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**Impacts of new technologies on household electricity demand:
From an individual household, a community,
and a national perspective**

A thesis
submitted in fulfilment
of the requirements for the degree
of
Doctor of Philosophy
at
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by
JORIS SUPPERS



THE UNIVERSITY OF
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Abstract

In the last century, humans have invented and implemented numerous technological advancements, which have not only brought comfort and security to our lives, they have also opened up possibilities which were previously implausible e.g. long-distance transport and communication. The main energy sources to power these advancements have been fossil-fuels; mainly gas, coal and oil, causing side effects such as an increase in greenhouse gas emissions. The consequences of this increase are difficult to predict; however, it is likely to warm the earth, which could have severe outcomes e.g. a rise in sea levels.

There has been a global movement to respond adequately to reduce human-produced greenhouse gas emissions. As part of this movement, the New Zealand government has proposed an energy strategy to reduce national greenhouse gas emissions, which includes decreasing the nation's dependence on fossil fuels, and increasing renewable electricity generation to 90% by 2025.

In New Zealand, the residential sector accounts for a large share of the national electricity demand, and vehicles driven in the country are predominantly fossil-fuelled. Therefore, the electrification of vehicles, and the inclusion of new technologies at a household level can have a significant impact on New Zealand achieving its energy strategy goals.

The aim of this research, thus, is to provide a greater understanding of the impact electric vehicles, solar PV systems, and home energy storage systems within the household can have on electricity demand at a household, community, and national level.

As part of this research: (1) a simulation tool, capable of calculating fine-grained (hourly) power output for solar panels at any location in New Zealand was created; (2) two small scale quantitative surveys were conducted to gather electricity usage data for New Zealand households; (3) a web interface allowing for a comparison of energy usage data from 32 different households was developed; (4) a modelling approach, capable of generating half hourly household electricity consumption data was constructed; and (5) a web-based tool, capable of simulating the impact of solar PV, an electric vehicle, and a home energy storage system, on electricity consumption was created.

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Contents

Abstract	ii
Acknowledgements	iii
List of Figures	xi
List of Tables	xvii
1. Introduction	1
1.1 Motivation.....	3
1.2 Research Questions	4
1.3 Approach.....	4
1.4 Contributions.....	6
1.4.1 Simulations	6
1.4.2 Database	6
1.4.3 Publications.....	7
1.5 Thesis Structure	8
2. Background	9
2.1 Electricity Industry.....	10
2.1.1 Generation.....	10
2.1.2 Transmission	13
2.1.3 Distribution	15
2.1.4 Retailing.....	16
2.1.5 Wholesale Electricity Market.....	17
2.2 Security of Supply.....	18
2.2.1 Hydro Risk Curves.....	18
2.2.2 Winter Energy Margin	20
2.2.3 Winter Capacity Margin.....	20
2.2.4 Reports	20
2.3 Peak Demand Problem.....	21
2.3.1 Demand-side Management	22
2.3.2 Demand Response.....	24
2.3.3 Peak Demand in New Zealand.....	26

2.3.4	Demand Response in New Zealand.....	27
2.4	New Zealand’s Energy Strategy.....	29
2.4.1	Diverse Resource Development.....	30
2.4.2	Environmental Responsibility.....	31
2.4.3	Efficient Use of Energy.....	32
2.4.4	Secure and Affordable Energy.....	33
2.5	Electricity Consumption.....	33
2.5.1	Household Consumption.....	35
2.6	New Technologies.....	36
2.6.1	Solar Panels.....	36
2.6.2	Electric Vehicles.....	38
2.6.3	Home Energy Storage Systems.....	39
2.6.4	Internet of Things.....	41
2.7	Summary.....	42
3.	Related Work.....	45
3.1	Load Profile Impact.....	46
3.1.1	Solar Photovoltaic Systems.....	46
3.1.2	Electric Vehicles.....	48
3.1.3	Home Energy Storage Systems.....	49
3.2	Short to Long Term Impacts.....	50
3.2.1	Greenhouse Gas Emissions.....	51
3.2.2	Cost Effectiveness.....	54
3.2.3	Social Impacts.....	56
3.3	Investments in the Transmission System.....	57
3.4	Summary.....	60
4.	Solar Panel Simulation.....	63
4.1	The Sun’s Position.....	64
4.1.1	Declination Angle.....	64
4.1.2	Equation of Time.....	65
4.1.3	Solar Time.....	66
4.1.4	Hour Angle.....	66
4.1.5	Elevation Angle.....	67
4.1.6	Zenith Angle.....	68
4.1.7	Azimuth Angle.....	68
4.2	Irradiance.....	69

4.2.1	Extraterrestrial Irradiance	71
4.2.2	Atmospheric Attenuation	72
4.2.3	Direct Normal Irradiance	72
4.2.4	Diffuse Horizontal Irradiance	73
4.3	Power Output	73
4.3.1	Angle of Incidence	73
4.3.2	Plane of Array Irradiance	74
4.3.3	Module Temperature	75
4.3.4	Cell Temperature	76
4.3.5	Module Power	77
4.3.6	Inverter Power	78
4.3.7	System Losses	78
4.4	User Interface	79
4.5	Findings	82
4.5.1	Tilt on Static Solar panels	82
4.5.2	Location	86
4.5.3	Tracking Systems	86
4.5.4	Costs	89
4.6	Summary	90
5.	Household Electricity Consumption.....	93
5.1	Surveys	93
5.1.1	Preliminary Survey	94
5.1.2	In-depth Survey	95
5.2	Database of Household Consumption	96
5.3	Findings	97
5.4	Household Load Model	100
5.4.1	Energy Values	102
5.4.2	Seasonal Factors	105
5.4.3	Regional Factors	108
5.4.4	Electricity Consumption Modelling	109
5.4.5	Output and Verification	110
5.5	Summary	112
6.	Household Simulation.....	113
6.1	User Interface	114
6.1.1	Storage and Generation	114

6.1.2	Energy Price	115
6.1.3	Household Consumption Data.....	116
6.1.4	Charging Strategy.....	117
6.1.5	Load Management.....	118
6.1.6	Electric Vehicles	119
6.1.7	Results	119
6.2	Energy Storage Strategies	122
6.2.1	Smart Battery Usage.....	124
6.3	Electric Vehicle Storage Strategies	125
6.4	Electric Vehicle Travel Patterns.....	128
6.4.1	Travel Times	128
6.4.2	Travel Distances.....	129
6.4.3	Energy Consumption.....	131
6.4.4	Annual Travel Distance.....	131
6.5	Calculations.....	132
6.6	Summary	134
7.	Results of Household Simulation	135
7.1	Solar PV System.....	137
7.1.1	Solar Energy	138
7.1.2	Grid Energy	139
7.1.3	Value to Consumers	141
7.2	Home Energy Storage System.....	143
7.2.1	Storage without a Solar PV System	144
7.2.2	Storage with a Solar PV System.....	147
7.3	Electric vehicles	149
7.3.1	Grid Energy	151
7.3.2	Value to Consumers	152
7.3.3	Electric Vehicle with a Solar PV System.....	154
7.3.4	Electric Vehicle with Distributed Storage and Generation	157
7.4	Summary	159
8.	Community Simulation.....	163
8.1	Solar PV Systems	164
8.1.1	Solar Energy	165
8.1.2	Grid Energy	165
8.2	Home Energy Storage Systems	167

8.2.1	Storage without Solar PV.....	167
8.2.2	Storage with Solar PV.....	173
8.3	Electric Vehicles.....	176
8.3.1	Grid Energy.....	177
8.3.2	Electric Vehicles with Solar PV.....	182
8.3.3	Electric Vehicles with Distributed Storage and Generation.....	187
8.4	Summary.....	191
9.	Countrywide Simulation.....	195
9.1	Solar PV Systems.....	196
9.2	Home Energy Storage Systems.....	201
9.2.1	Storage without Solar PV.....	202
9.2.2	Storage with Solar PV.....	206
9.3	Electric vehicles.....	209
9.3.1	Grid Energy.....	210
9.3.2	Electric Vehicles with Solar PV.....	214
9.3.3	Electric Vehicles with Distributed Storage and Generation.....	217
9.4	Summary.....	220
10.	Summary and Conclusions.....	223
10.1	Which new technologies are available at the household level?.....	224
10.2	What are the characteristics and use of these technologies?.....	224
10.3	How do the characteristics and use of these technologies impact the household, the community, and the nation?.....	225
10.3.1	Household.....	226
10.3.2	Community.....	228
10.3.3	Nation.....	229
10.4	Discussion and Future Work.....	229
	References.....	233
	Appendices.....	245
	Solar Panel Simulation Results.....	247
	Material for Preliminary Survey.....	251
	Material for In-depth Survey.....	259
	Material for Follow up Interviews.....	267
	Household Simulation Calculations.....	269

List of Figures

1.1	Research questions and the methods used to answer these questions.	5
2.1	New Zealand’s electricity supply from generation companies in 2014.	11
2.2	Average daily generation patterns for each season (in 2015) for New Zealand.....	13
2.3	Calculated hydro risk curves with historical controlled storage levels and future mean levels.	19
2.4	Wholesale energy prices in New Zealand at 30 minute intervals.	25
2.5	Annual electricity consumption by sector.	34
2.6	Average annual demand per residential site.	35
2.7	Estimated and target battery costs from 2008 – 2024.	40
3.1	Predicted annual impacts on greenhouse gas emissions of electric vehicles, solar PV systems, and home energy storage systems.....	53
3.2	Installed electricity generation capacity by fuel type.	58
3.3	Annual electricity generation by fuel type.	59
4.1	The sun’s position fluctuates from overhead the earth’s equator during the year....	65
4.2	The sun’s angular position in the sky at different solar times.	67
4.3	The zenith and elevation angles describe the angular height of the sun.....	67
4.4	Compass direction of the sun in the sky.	68
4.5	The effect of earth’s atmosphere on solar radiation.	69
4.6	The ten different weather stations used in NZSPOT.....	70
4.7	How the beam irradiance striking the surface of a solar panel is calculated.	74
4.8	Current-voltage (IV) curve for a solar panel showing the maximum power point. .	77
4.9	Location page of NZSPOT.....	79
4.10	Solar panel configuration page of NZSPOT.	80
4.11	Results page of NZSPOT.	81

