensity of the diffuse irradiation from the region near the horizon line	Reindl model [415]	Total overcast ($f_R = 0$). Hay model extended with a component for diffuse radiation coming from the horizontal line	ISO + CIRC and HB
$\frac{1 + \cos \beta}{2} \cdot P_1 \cdot P_2$	$P_1 = 1 + \cos^2 \theta_i \cdot \sin^3 \theta_z$ is the diffuse radiation coming from the vicinity of the sun's disk. $P_2 = 1 + \sin^3 \frac{\beta}{2}$ is the sky radiation from the region close to the horizon	Temps-Coulson model [413]		ISO + CIRC and HB

E.4.5 Data

Solar data for Adelaide are available from the Australian Bureau of Meteorology [260]. The most recent complete data set of 2010 is employed. 1-minute data are available in terms of global, mean direct, mean diffuse, mean terrestrial, and mean direct horizontal irradiation with their maximum, minimum, standard deviation and uncertainty. The values are hourly averaged and the daily profiles (24h for 365 days) are averaged per month for monthly profiles and then per season for daily seasonal profiles. The obtained global tilted solar irradiation seasonal profiles are then checked with the average daily and yearly solar levels in Adelaide. The obtained values are given in Table E.16.

TABLE E.16: Global solar irradiation on a tilted surface for seasonal daily profiles in Adelaide, South Australia [kW m^{-2}]. S=summer, W=winter, MS=mid-season.

hr	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
S	0.000	0.000	0.000	0.000	0.000	0.007	0.042	0.188	0.346	0.347	0.414	1.087
W	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.159	0.247	0.324	0.884
MS	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.150	0.308	0.332	0.404	1.070
hr	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
S	1.098	0.715	0.657	0.371	0.389	0.203	0.025	0.000	0.000	0.000	0.000	0.000
W	0.901	0.579	0.504	0.245	0.130	0.006	0.000	0.000	0.000	0.000	0.000	0.000
MS	1.080	0.699	0.631	0.342	0.315	0.108	0.004	0.000	0.000	0.000	0.000	0.000

E.5 Derivation of wind speeds at defined hub height

The considered wind turbines are horizontal axis. Wind turbines are characterised by a cut-in, a cut-out and a rated wind speed [m s^{-1}], see Figure E.8 [251, 375, 376]. The cut-in wind speed is the speed at hub height that is strong enough to start up the turbine. Wind speeds starting from the cut-in allow the turbine to generate electricity. The cut-out wind speed is the speed that is too high to allow safe operation of the turbine. At wind speeds above the cut-out, the turbine will be shut down to prevent damaging. The rated wind speed is the speed at which the turbine generates at the level equal to its rated capacity. To model the design and operation of the small-scale wind turbines is opted for the widely employed Weibull method for wind speeds below the rated wind speed [252, 273, 416–418]. The Weibull method describes a power curve model based on wind speeds characterised by a Weibull shape parameter k [252, 273], see Equations in Section D.2.2, Appendix D. More specifically, a wind turbine generates a certain amount of electricity averaged over each hour, depending on the average wind speed during that hour. The Weibull shape parameter is determined by the wind speed

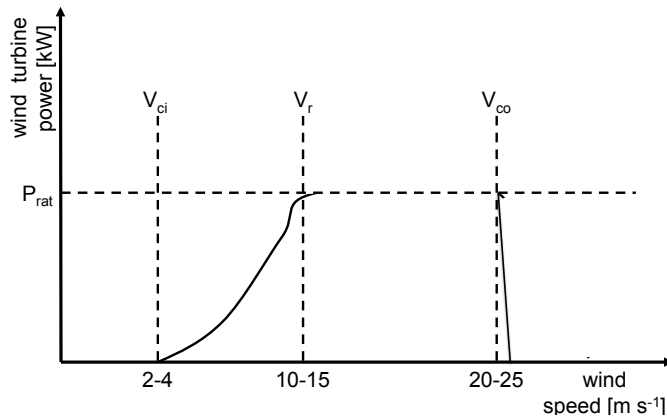


FIGURE E.8: Power curve of a wind turbine. P_{rat} =rated capacity, V_{ci} =cut-in wind speed, V_r =rated wind speed, V_{co} =cut-out wind speed.

distribution at a certain location during a certain day in the year and depends on the variability of the wind [252]. k usually takes up a value between 1 and 3. A smaller k indicates a more variable, gusty wind profile. If no information is given regarding the wind speed distribution, k is typically set to 2 [252, 263]. The wind speeds for Adelaide are obtained from the Australian Bureau of Meteorology [260]. Daily profiles of 24 hours for a year (2010) are averaged for each month and then for each season. The available values have been measured at an elevation of 8.3, above ground level. A hub height of 10 m above ground level is assumed for single story Adelaide houses. The wind speed conversion to a different hub height is carried out as [252, 263, 416, 419]:

$$V_{h2} = V_{h1} \cdot \left(\frac{h2}{h1}\right)^\alpha \quad (\text{E.14})$$

with $h1$ the height of the measurements and $h2$ the conversion height with respective wind speeds V_{h1} and V_{h2} . α is the power law exponent, which is typically empirically determined based on the height of the measurements, the climatic and geographic conditions, the season and time of day [263, 419]. Without specific site data, however, the average value of $\alpha = 1/7$ is widely accepted [252, 263, 416, 419]. Table E.17 presents the obtained daily profiles in each season of wind speeds in Adelaide.

E.6 Solar irradiation variability

To analyse the impact on the results of Scenario II with respect to variability of solar irradiation, average daily (24 hours) profiles for each irradiation level (≤ 1 to ≤ 9 kWh m^{-2} day^{-1}) are required. Real-time PV output data [kW] from Adelaide have been

TABLE E.17: Wind speeds at house hub height for seasonal daily profiles in Adelaide, Australia [m s⁻¹]. S=summer, W=winter, MS=mid-season.

hr	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
S	5.47	5.98	5.73	5.55	5.49	5.55	5.28	4.84	5.36	6.08	6.03	6.46
W	3.30	3.34	3.57	2.82	2.87	3.49	3.00	3.35	2.72	3.63	4.01	4.35
MS	4.78	4.30	4.72	4.67	4.41	3.93	3.48	2.88	3.27	3.83	4.40	4.62
hr	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
S	6.15	6.52	7.09	6.96	7.17	7.16	7.17	7.04	6.83	6.02	5.79	5.58
W	4.84	5.37	5.43	5.07	4.50	4.31	3.22	3.13	3.41	3.59	3.87	4.01
MS	5.44	6.15	6.34	6.91	6.86	6.04	5.20	5.37	4.72	4.09	4.09	4.18

obtained for 2012, which are divided by the total PV surface and panel efficiency to obtain the solar irradiation on a tilted panel [kW m⁻²]. For each day in the year, the hourly values are summed to obtain daily irradiation levels [kWh m⁻² day⁻¹]. Within each season, the daily (24h) profiles of the days that fall within the same irradiation level are averaged to obtain average daily profiles for each radiation level in each season, for summer see Table E.18, for winter see Table E.19 and for mid-season see Table E.20.

The hourly output of the implemented PV units in each season then becomes:

$$PE_{PV,i,s,h}^{GEN} \leq \min(A_i^{PV} \cdot PV_{rat}; \sum_l \frac{d_{l,s} \cdot It_{l,s,h}}{d_s} \cdot A_i^{PV} \cdot n_{PV}^{ELEC}) \quad \forall i, s, h \quad (E.15)$$

with d_s the number of days in each season (see Table 4.2) and $d_{l,s}$ the number of days in each season per radiation level, see Table E.21.