List of Figures

4.12	Power output for static solar panels at three different tilt angles.	84
4.13	Annual energy output of a static solar PV system in different cities.....	86
4.14	Power output for a static, azimuth tracking, and dual tracking solar PV system.	88
5.1	Snapshot of the web interface of the household database.	96
5.2	Mean daily electricity consumption for each household.	99
5.3	Comparison of the average consumption of the thirty households used in the household model with average consumption data from the Electricity Authority.	101
5.4	Modelling electricity consumption for a community of households.	102
5.5	A three-dimensional matrix for each season which holds measured energy values for each half hour period from the 30 selected households for all days in that season.	103
5.6	The five steps performed to transform the energy values from the seasonal matrices into a sorted two-dimensional matrix.....	104
5.7	Mean daily load profile for a weekday and weekend for different seasons.	106
5.8	The vector representing the average daily usage at half hour intervals for a season.	106
5.9	The vector representing the mean daily load profile of the whole year of all households.	107
5.10	Energy usage for a variety of different sized community of households.	110
6.1	Storage and generation tab of the household electricity usage simulation tool (HEUS).....	115
6.2	Energy price tab of HEUS.	116
6.3	Household consumption data tab of HEUS.	117
6.4	Charging strategy tab of HEUS.	118
6.5	Load management tab of HEUS.	118
6.6	Electric vehicle tab of HEUS.....	119
6.7	Results tab of the HEUS.	120
6.8	Two charts comparing grid load over a period of one year, showing the original load and the new load when considering the defined technologies.	121
6.9	Example day showing the impact of different home energy storage system charging strategies on electricity consumption.....	123
6.10	Example of slow and co-op EV charging strategy.	126

6.11	Example of greedy and saver EV charging strategy.	127
6.12	Trip legs by hour of week.	129
6.13	Average trip distance for each hour of the week.	130
6.14	Distribution of daily distances travelled per vehicle.	130
6.15	Annual distance travelled from 100 different simulated electric vehicles.	131
6.16	The different steps used in HEUS to calculate electricity usage of a household for each time-period.	132
7.1	Example household demand and energy generated from different sized solar PV systems on a typical day.	139
7.2	Mean annual load duration curves of all households with and without a solar PV system.	140
7.3	The percentage of daily and annual peaks occurring at a specific time of day, based on data from the 16-household set.	141
7.4	Costs and savings over a 25-year period for different sized solar PV systems on the representative households from the 16-household set.	142
7.5	Mean annual load duration curves of all households with a home energy storage system for each of the three investigated strategies.	145
7.6	Gross savings from selected households when using a home energy storage system.	146
7.7	Mean daily peak reduction for each month of the year for all 16 households with a solar PV system and a home energy storage system.	148
7.8	10-year savings from solar energy consumption with and without a home energy storage system in the 16 households.	149
7.9	Mean annual load duration curves of all households with the addition of an electric vehicle following different charging strategies.	152
7.10	Example household load profile on a typical day with a solar PV system and an electric vehicle in a co-op and saver charging strategy.	155
7.11	Costs and savings related to a household with a solar PV system and an electric vehicle during a 25-year period.	156
7.12	Example of fluctuation in grid load due to the home energy storage system being at full capacity.	158

List of Figures

7.13 Mean annual load duration curves of all households with a home energy storage system and an electric vehicle following the co-op charging strategy, with various sized solar PV systems.....	158
8.1 Grid load profile for a random day in the year of a community of households for different adoption levels of solar PV.....	166
8.2 Annual load duration curves for a community of households for three different levels of installed solar PV.....	167
8.3 Annual load duration curves for a community of households for three different levels of installed home energy storage systems.....	170
8.4 Energy stored in the home energy storage systems in a typical day following the co-op strategy..	172
8.5 Electricity consumption in a typical day with different adoption levels of home energy storage systems following the saver strategy.....	172
8.6 Energy generated with varying adoption levels of solar PV systems on a typical clear summer day compared to the standard electricity consumption from the community of households.....	173
8.7 Electricity consumption on a typical clear summer day with solar PV systems coupled with home energy storage systems.....	174
8.8 Annual load duration curves for a community of households with solar PV and home energy storage systems utilising the saver strategy.....	176
8.9 Annual load duration curves for a community of households with electric vehicles following the three charging strategies discussed.....	179
8.10 Electricity consumption for a community of households with electric vehicles utilising the slow strategy.....	180
8.11 Comparison of electricity consumption for different adoption levels of electric vehicles, following the co-op strategy on a random day of the year.....	181
8.12 Annual load duration curves for a community of households with electric vehicles following the co-op charging strategy.....	182
8.13 Annual load duration curves for a community of households with solar PV and electric vehicles following different charging strategies.....	186
8.14 Annual load duration curves for a community of households with solar PV, electric vehicles, and home energy storage systems following a co-op strategy....	189

8.15	Annual load duration curves for a community of 100 households with 100 electric vehicles, home energy storage systems and solar PV systems following a co-op scenario with different set limits.	189
8.16	Annual load duration curves for a community of households with solar PV, electric vehicles, and home energy storage systems following a saver scenario. ..	191
9.1	Daily solar generation at different solar adoption levels compared to the national electricity demand without solar PV.	199
9.2	Electricity demand at different solar adoption levels in the first full week of the year.	199
9.3	Annual load duration curves for the national electricity demand with different adoption levels of solar PV.	200
9.4	Annual load duration curves for the national electricity demand with home energy storage systems following the co-op strategy.	202
9.5	Typical energy storage behaviour of home energy storage systems following the co-op strategy at a 100% adoption level.	203
9.6	Comparison between a typical daily load profile without home energy storage systems, and 100% adoption of home energy storage systems following the saver strategy.	205
9.7	Annual load duration curves for the national electricity demand with home energy storage systems following a saver strategy.	206
9.8	Annual load duration curves for the national electricity demand with solar PV and home energy storage systems following a co-op strategy.	208
9.9	National electricity consumption on a typical day with a 100% adoption level of electric vehicles following different charging strategies.	210
9.10	Annual load duration curves for the national electricity demand with electric vehicles following different charging strategies.	212
9.11	Annual load duration curves for the national electricity demand with electric vehicles following a co-op strategy.	213
9.12	Annual load duration curves for the national electricity demand with solar PV and electric vehicles following a saver strategy.	215
9.13	Annual load duration curves for the national electricity demand with solar PV and electric vehicles following a co-op strategy.	216

List of Figures

9.14 Example day where electricity consumption is low and solar generation is high,
resulting in a sudden drop in electricity demand at the 50 and 100 % adoption
level. 217

9.15 Annual load duration curves for the national electricity demand with solar PV,
home energy storage systems, and electric vehicles following a saver strategy. ... 220

10.1 A comparison of the mean cost savings of the inclusion of different technologies,
following the saver strategy within 16 households from the in-depth survey. 228

List of Tables

2.1	Electricity generation and installed capacity.....	12
2.2	Visualisation and description of different load shape objectives.	23
2.3	New Zealand’s gross emissions by sector.....	31
3.1	Reduction in peak load using three different levels of PV penetration.	47
3.2	Impact of home energy storage systems in 10% of residential ICPs without PV and with a high level of PV.....	50
4.1	Values calculated by Sandia Laboratories for different module types and mounts .	76
4.2	Solar PV system setup used for the results obtained in this chapter.	82
4.3	Energy output from a static solar PV system at different tilt angles.....	83
4.4	NZSPOT calculated energy output for a 1.5KW solar PV system for a typical day in each month, compared with data from other solar calculators.....	85
4.5	Seasonal and annual energy output for different solar panel tracking systems.....	87
4.6	Solar component costs for calculating economic benefits of tracking.	89
5.1	Mean daily household energy usage for different seasons.....	97
5.2	Residential energy usage in different regions in New Zealand for 2015.	108
5.3	Electricity Authority consumption data compared to simulated consumption.....	111
7.1	Electricity prices based on real values from a New Zealand energy retailer.	136
7.2	Solar PV system assumptions.	137
7.3	Solar energy generated and consumed by households in a 25-year period.....	138
7.4	Home energy storage system assumptions, based on the Tesla Powerwall 2 AC..	143
7.5	Electric vehicle assumptions are based on a mid-range electric vehicle.....	150
7.6	Mean annual energy costs of an electric vehicle.....	153

List of Tables

8.1	Solar energy generated and exported, and grid electricity consumed in a community of 100 households.....	165
8.2	Annual energy stored with different levels of installed home energy storage systems.	168
8.3	Daily and annual peak demand change with home energy storage systems for different strategies.	171
8.4	Annual energy generated from solar PV systems and solar energy stored in the home energy storage systems in a community of households.	174
8.5	Daily and annual peak demand change, and standard deviation change, when integrating electric vehicles in a community of households.....	178
8.6	Simulation of electric vehicles following the co-op strategy in a community of 100 households.	181
8.7	Simulation of electric vehicles and solar PV in a community of 100 households utilising a saver strategy.	184
8.8	Simulation of electric vehicles and solar PV in a community of 100 households utilising a co-op strategy.	184
8.9	Simulation of electric vehicles, home energy storage systems, and solar PV in a community of 100 households utilising a co-op strategy.	188
8.10	Simulation of electric vehicles, home energy storage systems, and solar PV in a community of 100 households utilising a saver scenario.	190
9.1	Number of simulated households in different regions.....	197
9.2	Impact of solar PV systems in households across New Zealand on the national electricity demand.	198
9.3	Assumed national storage characteristics for different adoption levels of home storage.	201
9.4	Impact of home energy storage systems following the co-op strategy on the national electricity demand over a year.	204
9.5	Impact of home energy storage systems following the saver strategy on the national electricity demand over a year.	204
9.6	Impact of solar PV and home energy storage systems following the co-op strategy on the national electricity demand over a year.	207
9.7	Assumed number of electric vehicles and their collective capacity and charge rate at different national adoption levels.	209

9.8	Impact of electric vehicles following different charging strategies on the national electricity demand over a year.	211
9.9	Simulation of electric vehicles following a co-op strategy at a national level.....	213
9.10	Simulation of electric vehicles following a saver strategy with solar PV at a national level.	214
9.11	Simulation of electric vehicles following a co-op strategy with solar PV at a national level.	216
9.12	Simulation of solar PV, electric vehicles, and home energy storage systems following a co-op strategy at a national level.....	218
9.13	Simulation of solar PV, electric vehicles, and home energy storage systems following a saver strategy at a national level.	219

Chapter 1

Introduction

“The Stone Age did not end because we ran out of rocks. It ended because a disruptive technology ushered in the Bronze Age.”