TABLE E.18: Solar irradiation average summer daily profiles per radiation level, $It_{l,s,h}$ [kW m⁻²]. l_x =radiation level, S=summer.

hr	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
S_{l_0}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S_{l_1}	0.000	0.000	0.000	0.001	0.000	0.001	0.030	0.099	0.306	0.270	0.151	0.117
S_{l_2}	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.098	0.196	0.196	0.371	0.390
S_{l_3}	0.001	0.000	0.000	0.000	0.000	0.001	0.039	0.206	0.265	0.269	0.377	0.447
S_{l_4}	0.000	0.000	0.001	0.000	0.000	0.002	0.037	0.182	0.249	0.350	0.505	0.681
S_{l_5}	0.000	0.000	0.000	0.000	0.000	0.001	0.036	0.134	0.306	0.380	0.549	0.747
S_{l_6}	0.000	0.000	0.000	0.000	0.000	0.002	0.041	0.168	0.357	0.527	0.656	0.805
S_{l_7}	0.000	0.000	0.000	0.000	0.000	0.001	0.023	0.119	0.333	0.533	0.700	0.820
S_{l_8}	0.000	0.000	0.000	0.000	0.000	0.001	0.036	0.173	0.430	0.650	0.828	0.967
S_{l_9}	0.000	0.000	0.000	0.000	0.000	0.001	0.041	0.204	0.476	0.731	0.902	1.007
hr	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
S_{l_0}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S_{l_1}	0.107	0.209	0.234	0.075	0.052	0.080	0.028	0.001	0.000	0.000	0.000	0.000
S_{l_2}	0.242	0.216	0.270	0.162	0.141	0.080	0.044	0.003	0.000	0.000	0.000	0.000
S_{l_3}	0.413	0.339	0.350	0.327	0.264	0.154	0.059	0.004	0.000	0.000	0.000	0.000
S_{l_4}	0.673	0.494	0.462	0.364	0.229	0.207	0.085	0.006	0.000	0.000	0.000	0.000
S_{l_5}	0.809	0.762	0.657	0.507	0.420	0.275	0.100	0.011	0.000	0.000	0.000	0.000
S_{l_6}	0.869	0.853	0.775	0.592	0.504	0.382	0.130	0.013	0.000	0.000	0.000	0.000
S_{l_7}	0.932	0.941	0.914	0.826	0.678	0.438	0.186	0.018	0.000	0.000	0.000	0.000
S_{l_8}	1.023	1.041	0.998	0.889	0.728	0.492	0.231	0.031	0.000	0.000	0.000	0.000
S_{l_9}	1.058	1.089	1.039	0.937	0.775	0.554	0.275	0.048	0.000	0.000	0.000	0.000

TABLE E.19: Solar irradiation average winter daily profiles per radiation level, $It_{l,s,h}$ [kW m⁻²]. l_x =radiation level, W=winter.

hr	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
W _{l₀}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.062	0.092	0.126
W _{l₁}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.029	0.094	0.174	0.261
W _{l₂}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.036	0.142	0.271	0.377
W _{l₃}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.059	0.216	0.385	0.516
W _{l₄}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.087	0.267	0.479	0.647
W _{l₅}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.130	0.353	0.574	0.747
W _{l₆}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₇}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₈}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₉}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hr	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
W _{l₀}	0.132	0.153	0.113	0.090	0.049	0.005	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₁}	0.266	0.260	0.208	0.148	0.067	0.017	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₂}	0.426	0.444	0.349	0.259	0.136	0.027	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₃}	0.571	0.593	0.537	0.410	0.213	0.032	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₄}	0.715	0.711	0.627	0.499	0.319	0.059	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₅}	0.819	0.816	0.751	0.615	0.398	0.144	0.001	0.000	0.000	0.000	0.000	0.000
W _{l₆}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₇}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₈}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W _{l₉}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

TABLE E.20: Solar irradiation average mid-season daily profiles per radiation level, $It_{l,s,h}$ [kW m⁻²]. l_x =radiation level, MS=mid-season.

hr	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
MS _{l₀}	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.002	0.026	0.050	0.072	0.191
MS _{l₁}	0.001	0.001	0.000	0.000	0.000	0.000	0.009	0.039	0.093	0.148	0.167	0.206
MS _{l₂}	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.029	0.112	0.210	0.296	0.357
MS _{l₃}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.154	0.295	0.417	0.554
MS _{l₄}	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.035	0.126	0.259	0.423	0.506
MS _{l₅}	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.045	0.216	0.439	0.584	0.698
MS _{l₆}	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.074	0.266	0.501	0.697	0.835
MS _{l₇}	0.000	0.000	0.000	0.001	0.000	0.000	0.012	0.110	0.357	0.605	0.781	0.941
MS _{l₈}	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.157	0.376	0.655	0.885	0.996
MS _{l₉}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hr	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
MS _{l₀}	0.074	0.045	0.042	0.107	0.020	0.005	0.000	0.000	0.000	0.000	0.001	0.000
MS _{l₁}	0.197	0.182	0.144	0.064	0.061	0.043	0.005	0.000	0.000	0.000	0.000	0.000
MS _{l₂}	0.360	0.352	0.289	0.237	0.157	0.071	0.017	0.000	0.000	0.000	0.000	0.000
MS _{l₃}	0.613	0.551	0.473	0.316	0.176	0.074	0.015	0.000	0.000	0.000	0.000	0.000
MS _{l₄}	0.609	0.658	0.635	0.521	0.327	0.124	0.012	0.000	0.000	0.000	0.000	0.000
MS _{l₅}	0.788	0.787	0.714	0.573	0.391	0.157	0.019	0.000	0.000	0.000	0.000	0.000
MS _{l₆}	0.896	0.851	0.821	0.709	0.501	0.265	0.051	0.000	0.000	0.000	0.000	0.000
MS _{l₇}	1.001	1.000	0.941	0.796	0.600	0.322	0.069	0.001	0.000	0.000	0.000	0.000
MS _{l₈}	1.032	1.039	0.973	0.845	0.649	0.390	0.105	0.001	0.000	0.000	0.000	0.000
MS _{l₉}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

TABLE E.21: Number of days per radiation level (l_x) per season ($d_{l,s}$). W=winter, S=summer, MS=mid-season.

	l_0	l_1	l_2	l_3	l_4	l_5	l_6	l_7	l_8	l_9
W	3	12	41	44	20	3	0	0	0	0
S	0	1	3	5	4	10	12	27	47	11
MS	2	4	13	9	17	31	27	14	5	0

Appendix F

Additional analysis of Chapter 4

This Appendix provides additional analysis with regard to the developed cost-optimal DES design model of Chapter 4. The loop breaking constraint is detailed. Additionally, optcr-analysis and discrete technology capacities are presented.

F.1 Background loop breaking constraint

The system in this thesis requires constraints to develop thermal pipeline networks. These networks consists of pipelines from a house i to a house j . Multiple houses can be connected into a single directed network and multiple networks can exist. Network optimisation is thus an adaptation of a vehicle routing problem [420]. The routing problem optimises the route of the transport service with respect to an objective. In this work multiple pipelines can be installed that can send thermal power from source houses with CHP units to transferring or sink houses for consumption. The problem is formulated based on integer programming [253, 421]:

$$OH_j \geq OH_i + 1 - n_h \cdot (1 - YP_{i,j}) \quad \forall i, j \text{ and } i \neq j \quad (\text{F.1})$$

Here are i and j houses in the neighbourhood and OH_i is a positive integer variable that indicates for each house the visiting order in the network (strictly increasing from source to sink houses). $YP_{i,j}$ is a binary variable that indicates the implementation and existence of a pipeline between houses i and j , and n_h is the total number of houses in the neighbourhood [96]. Multiple sub-networks are here allowed but due to the strictly

increasing order variable, no closed loops are allowed. Note that only directed closed networks are excluded, with all pipes oriented in the same direction, see Figure F.1.



FIGURE F.1: Schematic of closed (left, not allowed) and non-closed (right, allowed) directed pipeline networks between nodes, adapted from Mehleri et al. [96].

Closed loops of directed pipelines are thus not allowed through Equation F.1. Proof of this theorem has been presented in Liu et al. [253]. The Theorem on subtour elimination is summarised below. Assume that a closed directed pipeline network consisting of n houses i and $n \geq 2$ is adopted in a solution. The binary pipeline connection variables for the n houses are then all equal to 1 since a pipeline is installed between each house pair i and j :

$$YP_{i_1, i_2} = YP_{i_2, i_3} = \dots = YP_{i_{n-1}, i_n} = YP_{i_n, i_1} = 1 \quad (\text{F.2})$$

This leads to the following constraints based on Equation F.1:

$$\begin{aligned} OH_{i_2} - OH_{i_1} &\geq 1, & OH_{i_3} - OH_{i_2} &\geq 1, & \dots \\ OH_{i_n} - OH_{i_{n-1}} &\geq 1, & OH_{i_1} - OH_{i_n} &\geq 1 \end{aligned} \quad (\text{F.3})$$

Summing the above constraints leads to the contradiction:

$$OH_{i_1} - OH_{i_1} (= 0) \geq n \quad (\text{F.4})$$

which implies that there can be no closed loops in the system.

F.2 optcr

The developed model is applied to a neighbourhood in Adelaide. Global optimality was employed in order to be able to compare the results of various case-studies and analyses. The model in Scenario II namely leads to multiple discrete feasible designs for an optcr smaller or equal than 10 %. These multiple designs only differ slightly, or not even, in cost, but do differ in capacity, siting, sizing and existence of units. Even an optimality

gap of 1 % or 1.5 % changes the structure of the pipeline network compared to global optimality (see Table F.4). For an optimality gap greater than 1.58 %, pipelines and microgrid infrastructure are even no longer installed. There is thus a range of designs that neighbourhoods can take into account if they consider an increase in cost of less than 10 %. The following Tables summarise key results for discrete feasible designs: distribution of cost (F.1), installed capacity and location of boilers and CHP units (F.2), PV units (F.3), heat storage units as well as pipeline and microgrid existence (F.4).

TABLE F.1: Cost distribution [AUD y^{-1}] of feasible designs for $\text{optcr} \leq 10\%$.

	C^{tot}	C^{inv}	C^{om}	C^{fuel}	C_{buy}^{grid}	C_{sell}^{grid}
0%	22264.091	3797.676	1294.285	14234.890	3266.663	329.424
0.01%	22264.109	3797.676	1294.298	14234.896	3266.663	329.424
0.05%	22264.109	3797.676	1294.298	14234.896	3266.663	329.424
0.09%	22264.109	3797.676	1294.298	14234.896	3266.663	329.424
0.11%	22264.109	3797.676	1294.298	14234.896	3266.663	329.424
0.12%	22264.109	3797.676	1294.298	14234.896	3266.663	329.424
0.14%	22265.892	3798.105	1294.344	14235.209	3267.046	328.813
0.15%	22265.892	3798.105	1294.344	14235.209	3267.046	328.813
0.17%	22268.335	3798.105	1294.181	14229.789	3275.072	328.813
0.18%	22269.928	3801.603	1294.452	14236.230	3267.046	329.403
0.35%	22308.564	3808.961	1300.440	14155.375	3364.909	321.122
0.38%	22308.564	3808.961	1300.440	14155.375	3364.909	321.122
0.43%	22308.564	3808.961	1300.440	14155.375	3364.909	321.122
0.44%	22308.564	3808.961	1300.440	14155.375	3364.909	321.122
0.45%	22309.618	3809.097	1300.433	14155.312	3364.909	320.133
0.47%	22313.479	3811.784	1300.453	14154.109	3367.266	320.133
0.49%	22313.479	3811.784	1300.453	14154.109	3367.266	320.133
0.50%	22313.479	3811.784	1300.453	14154.109	3367.266	320.133
0.73%	22365.502	3869.015	1300.652	14169.203	3347.753	321.122
0.78%	22375.318	3869.772	1301.009	14165.288	3359.384	320.134
0.81%	22375.318	3869.772	1301.009	14165.288	3359.384	320.134
1.35%	22375.318	3869.772	1301.009	14165.288	3359.384	320.134
1.58%	22375.318	3869.772	1301.009	14165.288	3359.384	320.134
3.06%	22717.462	3055.961	1389.063	13318.404	5262.118	308.084
3.19%	22717.462	3055.961	1389.063	13318.404	5262.118	308.084
6.35%	23482.818	4870.104	1651.977	13318.404	4481.931	839.599

F.3 Discrete technology capacities

Instead of continuous capacity ranges for technologies, bound by upper and lower levels, a discrete number of fixed capacities can be adopted that could be available in the market. Below an implementation example of CHP units with k different discrete electrical capacities, $DG_{CHP,k}^{MAX}$ [kW], is presented, adapted from Mehleri et al. [95, 96]. Each house (i) can only install a single CHP unit of type k , decided through binary variable

TABLE F.2: House (h_i) B and CHP capacity [kW] of feasible designs for $\text{optcr} \leq 10\%$.

	Boiler (B)					CHP	
	h_1	h_2	h_3	h_4	h_5	h_1	h_2
0%	5.068	6.335	6.968	7.602			2.080
0.01%	5.068	6.335	6.968	7.602			2.080
0.05%	5.068	6.335	6.968	7.602			2.080
0.09%	5.068	6.335	6.968	7.602			2.080
0.11%	5.068	6.335	6.968	7.602			2.080
0.12%	5.068	6.335	6.968	7.602			2.080
0.14%	5.068	6.335	6.968	7.602			2.077
0.15%	5.068	6.335	6.968	7.602			2.077
0.17%	5.068	6.335	6.968	7.602			2.077
0.18%	5.068	6.335	6.968	7.602			2.077
0.35%	5.701	6.335	6.968	7.602		1.889	
0.38%	5.701	6.335	6.968	7.602		1.889	
0.43%	5.701	6.335	6.968	7.602		1.889	
0.44%	5.701	6.335	6.968	7.602		1.889	
0.45%	5.701	6.335	6.968	7.602		1.889	
0.47%	5.701	6.335	6.968	7.602		1.882	
0.49%	5.701	6.335	6.968	7.602		1.882	
0.50%	5.701	6.335	6.968	7.602		1.882	
0.73%	5.701	6.335	6.968	7.602		1.889	
0.78%	5.701	6.335	6.968	7.602		1.875	
0.81%	5.701	6.335	6.968	7.602		1.875	
1.35%	5.701	6.335	6.968	7.602		1.875	
1.58%	5.701	6.335	6.968	7.602		1.875	
3.06%	5.068	5.701	6.335	6.968	7.602		
3.19%	5.068	5.701	6.335	6.968	7.602		
6.35%	5.068	5.701	6.335	6.968	7.602		

TABLE F.3: House (h_i) PV capacity [kW] of feasible designs for $\text{optcr} \leq 10\%$.

	PV					tot
	h_1	h_2	h_3	h_4	h_5	total
0%	1.684	1.895	2.107	2.318	2.529	10.533
0.01%	1.684	1.895	2.107	2.318	2.529	10.533
0.05%	1.684	1.895	2.107	2.318	2.529	10.533
0.09%	1.684	1.895	2.107	2.318	2.529	10.533
0.11%	1.684	1.895	2.107	2.318	2.529	10.533
0.12%	1.684	1.895	2.107	2.318	2.529	10.533
0.14%	1.684	1.895	2.107	2.318	2.529	10.533
0.15%	1.684	1.895	2.107	2.318	2.529	10.533
0.17%	1.684	1.895	2.107	2.318	2.529	10.533
0.18%	1.684	1.895	2.107	2.318	2.529	10.533
0.35%	1.684	1.856	2.107	2.337	2.529	10.513
0.38%	1.684	1.856	2.107	2.337	2.529	10.513
0.43%	1.684	1.856	2.107	2.337	2.529	10.513
0.44%	1.684	1.856	2.107	2.337	2.529	10.513
0.45%	1.684	1.895	2.107	2.318	2.529	10.533
0.47%	1.684	1.895	2.107	2.318	2.529	10.533
0.49%	1.684	1.895	2.107	2.318	2.529	10.533
0.50%	1.684	1.895	2.107	2.318	2.529	10.533
0.73%	1.684	1.856	2.107	2.337	2.529	10.513
0.78%	0.601	2.465	2.400	2.511	2.557	10.534
0.81%	0.601	2.465	2.400	2.511	2.557	10.534
1.35%	0.601	2.465	2.400	2.511	2.557	10.534
1.58%	0.601	2.465	2.400	2.511	2.557	10.534
3.06%	2.193	1.913	2.125	2.337	2.549	11.117
3.19%	2.193	1.913	2.125	2.337	2.549	11.117
6.35%	3.183	3.583	3.983	4.375	4.775	19.899

TABLE F.4: House (h_i) HST capacity [kW], pipeline and microgrid existence of feasible designs for $\text{optcr} \leq 10\%$.