— Tony Seba

Rapid advancement and integration of Information Communication Technology (ICT) has supported new technological developments such as wireless communication and digital data management. This has not only improved current industry structures, it has also forced new business models and restructuring of industrial sectors [1]. Therefore, this technology can be called disruptive, as it forces sectors to incorporate such technology to stay competitive and relevant. This restructuring of sectors can bring improvements and new capabilities that were previously implausible.

The electricity sector is structured to follow a linear grid model, with a centralised generation node supplying electricity to multiple demand nodes. This structure has remained relatively unchanged for the past 100 years, however, with the advancements in new technology, this sector has been described as the next frontier of the ICT revolution [1]. New technologies have the potential to significantly alter electricity demand by: introducing new loads, smoothing existing loads, and bringing controllability to loads. On the supply side, potential technologies include distributed generation systems (e.g. solar PV), reducing the

need or capacity of transmission lines, and providing an opportunity to trade excess generation. Other technologies include home energy storage systems (HESS), which would allow households to utilise surplus distributed generation, and take advantage of electricity prices, by storing electricity when prices are low and/or selling stored electricity when prices are high. The HESSs could collectively reduce network demand, provide load management, and store excess electricity from renewable sources. These behaviours would allow for better network planning, reducing costs in the electricity industry, and incentivising electricity from renewable sources. To actualise the benefits of new technologies, ICT needs to be extensively incorporated into the electricity sector, to allow coordination and control of electricity behaviour. This implies the electricity sector will follow a new structure, with multiple generation nodes supplying electricity to multiple demand nodes.

New Zealand's electricity demand in households is expected to grow, due to population growth and new energy usage technologies, such the heat pump and electric vehicle (EV). This demand growth carries implications for an electricity network which follows the existing linear model. These implications include having sufficient central generation capacity to meet demand, and having sufficient distribution capacity to transmit electricity and prevent vulnerability issues, such as a reduction in voltage (brownouts) and loss of electricity (blackouts) [2]. A new electricity network with distributed generation, distributed storage, and controllable load will be better equipped to handle these implications.

To understand the extent of disruption new technologies could have on the electricity sector, this research focuses on new technologies available to the residential sector and how they impact the electricity system. This focus is taken because the residential sector has the highest impact on the national peak demand [3], and new technologies within this sector display the greatest disruption capabilities, e.g. decentralisation or electricity supply through distributed generation and distributed storage.

1.1 Motivation

In the last century, humans have invented and implemented new technological advancements, both on a small scale (e.g. household appliances) and on a large scale (e.g. the electricity grid). These technological advancements have not only brought comfort and security to our lives, they have also brought new possibilities which were previously implausible e.g. long-distance transport and communication. The main energy sources to power these advancements have been fossil-fuels; mainly gas, coal and oil. One of the side effects of burning such fossil-fuels is a change of the greenhouse effect through the increase of the concentration of atmospheric carbon dioxide (CO₂). The consequences of this increase are difficult to predict, however, it is likely to warm the earth [4], which is often referred to as “Climate Change”. The main negative impacts are a rise in sea levels (caused by thermal expansion and melting ice caps), more extreme weather patterns, and more extreme heat waves and droughts [5].

The main motivation of this research is to provide a greater understanding of the impact new technologies, within the household and with current electricity tariffs, can have on electricity demand at a household, community, and national level. This knowledge can subsequently help with future electricity tariff structuring to reduce greenhouse gas emissions by incentivising these technologies to utilise renewable generation, rather than fossil-fuelled generation. This in turn will support the conservation of fossil-fuel reserves for specialised use, where renewable resources will not suffice e.g. rocket fuel. This conservation is necessary as fossil-fuels are prehistoric plants and animals which have been buried and decomposing for millions of years, making it implausible to manufacture. It is predicted that fossil fuel reserves for oil, gas and coal will deplete in approximately 35, 37 and 107 years, respectively, at current consumption levels [6]. This implies, that we must efficiently manage our reserves and transition into renewable energy sources.

1.2 Research Questions

In order for New Zealand to reduce its greenhouse gas emissions, as mentioned above, a shift in the way electricity is generated, distributed and consumed is needed [7]. Considering the growth of population and energy usage per head, the general concept of new energy technologies within a household following a collective behaviour is very promising. Thus, the main research question to be addressed in this thesis is:

How can new energy technologies within a household potentially impact New Zealand's residential electricity demand profiles?

This research question is answered by investigating three more specific research questions, as follows:

1. Which new technologies are available at a household level?
2. What are the characteristics and use of these technologies?
3. How do the characteristics and use of these technologies impact the household, the community, and the nation?

These three questions guide the research, undertaken as part of this thesis. The approaches used to answer these questions are outlined as follows.

1.3 Approach

The three research questions, as stated above, are answered through a mixed methods approach. As follows, each research question is outlined with its respective research method(s).

The first question of this thesis, *which new technologies are available at the household level?* is answered through a literature review. This review shows that among the new technologies the greatest disruption comes from solar PV systems, EVs, and HESSs.

The second question, *what are the characteristics and use of these technologies?* is focused on providing further insight into the previously established technologies' behaviour. This question is answered through a literature review on the capabilities of each technology. Additionally, a simulation tool was developed to calculate fine-grained (hourly) power output for solar panels at any location in New Zealand.

The third question, *how do the characteristics and use of these technologies impact the household, the community, and the nation?* serves as the core component of this research. Focus is given to the impact these technologies have on the household level, the neighbourhood level (community of households), and national level. The first step to answer this question is to gather accurate household and national electricity usage data. The New Zealand government provides detailed electricity usage data on the national level, however, there is also limited available fine-grained data on household electricity usage in New Zealand. To gather accurate household data a small scale quantitative survey with household dwellers in collaboration with the local distribution company (WEL Networks) was carried out. Using the collected data from the first step and the previous questions, a web-based tool was created to simulate the impact new technologies have on a household, community of households, and national level.

A summary of the research questions and respective methods to answer these questions are depicted in Figure 1.1.

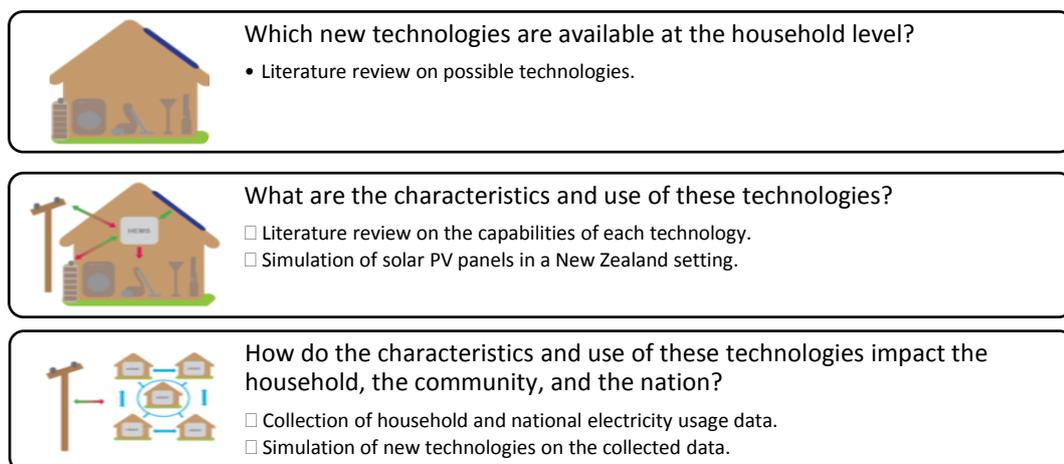


Figure 1.1: Research questions and the methods used to answer these questions.

1.4 Contributions

In addition to providing answers to the three research questions (Section 1.3), three further research contributions are evident in this thesis: (1) software simulations of electricity generation and use, (2) a database of household electricity consumption patterns, and (3) the publication of several research papers arising from the research. Each of these contributions will be outlined as follows.

1.4.1 Simulations

Two web-based simulations were created as part of this research. The first is called NZSPOT (New Zealand solar panel output tool) which simulates the fine-grained power output of solar panels, depending on their location and orientation in New Zealand. This simulation allows researchers, businesses and the public to gain more accurate understanding of the effects of installation location and orientation on a solar panels' power output. This simulation has been made accessible at <http://nzspot.cms.waikato.ac.nz/>. The second simulation, called HEUS (Household electricity usage simulation), mimics electricity usage with the adoption of different technologies, such as solar PV systems, EVs, and HESSs. It allows researchers, businesses and the public to gain a better understanding of savings and different energy patterns that can occur with these technologies. This simulation is also accessible at <http://ei.cms.waikato.ac.nz/hems/>.

1.4.2 Database

The survey conducted to gather electricity consumption data from households in New Zealand, described in Chapter 5, resulted in a web-based database (available at <http://ei.cms.waikato.ac.nz/data>). This database provides an insight into the energy consumption patterns of Waikato households. The participants of this survey are able to compare and understand their electricity usage, which could potentially influence them to make more efficient energy choices. Furthermore, fellow

researchers and businesses can also benefit from this database, by having access to a user friendly visualisation of representative household energy usage patterns.