	HST					Pipe	MG
	h_1	h_2	h_3	h_4	h_5		
0%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.01%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.05%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.09%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.11%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.12%	0.749	1.530	0.936	1.029	1.123	2 to 4	✓
0.14%	0.749	1.557	0.936	1.029	1.123	2 to 4	✓
0.15%	0.749	1.557	0.936	1.029	1.123	2 to 4	✓
0.17%	0.749	1.557	0.936	1.029	1.123	2 to 4	✓
0.18%	0.749	1.557	0.936	1.029	1.123	2 to 4	✓
0.35%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.38%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.43%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.44%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.45%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.47%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.49%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.50%	1.160	0.842	0.936	1.029	1.123	1 to 2	✓
0.73%	1.178	0.842	0.936	1.029	1.123	1 to 3	✓
0.78%	1.200	0.842	0.936	1.029	1.123	1 to 3	✓
0.81%	1.200	0.842	0.936	1.029	1.123	1 to 3	✓
1.35%	1.200	0.842	0.936	1.029	1.123	1 to 3	✓
1.58%	1.200	0.842	0.936	1.029	1.123	1 to 3	✓
3.06%	0.749	0.842	0.936	1.029	1.123	–	–
3.19%	0.749	0.842	0.936	1.029	1.123	–	–
6.35%	0.749	0.842	0.936	1.029	1.123	–	–

$B_{CHP,k,i}$:

$$\sum_k B_{CHP,k,i} \leq 1 \quad \forall i \quad (\text{F.5})$$

Electricity generated by the CHP unit in each hour h is limited by its installed capacity:

$$PE_{CHP,i,s,h}^{TOT} \leq \sum_k B_{CHP,k,i} \cdot DG_{CHP,k}^{MAX} \quad \forall i, s, h \quad (\text{F.6})$$

Similarly, the different discrete CHP units could have different efficiencies $n_{CHP,k}^{elc}$ or heat to electricity ratios $HER_{CHP,k}$, this was presented by, e.g. Wouters et al. [248].

Appendix G

Background on availability

This Appendix provides some additional concepts regarding availability in support of Chapter 5. Component and system availability is elaborated on together with additional detail on analytical system availability methods.

G.1 Component availability

A component failure rate function $z(t)$ determines the expected outages of a certain component type over time [23]:

$$z(t) = \frac{1}{N_o(t)} \frac{dN_f(t)}{dt} \quad (\text{G.1})$$

N represents here the number of identical components of which N_o components still work and N_f components definitely failed at a certain time t . $\frac{dN_f(t)}{dt}$ is the instantaneous component failure rate.

The assumption of constant component failure (λ) and repair (μ) rates over a certain time follows an exponential probability distribution [53, 291]. When looking at the availability of a component, a distinction has to be made between repairable and non-repairable components. With non-repairable components, the availability, $A(t)$, is equal to the reliability, $R(t)$ [53]. For repairable components, probability theory can be used and exponential repair rates are included (see [53]). The availability of a component assumed available at time zero then becomes:

$$A(t) = \frac{\mu}{\lambda + \mu} - \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t} \quad (\text{G.2})$$

The asymptotic component availability and unavailability are then, respectively:

$$\lim_{t \rightarrow \infty} A(t) = A(\infty) = \frac{\mu}{\lambda + \mu} \quad \text{and} \quad U(\infty) = 1 - A(\infty) = \frac{\lambda}{\lambda + \mu} \quad (\text{G.3})$$

G.2 System availability

Regarding the appropriate technique to assess reliability and availability of electricity systems, no general consensus exists [293, 294]. There are probabilistic criteria, commonly accepted indices and analytical as well as simulation based evaluation techniques [293, 294]. Different evaluation techniques are given below.

G.3 Analytical availability methods

Billinton et al. [55, 282], Chowdhury et al. [422], Villemeur et al. [53], Wouters [296] and Logacio [285] detail various probabilistic techniques to assess system availability. The most common analytical techniques are summarised in the following Sections.

G.3.1 Success Diagram Method (SDM)

This technique reduces component sequences in the system to series or parallel subsystems to enable employing reliability and availability mathematical techniques using failure and repair rates of components and the sequence between them [53, 55, 282]. These subsystems are then recombined in order to determine overall system dependability. Additionally, stand-by equipment and switching actions can be integrated. The SDM – or Reliability Block Diagram – was historically the first method employed for system reliability assessment (established in the early 1960s) [53]. This technique is still widely employed in various industrial applications of non-repairable systems. Under specific conditions, also repairable systems can be evaluated to determine dependability attributes, such as reliability and maintainability [53].

The aim is to reduce the system as much as possible into combinations of serial and parallel sequences of blocks that are connected through in- and outputs [53]. A serial sequence of components has to work all together in order for the (sub)system to work as intended [30, 423]. In a parallel sequence of components only one of the components

needs to function in order for the (sub)system to work as intended [30, 423]. Series and parallel systems can represent a redundant system between in- and output [30, 286, 291].

The main advantage of this technique is that system availability and reliability can be obtained in a straightforward manner. Furthermore, mostly simple non-repairable systems can be analysed without looking in detail at causes and effects of component failures. The main disadvantages of this technique are that the system must be reducible to series and parallel connections of components. Hence, this technique is only applicable to non-complex systems. Furthermore, only overall system reliability or availability can be assessed, not the probability of partial operating states or subsystems. Additionally, components and events must be independent of each other; hence no component can appear more than once in the block diagram and only active redundancy is allowed [53]. This technique is only applicable for repairable systems under the condition that events in the block diagram occur independently from each other [53]. If this method is applicable to a system, the calculation of the dependability attributes is straightforward. A series system of components with availability a_i is given in Figure G.1. With constant component failure (λ_i) and repair (μ_i) rates, and assuming that each component was available at time zero, series system (un)availability is [53]:

$$A(t) = \prod_{i=1}^n a_i(t) = \prod_{i=1}^n \left[\frac{\mu_i}{\lambda_i + \mu_i} + \frac{\lambda_i}{\lambda_i + \mu_i} e^{-(\lambda_i + \mu_i)t} \right] \quad (\text{G.4})$$

$$U(t) = 1 - \prod_{i=1}^n a_i(t) \quad (\text{G.5})$$

The asymptotic (un)availability becomes then equal to [53]:

$$A(\infty) = \lim_{t \rightarrow \infty} A(t) = \prod_{i=1}^n \frac{\mu_i}{\lambda_i + \mu_i} = \prod_{i=1}^n a_i \quad (\text{G.6})$$

$$UA(\infty) = 1 - A(\infty) = 1 - \prod_{i=1}^n \frac{\mu_i}{\lambda_i + \mu_i} = 1 - \prod_{i=1}^n a_i = 1 - \prod_{i=1}^n (1 - ua_i) \quad (\text{G.7})$$

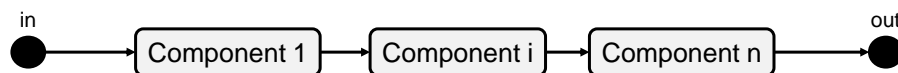


FIGURE G.1: Series connection of components, adapted from Villemeur [53].