1.4.3 Publications

The literature reviews conducted to answer the three research questions resulted in several papers being published and presented at conferences. These publications, listed as follows, allowed for discussion and review of preliminary findings of this research with fellow researchers.

Suppers, J., & Apperley, M. (2016, July 6-7). *Energy Behaviour in a Community of Smart Homes*. Paper presented at The Energy Cultures Conference, Wellington, New Zealand.

Apperley, M., & Monigatti, P., & Suppers, J. (2015, July 6). *Grid-Lite: A network Integrated semi-autonomous local area electricity system*. Proceedings 4th International Conference on Green IT Solutions, Milan, Italy.

Suppers, J., & Apperley, M. (2015, September 14-18). *Interactive solar panel simulation tool - From Global Horizontal Irradiance to PV output*. Paper presented at Fostering Smart Energy Applications workshop at INTERACT, Bamberg, Germany.

Suppers, J., & Apperley, M. (2014, August 5-8). *Developing useful Visualizations of Domestic Energy Usage*. Paper presented at the 7th International Symposium on Visual Information Communication and Interaction, Sydney, Australia.

Suppers, J., & Apperley, M. (2014, May 27). *Why aren't we all living in Smart Homes?* Proceedings of the AVI 2014 Workshop on Fostering Smart Energy Applications through Advanced Visual Interfaces, Como, Italy.

1.5 Thesis Structure

As follows, the structure of this thesis is outlined. Chapter 2 provides an insight into New Zealand's electricity sector, challenges this sector is facing, and upcoming technologies in the residential sector. Chapter 3 is an overview of related research on new technologies and their impact on the electricity sector. In Chapter 4 the solar panel output simulation tool (NZSPOT) is explained, detailing the calculations, interface and results of this tool. Chapter 5 presents the findings of a survey carried out to collect household usage data in the Waikato region. It also outlines the database, created as part of this survey. Chapter 6 provides an overview of the calculations and interface of the created household electricity usage simulation tool (HEUS). In Chapter 7, results obtained using HEUS, with the household data from Chapter 5, and the generation data from NZSPOT, are analysed. Similarly, Chapter 8 analyses the results from HEUS, with electricity usage data from a community of households. Chapter 9 provides an insight into the impact new technologies have on the country's electricity usage. Chapter 10 concludes the research with a summary and possible future work.

Chapter 2

Background

“We will make electricity so cheap that only the rich will burn candles.”

— Thomas Edison

The discovery of electricity and the development of electrical devices, such as the incandescent light bulb, has not only made our lives more comfortable, it has also allowed for many technological and medical advancements. Without electricity, there would be no practical lighting, internet, computers, and numerous other machines that assist and benefit humans. Electricity is arguably the biggest influence on mankind, it has helped push humanity forward, and a world without it would be inconceivable.

This chapter provides an insight into New Zealand’s electricity sector and the challenges this sector is facing, now and in the future. The chapter begins with an overview of the sectors involved in the electricity industry, followed by the mechanisms involved in maintaining security of supply in the short and long term, and the causes and solutions for the peak demand problem. Furthermore, the energy strategy proposed by the New Zealand government [8], and an overview of New Zealand’s electricity consumption are provided. The chapter then ends with a summary of new energy technologies available for households.

2.1 Electricity Industry

Since the Ministry of Energy¹ assumed responsibility for electricity policy advice and regulation in 1978, the electricity sector in New Zealand has undergone drastic changes to support vigorous competition, fragment monopolies, regulate natural monopolies, and promote efficient use of electricity [9]. These changes include the start of deregulation in the 1980s, followed by the commencement of the wholesale electricity market and the legislative reform of the electricity industry in the 1990s, and more recently, a single governance of the electricity industry in 2003 [9]. With these changes, New Zealand's electricity industry has been separated into five main sectors: generation, transmission, distribution, retailing, and the wholesale electricity market. These sectors are discussed as follows.

2.1.1 Generation

The role of the generation sector is to supply electricity to the electricity network. This electricity supply is dominated by three state owned companies (Mighty River Power, Meridian Energy, and Genesis Energy) and two publicly owned companies (Contact Energy and TrustPower). Figure 2.1 shows the distribution of the market share of electricity supply. It shows that the percentage of electricity supply by these five companies amounted to over 90% of New Zealand's total electricity generation in 2014, with the remaining generation (Other) supplied by independent power producers and on-site generators.

¹ This Ministry was abolished in December 1989, with electricity policy advice and regulation currently being handled by the Ministry of Business, Innovation and Employment [9].

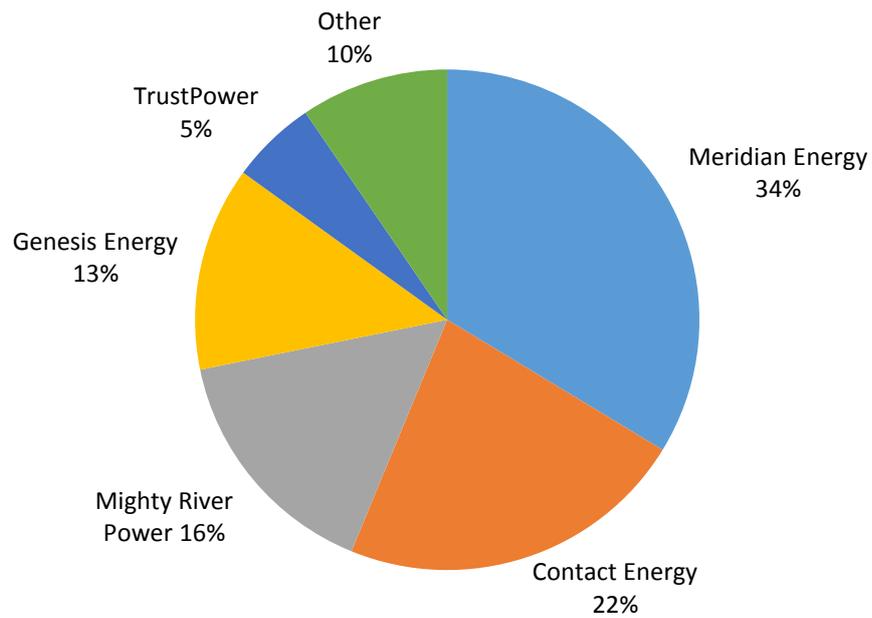


Figure 2.1: New Zealand’s electricity supply from generation companies in 2014 [10].

In 2015 New Zealand’s net electricity generation was 42,872 GWh with 80.8% coming from renewable sources. This net generation has increased by 1% from the previous year with a 0.8% increase coming from renewable sources [11]. Table 2.1 shows the breakdown of this generation by energy source. This breakdown shows that New Zealand’s electricity supply is dominated by hydro (56.6%), followed by other renewable sources (24.2%), and the remaining supply coming from fossil fuels (19.2%). This renewable share is expected to grow since New Zealand has committed to achieve 90% renewable energy generation by 2025 [8].

Table 2.1: Electricity generation and installed capacity by energy source [11].

Energy Source	Annual Generation (GWh)		Annual change (%)	Capacity 2015 (MW)
	2014	2015		
Hydro	24,076	24,293	0.9	5,348
Geothermal	6,871	7,411	7.9	986
Biogas	231	231	0.2	47
Wood	354	347	-1.9	63
Wind	2,192	2,333	6.4	690
Solar	17	34	96.0	35 ²
Oil	3	1	-67.9	167
Coal	1,831	1,756	-4.1	557
Gas	6,570	6,418	-2.3	1,555
Waste Heat	51	53	3.2	19
Total	42,196.7	42,876.5	1.6	9,466
Renewable Share	80%	80.8%	0.8%	76%

Electricity in New Zealand is sold on a wholesale electricity market in half hour periods to interested parties. By observing the generation mix for these half hour periods, as shown in Figure 2.2, it becomes evident there is a mix of continuous and intermittent electricity supply. Geothermal, wind and cogeneration remains relatively consistent throughout the year³, while fossil fuel generation (gas, diesel and coal) ramps up and down to adjust for variability in the national electricity demand. It is also evident, from Figure 2.2, that most the variability is managed from hydro generation.

² Solar capacity has been estimated using Electricity Authority data on installed distributed generation. This data can be found at: <http://www.emi.ea.govt.nz/>.

³ Although, on a given day electricity supply may differ from these energy sources, e.g. wind power is highly fluctuant on a daily basis, however, over a longer period of time the power output becomes relatively consistent.



Figure 2.2: Average daily generation patterns for each season (in 2015) for New Zealand (Data from: emi.ea.govt.nz).

The electricity sold from generation companies is sent from power stations to grid injection points and is then transmitted by the transmission sector. The transmission sector is explained in more detail as follows.

2.1.2 Transmission

The transmission sector has the role of transporting electricity from power stations to grid exit points. These grid exit points supply electricity to the distribution networks and directly to large industrial consumers. Electricity is transported through a transmission network, often referred to as the national grid and owned as well as operated by a state-owned enterprise named Transpower. This national grid

includes 11,743 km of high-voltage transmission lines and supplies around 200 grid exit points [12] with electricity from more than 200 generation plants [13]. This national grid also connects the North and South Island through a high-voltage direct-current cable (HVDC), allowing bidirectional flow of electricity.

In 2014, the North Island accounted for approximately two thirds (61.6%) of the national electricity demand, while the South Island accounted for approximately a third (38.4%) of demand. Almost a third of the demand in the South Island comes from the Tiwai Point Aluminium Smelter, while in the North Island almost half of the demand comes from Auckland and Northland area [11]. The majority of hydro generation capacity is in the South Island (3,513MW) while the North Island only has half of this capacity (1,822MW) [11]. The HVDC linking the islands is therefore, predominantly used to supply electricity from the major hydro generators in the South Island to the North Island. During dry seasons, when hydro generation is low, the North Island is capable of supplying electricity to the South Island from other energy sources e.g. geothermal.

Transpower ensures that the national grid is capable of transmitting power between power stations and grid exit points within and between both islands. This requires installation and maintenance of the physical infrastructure of electric power transmission, capable of transferring electricity from a wide range of power stations to large companies and distribution networks. Along with meeting the physical requirements of the grid, the state-owned enterprise acts as a system operator, which aims to co-ordinate the supply and demand for electricity in real-time to avoid fluctuations and interruptions in supply. Transpower coordinates the supply of electricity through a wholesale electricity market by instructing which power stations can supply electricity at a trading period and how much they can generate. The electricity market is further explained in Section 2.1.5. When power stations generate the instructed amount of electricity, Transpower proceeds to transport this electricity to large companies and distribution networks. The distribution network is described in more detail as follows.

2.1.3 Distribution

The distribution sector is in charge of transferring electricity from the national grid to homes and businesses across New Zealand. This transfer of electricity happens through networks of overhead wires and underground cables, throughout New Zealand. There are currently 39 of these networks, mainly owned by 29 distribution companies [13]. Each distribution company is responsible for a region in New Zealand and is regulated, since they are natural monopolies. Most of these distribution companies are owned by trusts or local councils, but some consist of public listings and shareholder co-operatives.

These distribution companies are billed annually by Transpower to receive electricity from the national grid [14]. The bill typically includes a connection and interconnection fee. The connection fee covers asset recovery, operation, and maintenance costs. The interconnection fee is based on the distributor's contribution to a regional coincident peak demand. This contribution is based on the average of the 12 highest peaks over the year at a given grid exit point. In Transpower's 2016/2017 pricing plan (from 1st April 2016 to 31st March 2017) the total connection costs were \$128.6m while the total interconnection costs were over 5 times more, at \$662.1m [14]. This creates an incentive for distributors to minimise peak demand in order to reduce their interconnection costs. Two typical methods to minimise peak demand are used by distributors. The first method is using demand response programmes that manage industrial and residential loads. The second method is using time-of-use pricing to give financial incentives to consumers in order to shift or reduce load from peak periods. Most distribution companies in New Zealand do not directly charge the consumer for their services, instead they have a contractual agreement with the retailers who pass the costs on to the consumers. The retailers in New Zealand are described as follows.

2.1.4 Retailing

The role of the retailers, also known as power companies is to sell electricity to households and businesses. There are over 20 retailers in New Zealand, however the market is largely dominated by 5 retailers. These retailers own over 90% of the market share, with the following shares: Genesis Energy (25%), Contact Energy (21%), Mercury NZ (formerly Mighty River Power) (19%), Meridian Energy (13%), TrustPower (13%) [15]. These five major companies are also the main generating companies and are obligated to buy and sell their electricity on the electricity market to prevent monopolies and inequity. This allows smaller retailers to compete, and also creates a competitive fringe for these five big retailers to reduce costs, innovate to stay appealing to customers, and cater to their needs [16]. Some recent innovations include website applications to monitor and manage electricity usage, a variety of different pricing structures, join-up incentives, billing management systems, and rates targeted at electric vehicles (EVs) [13]. It has to be noted that different innovations appeal to different types of consumers as discussed in [17]. Another innovation is the *What's My Number* campaign which was created by the Electricity Authority, who also regulates the electricity market. The campaign promotes the benefits consumers can have when switching electricity retailers⁴. This campaign has a free webpage tool where consumers can easily compare power bills and potential savings between retailers. This campaign was created to achieve competitive pressure by increasing the consumers' willingness to switch retailers⁴.

The retailers buy electricity from the wholesale electricity market, and pay the distribution company to deliver this electricity. The charges for generation, distribution (which includes transmission costs), and retailing of electricity, are bundled and billed to the end user. The wholesale electricity market, where the electricity is sold to the retailer, is described as follows.

⁴ Background information on the *What's My Number* campaign is available at www.whatsmynumber.org.nz.

2.1.5 Wholesale Electricity Market

New Zealand's wholesale electricity market commenced in 1996 under a multilateral contract to support a competitive trading platform for wholesale electricity [9]. The wholesale electricity market follows the Electricity Industry Participation Code (EIPC)⁵ and is regulated by the Electricity Authority. The Electricity Authority contracts out the services to operate this wholesale market to New Zealand Exchange (NZX) and Transpower [18].

NZX runs a trading platform titled WITS (wholesale information and trading system) which receives offers from generation companies to supply electricity for future trading periods (48 half-hour periods in the day) at specific grid injection points. NZX also receives bids from retailers (and some large companies) to withdraw electricity from grid exit points. These bids and offers are sent to Transpower. Transpower's task, as the system operator, is to avoid fluctuations in frequency or disruption in electricity supply. This requires a real-time balance between supply and demand while maintaining security of supply. Transpower achieves this by analysing the bids and offers they receive, and calculating the optimal combination of generation sources to meet current and future demand, while ensuring sufficient reserves to manage any future system events. After these calculations, Transpower then instructs NZX with the quantity and price of electricity generation. NZX then determines a final price for each grid exit point and grid injection point. The calculations carried out by Transpower that help to determine the security of supply are described in the following section.

⁵ The Electricity Industry Participation Code is available at: <http://www.ea.govt.nz/code-and-compliance/the-code/>.

2.2 Security of Supply

Security of supply in the electricity industry can be defined as a guarantee for electricity supply to meet current and future electricity demand. Transpower as the system operator has the role of maintaining New Zealand's security of supply.

New Zealand as an isolated country, is in a unique position as it cannot buy electricity from neighbouring countries, instead it relies on managing a combination of local energy resources to meet demand. Fortunately, New Zealand has abundant renewable energy sources available to generate electricity. The most significant is hydro generation, which currently accounts for more than half of New Zealand's electricity supply. These hydro generators also utilise lakes that store inflow (rainfall and snowmelt) as hydro storage. With such reliance on hydro generation and hydro storage, New Zealand's electricity supply is vulnerable to the variability of rainfall. In the absence of inflow, there is only enough hydro storage to meet winter energy demand for a few weeks. The variability of rainfall, therefore correlates with the variability of hydro generation and storage, and without sensible management for dry periods there is a risk in security of supply. To assess the risk in security of supply, Transpower estimates hydro risk curves, a winter energy margin, and a winter capacity margin. These estimates, along with a weekly report by Transpower which describes the condition of the nation's security of supply are described as follows.

2.2.1 Hydro Risk Curves

With New Zealand's strong reliance on electricity supply from hydro generation, an important role to minimise supply risk, is monitoring hydro storage. Hydro storage in New Zealand is mostly situated in lakes Taupo, Tekapo, Pukaki, Te Anau, Hawea and Manapouri. Transpower has divided hydro storage into two categories to help determine the security of supply. The first category is controlled hydro storage; these are any hydro storage units that are controllable and available to generate electricity from these five main lakes. The second category is contingent hydro storage, which are hydro storage units that are only used to generate

electricity under emergency conditions or to mitigate a risk of shortage.

Transpower gathers information from the National Institute of Water and Atmospheric Research (NIWA), the Electricity Authority, generators, local authorities, and further sources to determine the available controlled and contingent hydro storage [19]. Transpower calculates Hydro Risk Curves (HRC) which illustrate the controlled hydro storage levels over a calendar year and indicate the risk of any future shortages. These HRC calculations forecast electricity demand (accounting for price response and transmission loss), simulate market behaviour, and simulate generation outages (planned and unplanned).

The HRC show the potential energy (in GWh) stored in these controlled hydro storage lakes for 6-18 months in the future. There are numerous risk curves, each at different percentages, from 1-10%, as shown in Figure 2.3. If the controlled storage level intersects a risk curve, based on historical records, there is that particular percentage of chance that all the controlled storage will be depleted. For example: “If the amount of controlled storage intersects the 10% risk curve, one in ten historical inflow sequences from the last 80 years would lead to controlled storage running out.” [20].

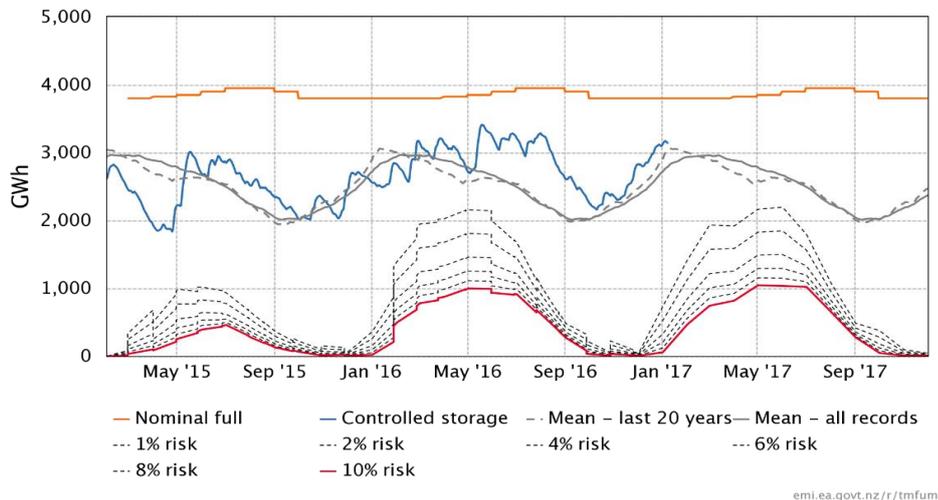


Figure 2.3: Calculated hydro risk curves with historical controlled storage levels and future mean levels⁶.

⁶ Figure retrieved from the Electricity Authority website on the *Historical hydro risk curves* webpage, available at <http://www.emi.ea.govt.nz/>.

2.2.2 Winter Energy Margin

Winter Energy Margin (WEM) is the percentage difference between the expected demand and expected supply during winter (1st April to 30th September). The WEM is set at 14-16% for New Zealand and 25.5-30% for the South Island [21]. A higher WEM percentage represents an oversupply. A lower percentage represents a small difference in expected demand and expected supply, which if too close could represent a possible risk for undersupply.