A parallel system is illustrated in Figure G.2. The availability of a *repairable parallel system* is found by taking the complement of the product of the unavailabilities of its

components [53]. The unavailability of a repairable system equals the product of the unavailability of its components [53]. Using the assumption of constant failure and repair rates and the availability of the components at time zero, the availability of the parallel system is [53]:

$$A(t) = 1 - \prod_{i=1}^n \left[\frac{\lambda_i}{\lambda_i + \mu_i} (1 - e^{-(\lambda_i + \mu_i)t}) \right] \quad (\text{G.8})$$

The asymptotic availability then becomes [53]:

$$\begin{aligned} A(\infty) &= \lim_{t \rightarrow \infty} A(t) = \sum_{i=1}^n \frac{\mu_i}{\lambda_i + \mu_i} = \sum_{i=1}^n a_i \quad (\text{G.9}) \\ &= 1 - \prod_{i=1}^n \frac{\lambda_i}{\lambda_i + \mu_i} = 1 - \prod_{i=1}^n ua_i \end{aligned}$$

$$UA(\infty) = 1 - A(\infty) = 1 - \sum_{i=1}^n a_i = \prod_{i=1}^n ua_i(t) \quad (\text{G.10})$$

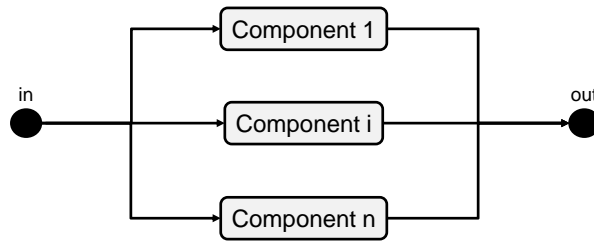


FIGURE G.2: Parallel connection of components, adapted from Villemeur [53].

G.3.2 Cut and Tie Set methods

The Cut Set method looks to visually identify the system ‘cut sets’. System cut sets are a combination of system components that result in total system failure if they all fail. Cut sets can hence not identify the probability of partly available states. This visual method is thus only applicable to small non-complex systems. The Tie Set method employs a similar technique to the Cut Set method, resulting in similar limitations. System tie sets are a combination of system components that result in total system failure if one of them fails. The Tie Set method is less frequently employed in practice.

G.3.3 Fault Tree Analysis

The fault tree analysis identifies all individual causes of system failure. All component faults that lead to system failures are then implemented in a logic tree-like structure. Partial and fully failed system states as well as their causes can hereby be identified. As each individual system failure requires a separate tree diagram of its causes, the fault tree can become complex.

G.3.4 Event Tree Analysis

This visual technique involves identifying all events that can occur in a system, enabling identification of partially and fully failed system states. System state probabilities can be obtained as the product (series relation) of the probability of the different causes that lead to the state. The main disadvantage of this technique is that component repair cannot be included.

G.3.5 State Space Diagram (SSD) or Markov method

This technique involves determining a visual representation of identified system states and transitions between them. System state transitions relate to the failure or repair of system components. This technique is thus flexible to include and extend to different states, and failure and repair events. Each state transition is time related. The probability of occurrence of identified states is thus determined at each time. At any point in time the state probabilities will sum up to 1 as the system can only be in a single state. The State Space method can analyse repairable and non-repairable systems [53]. A state diagram is constructed containing all the different states of the system, i.e. operating, partial-operating and failed states [53, 55, 282]. The initial state is the state where the system is fully operational. Additionally, a time aspect can be integrated in determining the probability of each state after a certain time interval.

The diagram is constructed as in Chapter 5, Section 5.2.2.3. First, system states and components that make up the system are identified. Each component is either failed or operational. A system with n components can thus have at most 2^n system states [53]. Second, transition possibilities between the defined system states have to be identified as well as their cause, which is either a failure or a repair action [53]. Last, transition

probabilities between states are calculated from indices. The probability of occurrence of system states are obtained through, for example, the transition matrix method [53, 56].

The main requirements to employ this technique are that the system can only be in one of the determined states and it can transition between states [292]. The transition between and the occurrence of states is independent and homogeneous (Markov). This implies that the long term state transition rates are time independent [292]. The main advantages of this method are that algorithms can be readily implemented [292], the method is versatile in that it can include system changes and repairs [292], it is one of the most used dependability evaluation techniques [292], it can incorporate failure, repair and any type of failure state, and the State Space Diagram Markov method can be dynamic with time. The main disadvantages are that the technique can become very complex for large systems with a lot of components, i.e. a lot of system states and transitions [292], failure and repair rates of the different components have to be known in order to be able to find the final state probabilities, and detailed knowledge of the system operation and its components has to be known.

Appendix H

Logic-gate operations

This Appendix provides some additional concepts regarding logic-gate operation of mutually exclusive binary variables in support of Chapter 5. Logic-gate operation is a way to perform integer programming. Different combinations of technologies can in this way be represented by a series of ones and zeros, which enables ‘switching on’ and ‘switching off’ of technologies to represent the system configurations. Figure H.1a represents a simple AND-gate with two binary inputs. An AND-gate represents a series connection of binary inputs of which the binary output value can be found as [51–53]:

$$C = A \text{ AND } B = A \wedge B = A \cdot B \quad (\text{H.1})$$

This relation can be linearised as follows, using the procedure presented in [107, 310]:

$$\begin{aligned} C &\geq \sum (\text{inputs}) - (\text{number of inputs} - 1) \\ &\leq \text{each input} \end{aligned} \quad (\text{H.2})$$

$$\begin{aligned} C &\geq A + B - 1 \\ C &\leq A \quad \text{and} \quad C \leq B \end{aligned} \quad (\text{H.3})$$

A NOT-gate inverts its input [51–53]. With A a binary variable this becomes:

$$\text{NOT } A = \bar{A} = 1 - A \quad (\text{H.4})$$

A simple OR-gate is presented in Figure H.1b and represents a parallel configuration of binary inputs. Binary output (E) of an OR-gate with binary inputs (F , G) can be

implemented as:

$$E = F \text{ OR } G \tag{H.5}$$

$$E \leq F + G \quad \text{and} \quad E \geq F \quad \text{and} \quad E \geq G \tag{H.6}$$

If the inputs are mutually exclusive, the output E can be found as [51–53]:

$$E = F \text{ OR } G = F \vee G = F + G \tag{H.7}$$

A combination AND-NOT gate is presented in Figure H.1c. The output is found as:

$$P = K \text{ AND } \bar{L} \text{ AND } M \tag{H.8}$$

Which is linearised using the procedure presented in [107, 310]:

$$P \geq K + (1 - L) + M - 2$$

$$P \leq K \quad \text{and} \quad P \leq 1 - L \quad \text{and} \quad P \leq M \tag{H.9}$$

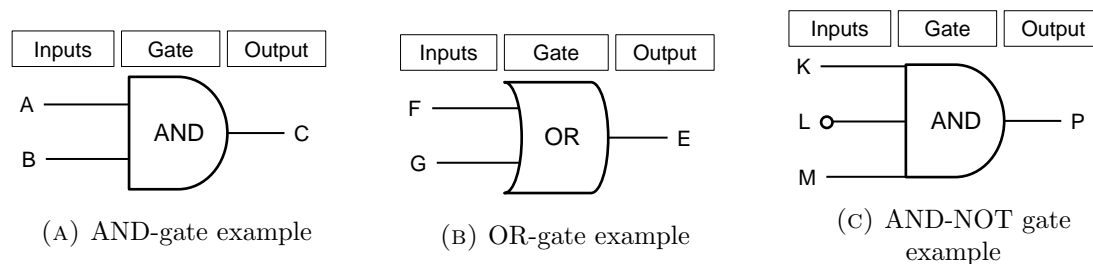


FIGURE H.1: Logic-gate operations.

TABLE H.1: Logic-gates truth tables.

AND-gate		
Value of binary input 1	Value of binary input 2	output
0	0	0
1	0	0
0	1	0
1	1	1
OR-gate		
Value of binary input 1	Value of binary input 2	output
0	0	0
1	0	1
0	1	1
1	1	1
NOT-gate		
Value of binary input		output
0		1
1		0

Appendix I

Additional equations and input parameters of Chapter 5

This Appendix provides some additional input parameters and linearisation procedures in support of Chapter 5. Component availability data is detailed together with threshold capacity dimensioning of batteries and PV units as well as system configurations.