2.2.3 Winter Capacity Margin

Winter Capacity Margin (WCM) is the expected available capacity of the North Island minus the expected North Island demand during the winter months. The WCM is set at 630 - 780 MW, with below 630 MW indicating that adding additional capacity would be justifiable, between these values representing an efficient level of capacity, and over 780 MW indicating a wasteful level of capacity [21].

2.2.4 Reports

The system operator releases a weekly report on HRC and an annual report on the WCM and WEM for the next 5+ years. The weekly report provides useful information on hydro storage levels and allows for managing supply risks in the shorter term through demand response programs and contingent hydro storage. The annual report provides an accurate estimate of the security of supply in the longer term, and assesses whether demand can be met. This report helps to indicate the trade-offs between costs and risks, to help assess whether it is economically viable for New Zealand to add new generation. The latest annual report suggests that New Zealand is in a period of oversupply until 2018, which is likely due to a lower than expected demand [21]. This oversupply is expected to end after 2018 when two 250MW fossil-fuelled steam turbine units (Huntly Rankine units) are decommissioned, since the WCMs and WEMs will fall below the security standards. However, Genesis Energy, the owner of the Huntly Rankine units, recently signed an agreement with other power companies to extend the life of these

plants until 2022 [22], which would bring WCM within security standards, and WEM within standards if high probability generation stations were also built. However, there is still a level of uncertainty about demand, which makes predicting security of supply difficult. This uncertainty is mainly due to the unknown operation period of the Tiwai Point Aluminium Smelter, which uses a seventh of New Zealand's power, and new technologies which may significantly change demand.

2.3 Peak Demand Problem

Demand in this context can be defined as the amount of power consumed from all grid exit points within a certain time period. The peak demand is therefore, described as the highest demand that has occurred over a given time period. The time period is typically measured half hourly, daily, seasonally, or annually, and demand is represented in units of power, such as watt-hours. In the residential sector, the loads which introduce spikes in demand, causing peak demands, are from high powered appliances such as the kettle, toaster, oven, washing machine and the dishwasher. During these peak demand periods, problems may occur due to inadequate electricity generation and/or transmission capacity. These inadequacies to meet demand with supply, cause an imbalance in voltage and frequency. A drop in frequency and voltage indicates a shortage of supply, whereas, a rise in frequency and voltage indicates an excess of supply.

New Zealand manages electricity supply through the wholesale electricity market. At times of low demand, power plants with the lowest marginal costs supply electricity, whereas at peak periods, almost all power plants are operating to meet demand. These low marginal cost plants are typically fuel efficient and have low operational costs. In New Zealand these low marginal cost plants provide a steady base load and are mainly wind, geothermal and hydro plants. During peak periods, additional hydro and thermal peaking power plants are scheduled. These peaking power plants ensure the necessary capacity is available to meet demand. However, these plants add an additional cost, as the industry must invest into power

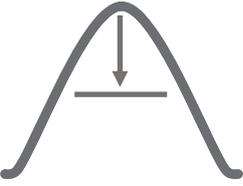
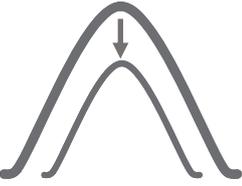
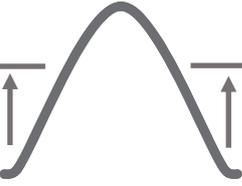
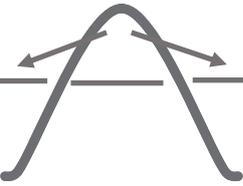
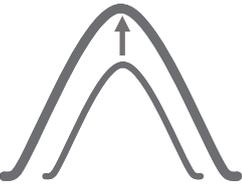
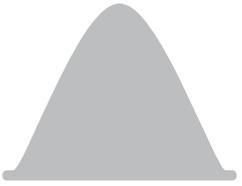
plants which can be left idling or switched off during off-peak times. Additionally, thermal plants run on coal, gas and diesel, which are comparatively more expensive to run and have high emissions and environmental impacts associated with them. Fortunately, for New Zealand, most of the peak demand is met by hydropower with fossil-fuelled generation accounting for less than 20% of New Zealand's total electricity generation. Another problem associated with peak demand, is the need for additional capacity on transmission and distribution networks.

Building additional generation and transmission capacity to prevent peak demand is costly, has environmental impacts, and can be time consuming. Another approach to manage peak demand, is managing demand on the consumer side. In extreme cases, there is an Automatic Under-Frequency Load Shedding (AUFLS) scheme in New Zealand which automatically disconnects selected loads to prevent a national blackout [23]. However, managing demand on the consumer side is typically done through demand-side management, which is explained as follows.

2.3.1 Demand-side Management

The term Demand-side management (DSM) for the electricity industry was first introduced by Clark Gellings, a senior executive at the Electric Power Research Institute (EPRI) in the United States of America in 1981 [24]. DSM is described as the actions carried out by electricity utilities to influence electricity behaviour on the consumer's side rather than the supply side. DSM has the potential benefit of avoiding additional infrastructure and costs needed to supply additional electricity during peak periods by managing the consumer's demand to prevent excessive peaks. The main actions which fall under the DSM umbrella term are: improving energy efficiency, load management, load growth, load conservation, and price initiatives. Implementing these actions on a utility scale, can achieve a particular load shape objective. Achieving these objectives delivers a manifold of benefits which are typically related to environmental and/or economic benefits. Table 2.2 visualises and describes some different load shape objectives.

Table 2.2: Visualisation and description of different load shape objectives⁷.

<p>Peak Clipping</p>  <p>Reduction of load during peak periods.</p>	<p>Strategic Conservation</p>  <p>Reduction in overall load.</p>	<p>Valley Filling</p>  <p>Increase of load during off-peak periods.</p>
<p>Load Shifting</p>  <p>Combination of Peak Clipping and Valley Filling.</p>	<p>Strategic Load Growth</p>  <p>Increase of overall load.</p>	<p>Flexible Load Shape</p>  <p>Load which can change as needed.</p>

⁷ Visualisations are replicated from the *load shape objectives* figure in [98].

2.3.2 Demand Response

Demand response is a form of demand-side management, specifically a load management action. Demand response is a change of a customer's electricity demand in response to a signal from an electric utility. The change in electricity demand from the consumer can be almost instantaneous. This quick response allows managing demand to maintain a safe margin between supply and demand. On the supply side, there are some limits to maintaining a safe margin, including: the delay to generate electricity, the cost to operate, and in extreme cases, insufficient supply to meet demand. Demand response seeks to overcome these limits by adjusting the demand instead of supply.

To adjust demand, utilities send a request to customers to reduce their load, which is typically directly or indirectly connected to these requests. Directly connected loads are often on dedicated control systems and shed load automatically once a request is received, or when certain market prices occur. This load shedding often reduces services such as lighting, heating, cooling, and machinery on a pre-planned prioritization scheme. Indirect loads are loads which are managed by the customer. Once the request is received, the customer decides to reduce, postpone or switch loads to on-site generation (e.g. diesel generation). Although demand response is usually used to reduce demand, it may also be used to increase loads when supply exceeds demand e.g. at high production times. Including demand response into an electricity system can improve economic efficiency in the electricity market, reduce price volatility, and improve system reliability.

Typically, customers are charged a flat rate per unit of energy they consume. With this flat rate, there is no clear incentive to manage demand according to the wholesale market prices. If customers are subject to wholesale market prices and have flexible loads, efficiency in welfare gains can be achieved. These gains are achieved by increasing consumption at low prices and decreasing consumption at higher prices, this would in turn help stabilise the market's clearing price.

A typical wholesale electricity market is volatile as depicted in Figure 2.4. This volatility is related to factors such as the inelasticity demand, uncertainty of demand, and supply capabilities. When supply capabilities are high, prices are

usually low, as power plants are competing to sell electricity. When supply capabilities are low, stand-by generation is required. These stand-by generators usually are expensive to run, which causes an increase in price. With an inelastic demand and insufficient supply capabilities, companies with a large market share could have market power. Market power is the ability for these companies to withhold a portion of their generation capacity to temporarily increase market price, and gain a large profit with their remaining online generators. Having a more elastic demand through demand response, would reduce the need for expensive generation and reduces the incentive to exercise market power.

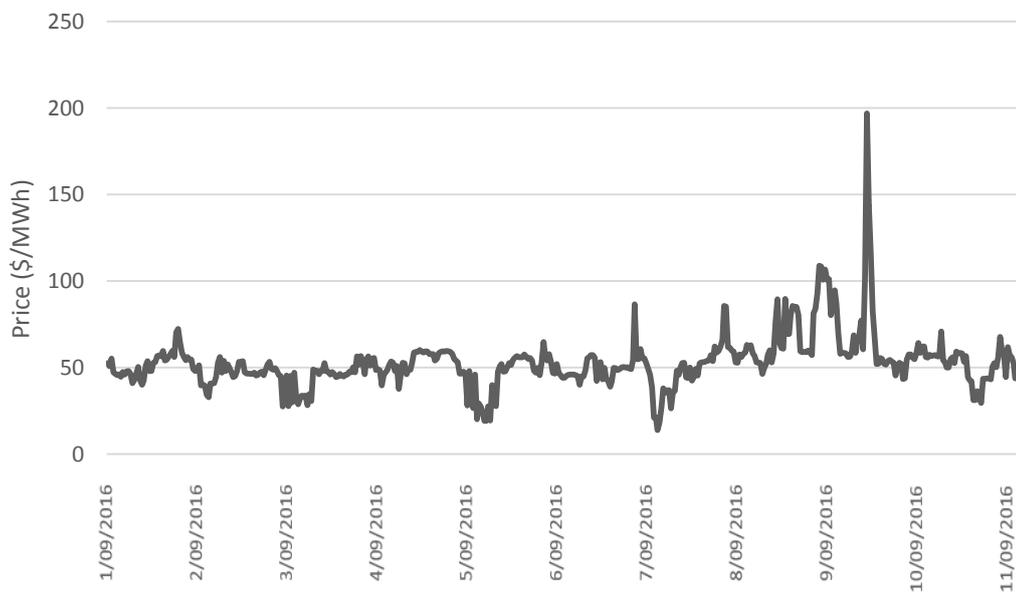


Figure 2.4: Wholesale energy prices in New Zealand at 30 minute intervals⁸.