I.1 PV threshold capacity and resource availability

I.1.1 PV threshold capacity

A PV unit available to a house, needs its output to be able to meet its house peak load:

$$PE_{PV,max,i}^{TOT} = C_{ELEC,i}^{PLOAD} = \max_{s,h}(C_{ELEC,i,s,h}^{LOAD} + \frac{C_{COOL,i,s,h}^{LOAD}}{COP_{airco}}) \quad \forall i \quad (I.1)$$

From Equation D.11, the worst case threshold capacity [m²] can be found as:

$$T_{PV,i}^{av} = \frac{C_{ELEC,i}^{PLOAD}}{n_{PV}^{ELEC}} \quad \forall i \quad (I.2)$$

I.1.2 Solar irradiation availability

PV unit resource availability relates to the availability of solar irradiation in an hour h to generate enough power to meet the load of the accommodating house in that hour. House 3 is taken as reference to assess the availability level based on an installed PV

unit of available capacity in its house. The other houses follow a similar approach. First average seasonal hourly irradiation profiles, adopted from real PV output (see Appendix E, Section E.6), are required. These irradiation values are transformed in an hourly PV output employing the threshold capacity and a rated efficiency. These power outputs are then compared with the household electrical demand for electricity and cooling in the same hour, see Table I.1. The number of hours per day that the PV generation is able to cover the load is: 5 of 24 (winter 20.8333 %), 4 of 24 (summer 16.6667 %), pr 7 of 24 (midseason 29.1667 %). Weighted with the number of days in each season, this leads to an average hourly solar resource availability of 22.2489 %.

TABLE I.1: PV output and household demand comparison [kW]. Wh_3 =winter electricity demands house 3, MSh_3 =mid-season electricity demands house 3, Sh_3 =summer electricity house 3, PV=PV output level.

	h1	h2	h3	h4	h5	h6	h7	h8	h9	h10	h11	h12
Wh_3	0.258	0.258	0.270	0.291	0.285	0.298	0.353	0.462	0.526	0.531	0.520	0.505
PV	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.074	0.259	0.469	0.639
Sh_3	0.479	0.500	0.459	0.439	0.405	0.416	0.497	0.574	0.740	0.874	0.934	1.049
PV	0.000	0.000	0.000	0.000	0.000	0.002	0.047	0.220	0.519	0.769	0.994	1.176
MSh_3	0.264	0.298	0.302	0.309	0.311	0.358	0.426	0.478	0.525	0.560	0.618	0.674
PV	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.080	0.297	0.560	0.770	0.927
	h13	h14	h15	h16	h17	h18	h19	h20	h21	h22	h23	h24
Wh_3	0.498	0.479	0.481	0.470	0.510	0.636	0.827	0.866	0.800	0.663	0.388	0.258
PV	0.708	0.726	0.625	0.478	0.264	0.049	0.000	0.000	0.000	0.000	0.000	0.000
Sh_3	1.103	1.215	1.261	1.363	1.383	1.314	1.214	1.015	0.747	0.556	0.563	0.545
PV	1.256	1.253	1.193	1.040	0.853	0.580	0.257	0.032	0.000	0.000	0.000	0.000
MSh_3	0.701	0.689	0.701	0.750	0.776	0.769	0.815	0.758	0.661	0.496	0.328	0.264
PV	1.012	0.999	0.927	0.765	0.530	0.253	0.046	0.000	0.000	0.000	0.000	0.000

I.2 Battery dimensioning

I.2.1 Battery resource availability

The *resource availability* of batteries is either the probability of an appropriately sized available CHP unit, an appropriately sized available PV unit, or, both an appropriately sized available CHP and PV unit. PV-CHP-charged battery availability is determined by a State Space Diagram of its charging options, see Figure I.1. Charging is unavailable without DG unit (state 4, $P_{s4} = UA_{EST}^{res} = ua_{pv} \cdot ua_{chp}$). Charging is available otherwise ($A_{EST}^{res} = P_{s1} + P_{s2} + P_{s3} = a_{pv} \cdot a_{chp} + a_{pv} \cdot ua_{chp} + ua_{pv} \cdot a_{chp}$).

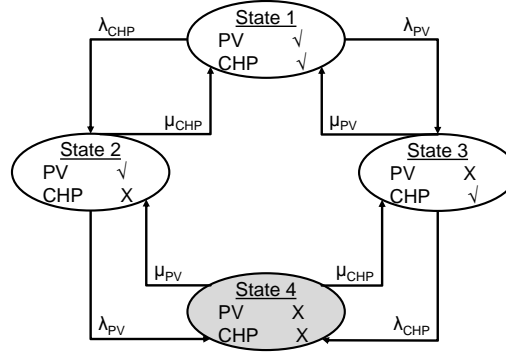


FIGURE I.1: PV-CHP battery charging State Space Diagram.

I.2.2 Battery capacity thresholds

Battery threshold capacity is determined based on an installation rule of thumb [424, 425] and the requirement that the battery should be able to provide the average hourly load of the house during the determined autonomy time (AT). This requires the battery maximum state of charge to be, with η the static loss and DOC the depth of charge:

$$ES_i^{max} = AT \cdot \frac{hr \cdot C_{ELECav,i}^{LOAD}}{(1 - \delta\chi)} + (1 - DOC) \cdot ES_i^{max} \quad (I.3)$$

Reworking this, the battery threshold capacity can be found as:

$$ES_i^{max} = T_{EST,i}^{av} = \frac{C_{ELECav,i}^{LOAD}}{(1 - \delta\chi) \cdot DOC} \cdot AT \quad (I.4)$$

Autonomy time is defined as the time the fully charged battery can supply the load of the house where it is installed in, typically expressed in number of hours (on-grid) or days (off-grid). The average hourly electricity demand for each house is found as:

$$C_{ELECav,i}^{LOAD} = \sum_{s,h} hr \cdot d_s \cdot (C_{ELEC,i,s,h}^{LOAD} + \frac{C_{COOL,i,s,h}^{LOAD}}{COP_{airco}}) \cdot 8760^{-1} \quad (I.5)$$

For the five houses these demands then become, $h_1 = 0.487\text{kW}$, $h_2 = 0.548\text{kW}$, $h_3 = 0.608\text{kW}$, $h_4 = 0.669\text{kW}$, and $h_5 = 0.730\text{kW}$. The respective threshold capacities are then for on-grid configurations ($AT=3$ hours): $h_1 = 2.088\text{kWh}$, $h_2 = 2.349\text{kWh}$, $h_3 = 2.610\text{kWh}$, $h_4 = 2.871\text{kWh}$, and $h_5 = 3.131\text{kWh}$, and for off-grid configurations ($AT=2$ days= 48 hours): $h_1 = 33.402\text{kWh}$, $h_2 = 37.581\text{kWh}$, $h_3 = 41.756\text{kWh}$, $h_4 = 45.930\text{kWh}$, and $h_5 = 50.102\text{kWh}$.

I.2.3 Charging resource availability for battery availability

Battery operation occurs through a daily roll-over, see Section D.2.3. Assume that for three consecutive hours (h_1, h_2, h_3), the battery needs to meet the average load of its accommodating house $C_{av,i,h}^{elec}$ [kW]. The worst case scenario requires the battery to be fully charged in a single hour preceding these three discharging hours (h_0). In h_0 , the battery is then at its lowest charge ($1 - DOC$) and in hours 1 to 3 the battery is fully discharged to meet the load. The following relations then hold ($\forall i, s, h$):

$$ES_{i,s,h_0}^{STO} = (1 - DOC) \cdot ES_i^{max} + hr \cdot (1 - \chi) \cdot PS_{EST,i,s,h_0}^{IN} \quad (I.6)$$

$$ES_{i,s,h_1}^{STO} = (1 - \eta) \cdot ES_{i,s,h_0}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1 - \delta\chi)} \quad (I.7)$$

$$ES_{i,s,h_2}^{STO} = (1 - \eta) \cdot ES_{i,s,h_1}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1 - \delta\chi)} \quad (I.8)$$

$$ES_{i,s,h_3}^{STO} = (1 - \eta) \cdot ES_{i,s,h_2}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1 - \delta\chi)} \quad (I.9)$$

whilst respecting the minimum charge requirement:

$$ES_{i,s,h_3}^{STO} = (1 - DOC) \cdot ES_i^{max} \quad (I.10)$$

The above relations are then reworked to find the required value of inflow in hour zero. From Equations I.9 and I.10:

$$(1 - DOC) \cdot ES_i^{max} = (1 - \eta) \cdot ES_{i,s,h_2}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1 - \delta\chi)} \quad (I.11)$$