Demand response can also help system reliability by responding to contingencies in the network, reducing the need for stand-by generation, balancing load and supply, and providing load curtailments that help restore reserves and maintain a safe reserve margin to respond to contingencies.

⁸ Data retrieved from *Wholesale energy prices* page at <http://www.emi.ea.govt.nz/>.

2.3.3 Peak Demand in New Zealand

In New Zealand, the residential sector accounts for approximately a third of the annual consumption and contributes to over half of the peak power demand [25]. New Zealand's largest peak demand occurs in the evenings during winter months. During this period, the residential electricity consumption increases by almost a factor of three from the summer season consumption. The most noticeable increases derive from space heating, hot water heating and lighting [26].

Peak demand in New Zealand is forecasted to grow from 6275MW at an average growth of 1.1% per annum to 7329MW by 2030 [27]. However, forecasting growth is challenging, due to the uncertainty of uptake of new technology, demand response programmes, and customer tariff structures. This uncertainty requires careful consideration of planning and building the required power plants and transmission infrastructure to supply peak demand, which may take several years to complete. This is challenging as the investments into additional capacity, such as power plants, need to be economical in short and long-term, while ensuring the security of supply.

There are two main issues with the growth in peak demand relating to the transmission infrastructure. The first issue is due to the limited transmission capacity, which limits the amount of power able to be transmitted. This is most evident in the transmission infrastructure which allows hydro plants in the South Island to supply electricity to the North Island. This transmission is through a HVDC which links both islands and is crucial, as most of the hydro plants are in the South Island while most demand is concentrated in the North Island. During peak periods, the supply is limited to the capacity of the HVDC which can result in the need of additional electricity generation and high wholesale prices for electricity. The second issue is the required investments into replacing and adding capacity to meet peak demand, while remaining economical.

2.3.4 Demand Response in New Zealand

Demand response (DR) is crucial to both the short-term benefits of power system reliability and market efficiency, and long-term benefits in deferring capital expenditure. These benefits have caused a major uptake of DR initiatives around the world. In New Zealand, these initiatives exist on all levels involved in the electricity infrastructure. These include the national grid, distribution, retailer and consumer level.

On the national grid level, there are five main DR mechanisms [28]. First, nodal pricing in half hourly periods in the wholesale electricity market stimulates competition amongst generators and provides incentives for purchasers to observe prices and adjust usage appropriately if possible. Second, a dispatchable demand regime, which allows purchasers in the wholesale electricity market to modify all or part of their demand to compete with generators, to set the price. Third, interruptible load, which is load made available from companies for instantaneous shedding or reducing to stabilise the systems frequency. Fourth, demand side bidding & forecasting (DSBF) is an initiative by the Electricity Authority to improve inputs into price forecast schedules. And last, demand response initiatives, as Transpower is a natural monopoly, it is strictly regulated and is required to first seek non-transmission solutions before considering major capital projects [29]. Transpower has been involved in demand response programmes since 2007 as a non-transmission solution [30]. In 2013, Transpower operated a demand side initiative programme outside of the market with users who had at least a 100kW discretionary load. At the end of the year, Transpower obtained 200 MW through this programme. In 2015, Transpower started a similar five-year DR programme with a reduced requirement of 20 kW peak load to stimulate more participation, that paid more focus on geographic regions that may be constrained in the future [30]. Transpower also ultimately has a target of obtaining 10% of peak national demand [31].

Distribution companies are charged by Transpower to use the national grid. These charges include a regional coincident peak demand (RCPD) which is based on the percentage of the distribution network's demand on a region's peak demand.

This RCPD charge provides an incentive for distribution companies to reduce demand, and consequently led to the implementation of demand response programs. Ripple control (RC) is a form of demand response that has been used for many decades in New Zealand [32] [33]. Ripple control is implemented in household hot water cylinders and remains the principal DR tool used by distributors. RC has been very successful in improving the utilisation of assets from generation, transmission and distribution. In 2006 the Electricity Commission estimated that a total of 880 MW of maximum load was available for control through RC [33]. Some examples of DR methods used by distribution companies to reduce RCPD charges are:

- Orion has implemented ripple control through hot water cylinder control, and peak and night rate price signalling. Since 1980, Orion has reduced an estimated 200MW peak demand, with 100-150 MW associated with RC [34].
- The lines company (TLC), a large distribution network, which is predominantly made up of remote rural settlements, farm connections, and holiday homes which account for up to 25% of residential connections⁹. This company charges customers proportionately to the assets required to supply electricity to the site. This is achieved through a capacity charge which is based on the average of the six highest two hour peaks recorded during periods of load control [35].
- Vector along with ripple control, has implemented programs involving solar PV and energy storage systems to reduce peak demand. These programs include: an initiative which offered installation of a solar PV system combined with a home energy storage system (HESS) for domestic customers [36], installing 130 solar PV systems and HESSs on selected sites¹⁰, and installing a 1MW grid connected battery storage system¹¹.

⁹ Percentage taken from *Holiday homes* page at <http://www.thelinescompany.co.nz/>.

¹⁰ Program is described in the *Bright future for some Auckland individuals, families, schools and community groups* page at <https://www.vector.co.nz/>.

¹¹ More details of the battery storage system are accessible at the *Vector unveils Asia Pacific's first grid scale Tesla Powerpack* page at <https://www.vector.co.nz/>.

The retailer is tasked with the sale of electricity to an end-use customer. This sale includes the cost from Transpower, distribution networks, electricity generation and a service fee from the retailer. Typically, retailers in New Zealand charge a fixed price on energy, and with the variability of electricity costs on the electricity whole-sale market, these retailers take a financial risk with spiking prices. To reduce these risks, retailers may use ripple control to reduce load during high prices. However, with the pressure of consumer wants, competition between retailers, and installation of Smart Meters, there has been a wider adoption of time-of-use pricing. Time-of-use pricing is used as a DR mechanism to incentivise usage when electricity is cheaper. Time-of-use pricing usually has different prices for different time periods in the day, these periods are typically split into day/night or peak/off-peak/shoulder times. Some retailers also prevent the financial risk by billing the customer real-time pricing based on spot market prices.

Historically demand response in households was primarily done through ripple control on hot-water cylinders, controlled by the distribution network. Although this RC technology was present in households, consumers had little to no control in performing demand response. However, with the introduction of time-of-use pricing, and the uptake of many new technologies that are capable of demand-side-management [37], there is a potential for consumers to directly perform demand response, and contribute to managing peak demand and network constraints.

2.4 New Zealand's Energy Strategy

Globally, there have been two challenges related to electricity supply: maintaining energy security and responding adequately to climate change. Facing these challenges is a major undertaking for all nations. In New Zealand, the government proposed an energy strategy for the energy sector to respond to these challenges, while continuing to improve energy intensity¹² by 1.3% per year [8]. This strategy focuses on four priorities: (1) diverse resource development, (2) environmental

¹² Energy intensity is the measure of the units of energy per unit of gross domestic product (GDP).

responsibility, (3) efficient use of energy, and (4) secure and affordable energy.

2.4.1 Diverse Resource Development

New Zealand's energy resources contribute to the country's economic growth and living standards. Further development in a diverse range of energy resources can bring wealth through export of energy products, expertise, and technologies, and provide downwards pressure on energy prices within New Zealand [8]. To facilitate the development of energy resources, the government's focus will include the expansion of renewable energy resources and embracing new energy technologies.

This focus has led to a target of 90% renewable electricity generation by 2025. With a greater mix of renewable electricity, which will most likely come from a diverse range of sources, will help the country become more resilient to fluctuating commodity prices, improve energy security, and reduce greenhouse gas emissions. To facilitate the uptake of renewable generation the government provides the regulatory framework to support further investment in appropriate renewable projects. This framework requires that the national benefits of renewable electricity must be considered in the resource consenting process for future generation projects. Another technique is including a price of carbon through the emissions trading scheme, which incentivises investments into less polluting generation.

New Zealand's energy growth is forecasted to slow down; this means that the 90% target cannot be achieved by simply adding additional renewable capacity. However, what has been seen in the past 5 years is a growth in renewable generation, especially geothermal and wind generation, and decommissioning of fossil fuel generation [38]. This is shown with the decommissioning of gas fired generation, such as the 150MW Southdown and the 400MW Otahuhu power plants, and the two 250 MW coal fired generators in Huntly [38], with the remaining two 250 MW to be decommissioned by 2022 [22].

The development and advances of new energy technologies can also allow New Zealand to benefit from previously untapped energy resources and efficiently utilise current generation. One such example is solar panels with storage, which could help better manage the intermittency of renewable generation [39].

2.4.2 Environmental Responsibility

In 1991, the New Zealand government passed the Resource Management Act (RMA) which provides a resource management framework that promotes the sustainable management of natural and physical resources [40]. This requires any future developments of electricity generation, to consider the benefits and adverse effects on the environment [8].

The government has set four national targets for reducing the countries greenhouse gas emissions (GHG). These targets are based on 1990 GHG levels, and are: an unconditional target of 5% and a conditional target (if there is a comprehensive global agreement) of 10-20% by 2020, 11% by 2030, and 50% by 2050 [8] [41]. Some policies that encourage these reductions, include the New Zealand emissions trading scheme, which incentivises more investment in renewable energy and in energy efficiency and conservation.

Table 2.3: New Zealand's gross emissions by sector (data from [42]).