Equation I.11 can be reworked to:

$$ES_{i,s,h_2}^{STO} = \frac{1}{(1 - \eta)} \cdot [(1 - DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1 - \delta\chi)}] \quad (I.12)$$

Combining Equation I.12 with Equation I.8:

$$\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] = (1-\eta) \cdot ES_{i,s,h_1}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \quad (I.13)$$

and reworked to:

$$ES_{i,s,h_1}^{STO} = \frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] + hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \right] \quad (I.14)$$

Combining Equation I.14 with Equation I.7:

$$\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] + hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \right] = (1-\eta) \cdot ES_{i,s,h_0}^{STO} - hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1-\delta\chi)} \quad (I.15)$$

and reworking it to:

$$ES_{i,s,h_0}^{STO} = \frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] + hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \right] + hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1-\delta\chi)} \right] \quad (I.16)$$

And then combining Equation I.16 with Equation I.6:

$$\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] + hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \right] + hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1-\delta\chi)} \right] = (1-DOC) \cdot ES_i^{max} + hr \cdot (1-\chi) \cdot PS_{EST,i,s,h_0}^{IN} \quad (I.17)$$

The required battery charge inflow in a certain hour h_0 can then be found as:

$$PS_{EST,i,s,h_0}^{IN} = \frac{1}{hr \cdot (1-\chi)} \cdot \left[\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot \left[\frac{1}{(1-\eta)} \cdot [(1-DOC) \cdot ES_i^{max} + hr \cdot \frac{PS_{EST,i,s,h_3}^{OUT}}{(1-\delta\chi)}] + hr \cdot \frac{PS_{EST,i,s,h_2}^{OUT}}{(1-\delta\chi)} \right] + hr \cdot \frac{PS_{EST,i,s,h_1}^{OUT}}{(1-\delta\chi)} \right] - (1-DOC) \cdot ES_i^{max} \right] \quad (I.18)$$

With known inputs of $\chi = 10\%$, $\eta = 0.1\%$, $DOC = 70\%$, $ES_i^{max} = T_{EST,i}^{av}$ and $h_1 = 2.088\text{kWh}$, $h_2 = 2.349\text{kWh}$, $h_3 = 2.610\text{kWh}$, $h_4 = 2.871\text{kWh}$, and $h_5 = 3.131\text{kWh}$, $PS_{EST,i,s,h_{1-3}}^{OUT} = C_{ELECav,i}^{LOAD}$, and $\delta\chi = 15\%$, the input charging required in one hour can then be found for each hour. The installed PV unit or CHP unit that accompanies the installed battery must thus be able to provide this inflow together with the maximum demand in the house, in the worst case scenario. This requires an additional PV and CHP capacities of $h_1 = 1.914$, $h_2 = 2.154$, $h_3 = 2.393$, $h_4 = 2.632$, and, $h_5 = 2.871$ [kW]. The following constraints take this into account. If a PV unit is available to a battery (binary variable $Y_{PV,i}^b$) this additional capacity requirement C_i^{EXTRA} [kW] is required:

$$DG_{PV,i}^{MAX} \geq \frac{T_{PV,i}^{av} + C_i^{EXTRA}}{PV_{rat}} \cdot Y_{PV,i}^b \quad \forall i \quad (\text{I.19})$$

$$\text{with: } Y_{PV,i}^b + B_{PV,i} \leq 1 \quad \text{and} \quad B_{PV,i}^{av} \leq Y_{PV,i}^b \quad \forall i \quad (\text{I.20})$$

Similarly, the CHP capacity is adapted:

$$DG_{CHP,i}^{MAX} \geq (T_{CHP,i}^{av} + C_i^{EXTRA}) \cdot Z_{CHP,i}^b + (T_{MG,i}^{av} + C_i^{EXTRA}) \cdot Z_{MG,i}^b \quad \forall i \quad (\text{I.21})$$

with the following (AND-NOT, Appendix H) relations between CHP binaries:

$$Z_{CHP,i}^b = Y_{CHP,i}^b \wedge \overline{B_{MG,i}^{av}} \quad \text{and} \quad Z_{MG,i}^b = Y_{CHP,i}^b \wedge B_{MG,i}^{av} \quad \forall i \quad (\text{I.22})$$

$$Y_{CHP,i}^b = B_{CHP,i}^{av} \vee B_{CHP,i} \quad \forall i \quad (\text{I.23})$$

The battery is thus only available with available DG generation capacity:

$$B_{EST,i}^{av} \leq Y_{PV,i}^b + Y_{CHP,i}^b \quad \text{and} \quad B_{EST,i}^{av} \geq \max(Y_{PV,i}^b, Y_{CHP,i}^b) \quad \forall i \quad (\text{I.24})$$

I.3 Potential electrical system configurations

A Markov Chain, similar to Figure I.1, determines the (un)availability of each system configuration. If appropriately sized, each technology is assumed able to meet the load of its accommodating house. Hence, system configurations are unavailable if all their components ($tech_c$) are unavailable:

$$ua_{con} = \prod_{tech_c=1}^n ua_{tech_c} \quad (\text{I.25})$$

Appendix J

Additional model equations of Chapter 6

This Appendix provides more detail on model equations in support of Chapter 6.

J.1 Decentral scale

J.1.1 Residential DG export

Locally generated DG electricity by individual houses, $\sum_{tech} PE_{techDG,i,s,h}^{SAL}$ [kW], can be exported at a single tariff, T_{MG}^{SAL} [AUD kWh⁻¹]. Total yearly neighbourhood income, C_{SAL}^{GRID} [AUD y⁻¹], from electricity export is then obtained as:

$$C_{SAL}^{GRID} = \sum_{techDG,i,s,h} hr \cdot d_s \cdot T_{MG}^{SAL} \cdot PE_{techDG,i,s,h}^{SAL} \quad (J.1)$$

With hr the duration of each hourly h time interval, d_s the number of days in each season s and i the number of neighbourhood houses.

J.1.2 Economies-of-scale

Total CHP costs and capacities are obtained for each house i , with $\sum_{t=1}^n a_{t,i} = 1$ ($\forall i$):

$$C_{CHP,i}^{TOT} = \sum_{t=1}^n f(\zeta_t) \cdot a_{t,i} \quad \text{and} \quad DG_{CHP,i}^{MAX} = \sum_{t=1}^n \zeta_t \cdot a_{t,i} \quad \forall i \quad (J.2)$$

J.2 Central scale

CHP units are the only considered units for upscaling to central scales, potentially combined with a central absorption chiller.

J.2.1 Technology constraints

The potential single central CHP unit (*chpct*) is modelled similar to the decentral units (see Section D.2.2 and Equation 6.5). With $\sum_{t=1}^n a_{t,chpct} = 1$, the installed capacity and total investment cost of the central CHP (*chpct*) is determined as:

$$C_{chpct}^{TOT} = \sum_{t=1}^n f(\zeta_t) \cdot a_{t,chpct} \quad \text{and} \quad DG_{chpct}^{MAX} = \sum_{t=1}^n \zeta_t \cdot a_{t,chpct} \quad (\text{J.3})$$

Furthermore, similar capacity constraints as with the decentral CHP units are in place. Total installed CHP capacity must be within $\in [L_{CHP}; U_{CHP}]$ characterised by a binary selection variable B_{chpct} :

$$B_{chpct} \cdot L_{CHP} \leq DG_{chpct}^{MAX} \leq B_{chpct} \cdot U_{CHP} \quad (\text{J.4})$$

Electricity generated by the central CHP unit in each hour of each season can either be used for circulation to neighbourhood houses ($PE_{chpct,s,h}^{CIRC}$), for export to the central grid ($PE_{chpct,s,h}^{SAL}$) or for central absorption chiller fuelling. Absorption chillers namely require electricity per kW generated cooling, determined through their electricity to cooling ratio, ECR , and transfer cooling to houses i ($QC_{acct,i,s,h}$):

$$PE_{chpct,s,h}^{CIRC} + PE_{chpct,s,h}^{SAL} + \sum_i QC_{acct,i,s,h} \cdot ECR \leq DG_{chpct}^{MAX} \quad \forall s, h \quad (\text{J.5})$$

Heat generated by the central CHP unit is determined by its total electricity generation ($PE_{chpct,s,h}^{TOT}$) and heat to electricity ratio (HER). The heat can be used for heating ($PH_{chpct,s,h}^{HEAT}$) or cooling purposes ($PH_{chpct,s,h}^{COOL}$) or can be dissipated ($PH_{chpct,s,h}^{DIS}$):

$$PE_{chpct,s,h}^{TOT} \cdot HER = PH_{chpct,s,h}^{HEAT} + PH_{chpct,s,h}^{COOL} + PH_{chpct,s,h}^{DIS} \quad \forall s, h \quad (\text{J.6})$$

Heat generated for both heating and cooling purposes can individually not exceed the maximum heat generated by the CHP unit, $\forall s, h$:

$$PH_{chpct,s,h}^{HEAT} \leq DG_{chpct}^{MAX} \cdot HER \quad \text{and} \quad PH_{chpct,s,h}^{COOL} \leq DG_{chpct}^{MAX} \cdot HER \quad (\text{J.7})$$

Additionally, heat for cooling purposes can only be generated if a central absorption chiller is installed (binary variable B_{acct}):

$$PH_{chpct,s,h}^{COOL} \leq B_{acct} \cdot U_{CHP} \cdot HER \quad \forall s, h \quad (\text{J.8})$$

The central absorption chiller follows the behaviour of decentral absorption chillers, with similar capacity bounds. Its installed capacity should be within upper and lower bounds $\in [L_{AC}, U_{AC}]$ determined by a binary variable B_{acct} .

$$\sum_i QC_{acct,i,s,h} \leq DG_{acct}^{MAX} \quad \forall s, h \quad (\text{J.9})$$

$$B_{acct} \cdot L_{AC} \leq DG_{acct}^{MAX} \leq B_{acct} \cdot U_{AC} \quad (\text{J.10})$$

J.2.2 Central pipeline constraints

Heating received by a house from the central CHP unit, can contribute to the house heat load in hour h , or, be transfer to other neighbourhood houses through a non-loop optimised pipeline network (see Section 4.3.2.3). Pipeline balances for an individual house and for the neighbourhood as a whole then become, respectively:

$$\begin{aligned} PH_{i,s,h}^{PIPE} + \sum_j QH_{j,i,s,h} - \sum_j QH_{j,i,s,h}^{LOSS} + QH_{chpct,i,s,h} - QH_{chpct,i,s,h}^{LOSS} \\ = QH_{i,s,h}^{LOAD} + \sum_j QH_{i,j,s,h} \quad \forall i, s, h \text{ and } i \neq j \end{aligned} \quad (\text{J.11})$$

$$\begin{aligned} \sum_i PH_{i,s,h}^{PIPE} + \sum_i QH_{chpct,i,s,h} - \sum_i QH_{chpct,i,s,h}^{LOSS} - \sum_{i,j} QH_{j,i,s,h}^{LOSS} - \sum_i QH_{i,s,h}^{LOAD} = 0 \\ \forall s, h \text{ and } i \neq j \end{aligned} \quad (\text{J.12})$$

J.2.3 Microgrid interaction

Central CHP electricity for microgrid circulation supplies houses i , $PE_{chpct,i,s,h}^{snd}$:

$$PE_{chpct,s,h}^{CIRC} = \sum_i PE_{chpct,i,s,h}^{snd} \quad \forall s, h \quad (\text{J.13})$$

Electricity send to each house is equal to what each house receives ($PE_{chpct,i,s,h}^{rec}$) from the central CHP unit, minus transfer losses:

$$PE_{chpct,i,s,h}^{snd} - PE_{chpct,i,s,h}^{LOSS} = PE_{chpct,i,s,h}^{rec} \quad \forall i, s, h \quad (\text{J.14})$$

The central electricity transfer losses are determined similarly to the decentral electricity losses (see Equation 4.17). The microgrid interaction balance is enforced through:

$$\sum_i PE_{chpct,i,s,h}^{snd} - \sum_i PE_{chpct,i,s,h}^{LOSS} = \sum_i PE_{chpct,i,s,h}^{rec} \quad \forall s, h \quad (\text{J.15})$$

Total microgrid transfers are bound by an appropriate upper bound P :

$$\sum_{i,s,h} (PE_{tech,i,s,h}^{CIRC} + PE_{chpct,i,s,h}^{snd}) \leq Z \cdot P \quad (\text{J.16})$$

J.2.4 Hybrid scale and scale differentiation constraints

DES can be set up as either decentral, central or hybrid. To allow the model to implement one of three scales, additional binary variables are introduced. B^{DCtech} becomes 1 if the neighbourhood has installed decentral DG and storage units, B^{CT} becomes 1 if the neighbourhood only has a central unit:

$$\begin{aligned} B^{DCtech} &\geq B_{techDG,i} \quad \text{and} \quad B^{DCtech} \geq B_{techST,i} \quad \forall i \quad (\text{J.17}) \\ B^{DCtech} &\leq \sum_i B_{techDG,i} + B_{techST,i} \end{aligned}$$

Binary B^{CT} becomes 1 if the neighbourhood only has a central unit, obtained through an AND-NOT relation (see Appendix H):

$$B^{CT} = B_{chpct} \wedge \overline{B^{DCtech}} \quad (\text{J.18})$$

Binary B^{DC} becomes 1 if the neighbourhood only has decentral units, obtained through an AND-NOT relation (see Appendix H):

$$B^{DC} = \overline{B_{chpct}} \wedge B^{DCtech} \quad (\text{J.19})$$

Appendix K

Economies-of-scale

This Appendix details the derivation of the employed economies-of-scale relation of total investment cost of small-scale CHP units in support of Chapter 6. The employed economies-of-scale relation for small-scale CHP units is adapted from Merkel et al. [244]. They focussed on small-scale CHP in the range of 1 to 27 kW based on CHP inventory studies in Germany. The obtained trend is taken from [426], which conducted a survey of available CHP technologies and capacities in the German market in 2011. The derived economies-of-scale power relation between installed CHP capacity [kW] and unit investment cost [€2011 kW⁻¹] was found as:

$$\text{Unit investment cost} = 3976.1 \cdot (\text{Installed capacity})^{-0.2497} \quad (\text{K.1})$$

Unit investment cost of the sample points, see Table K.1, were transformed from €2011 to AUD2011 using the average 2011 exchange rate of 1.348 between Euros and AUD [427]. Next, the total investment cost of the sample points, see Table K.1, was adjusted for Australian dollar inflation between 2011 and 2015 with an inflation rate of 8.46 % [428]. From these points, the final relation between total investment cost and installed capacity of CHP units could be determined as the power function:

$$C_{CHP}^{INV} = 5812.2 \cdot (DG_{CHP}^{tot})^{0.75} \quad (\text{K.2})$$

Note that relation K.1 is between *unit* investment cost and installed capacity, and relation K.2 between *total* investment cost and unit capacity. Total CHP investment cost is obtained by multiplying the unit investment cost with the installed capacity of the unit.

TABLE K.1: Economies-of-scale sample points after monetary transformations.

Cost transformation						
Capacity [kW]	[€2011 kW ⁻¹] [426]	[€2011]	[AUD2011 kW ⁻¹]	[AUD2011]	[AUD2015 kW ⁻¹]	[AUD2015]
0	0	0	0	0	0	0
1	3976	3976	5359	5359	5812	5812
2	3344	6688	4507	9014	4888	9777
3	3022	9067	4073	12220	4418	13253
5	2660	13301	3585	17927	3889	19444
8	2366	18925	3188	25507	3458	27665
11	2185	24033	2945	32391	3194	35131
15	2022	30330	2725	40878	2956	44336
20	1882	37637	2536	50726	2751	55018
27	1746	47142	2353	63536	2552	68912

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