Sector	kt CO ₂ equivalent		Change from 1990	
	1990	2014	kt CO ₂ equivalent	%
Energy	23,793.2	32,240.2	+8,447.0	+35.5
IPPU ¹³	3,578.9	5,193.6	+1,614.7	+45.1
Agriculture	34,351.1	39,585.3	+5,234.2	+15.2
Waste	4,105.2	4,085.4	-19.9	-0.5
Gross	65,828.4	81,104.4	+15,276.0	+23.2
LULUCF ¹⁴	-28,927.7	-24,414.8	+4,512.8	-15.6
Net (Inc. LULUCF)	36,900.7	56,689.6	+19,788.9	+53.6

¹³ Industrial processes and product use - Industrial Processes which release GHG while transforming materials (either chemically or physically) and GHG which are used in products e.g. refrigerators, and aerosols.

¹⁴ Land use, land use-change and forestry - Greenhouse gas emissions and removals from direct human-induced land-use change and forestry activities.

New Zealand's gross emissions have increased significantly since 1990, as shown in Table 2.3. In 1990, gross greenhouse gas emissions were 65,828.4 kilotonnes carbon dioxide equivalent (kt CO₂-e). In 2014, this increased by 23.2% to 81,104.4 kt CO₂-e, with the largest increase coming from the energy sector.

In the energy sector the largest increase, from 1990 to 2014, came from national transport (60.4%) and electricity generation (44.4%). The electricity sector accounts for approximately 16% of New Zealand's greenhouse gas emissions. In 2013 this sector had a 21% decrease from the previous year, mostly due to coal generation decreasing from 2,712 GWh to 1,624 GWh [43]. Given that the electricity sector is relatively small in the energy sector, even if it reduces its emissions to zero, it cannot solely meet New Zealand's GHG targets [39]. One opportunity to further reduce emissions would be electrification of other sectors, one such example could be EVs.

2.4.3 Efficient Use of Energy

Improving energy use efficiency is a priority for the New Zealand government as it is an 'enabler' to a range of benefits [8]. These benefits include economic growth, greenhouse gas reduction, and energy security. Two sectors which can have significant improvements in energy efficiency are transport and residential. Half of New Zealand's energy needs are met with oil, with most of it used in the transport sector [8]. The government's key focus on improving efficiency and reducing the dependence on oil is creating the most efficient mix of integrated modes and travel options. This includes efficiently improving roads, rail systems, public transport and improving infrastructure for walking or cycling. In the household sector the government is focused on improving home insulation and clean heating levels. One such programme is the "Warm Up New Zealand: Heat Smart programme" which has committed more than \$340 million over four years to subsidies insulation and clean heating devices for homeowners [8].

Along with these two sectors, the government is also focusing on informing the public of consumer choices around energy products and services. This includes: efficiency labelling and standards for products; reporting prices on domestic

electricity, gas and price margins for petrol and diesel; funding programmes to inform price comparisons between electricity retailers; and providing information on energy saving, renewable energy and energy efficiency options to households and business [8].

2.4.4 Secure and Affordable Energy

Energy security, particularly in oil and electricity, is crucial for New Zealand's economy and well-being of its people. The government suggests maintaining energy security at an affordable price, is best achieved through competitive markets. This is shown in the wholesale electricity market which keeps downwards pressure on electricity prices and gives incentives to invest in efficient generation sources. To maintain a reliable electricity system, it is suggested to have a diverse range of energy sources and locations. This has shown to work, as New Zealand was rated as third in a group of 25 countries for energy security, due to it having one of the most diverse power sectors¹⁵.

In the longer term, an investment in oil alternatives will ensure transport security. In addition, balanced rules will support a reliable and secure electricity supply. In 2009 the government conducted a major review on the electricity market, which resulted in a set of measures to increase security of supply. Some measures included phasing out the reserve energy scheme, and ensuring that there are incentives for market participants to manage supply risk. These incentives include a proposed floor on the spot price of electricity, and a requirement for companies to compensate consumers during conservation campaigns [8].

2.5 Electricity Consumption

New Zealand consumed 39,768 GWh of electricity in 2015, as depicted in Figure 2.5. It is estimated that industrial consumption was at 36%, residential

¹⁵ The ranking comes from the report of the U.S. Chamber of Commerce titled "International Index of Energy Security Risk" (2016 edition) and is available at <http://www.energyxxi.org/>.

consumption at 32%, commercial consumption at 24%, and consumption of agriculture, forestry and fishing at 7% [11].

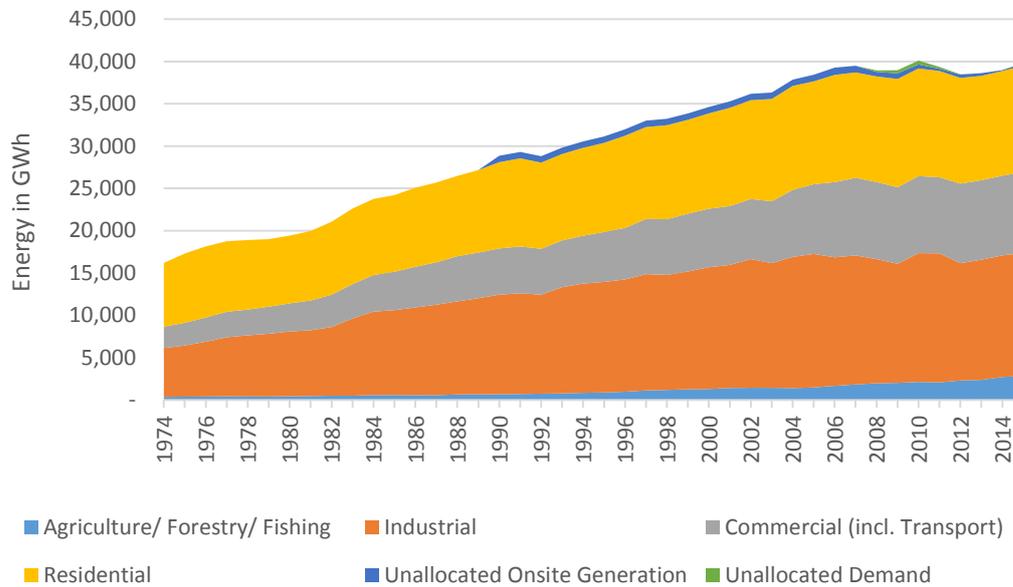


Figure 2.5: Annual electricity consumption by sector (data from [11]).

New Zealand’s electricity consumption in 2015 increased by 2% from the previous year, with the highest increase from agriculture, forestry and fishing (4%), followed by commercial (1.6%) and residential (1.4%). A recent study by the MBIE expects the growth of electricity consumption to average between 0.4% and 1.3% each year until 2050 [44]. Although, the residential sector has a relatively low growth compared to other sectors, it has the highest impact on winter peak demand [3] [7]. Therefore, it is crucial to understand how the residential sector consumes electricity, now and in the future, as it is a major driver of network investments. An analysis of electricity consumption in a household is discussed as follows.

2.5.1 Household Consumption

Electricity usage inside New Zealand households has steadily decreased by 7% from 2009 to 2014, with a small increase of 0.1% from 2014 to 2015 [11], as depicted in Figure 2.6.

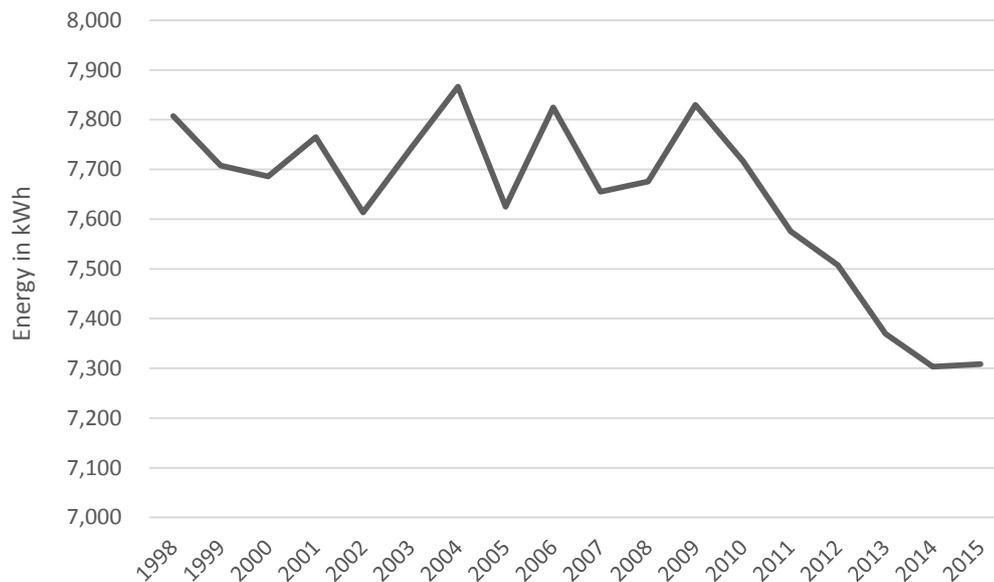


Figure 2.6: Average annual demand per residential site (data from [11]).

Contrary to the decrease in electricity consumption, there has been an increase in spending on electrical appliances, which has led to more appliances within households [45]. Since New Zealand participates in the National Strategy on Energy Efficiency (NSEE), these appliances are required to meet a minimum energy performance standard. This has led to many household appliances getting replaced to new efficient appliances. It is expected that the decrease in electricity consumption from households, as depicted in Figure 2.6, is largely due to households installing more heating efficient appliances, such as heat pumps [45] [46]. By installing these heating efficient appliances, the household becomes more efficient in space heating, which accounts for approximately 34% of electricity

consumption. These heating efficiencies are also supported through insulation of houses without subsidy and with subsidies, such as the “Warm Up NZ programme” which has insulated more than 290,000 homes since 2009¹⁶.

Although, the electricity consumption within households has had a small increase of 0.1% from 2014 to 2015, the uptake of new technologies could significantly increase and alter household electricity consumption. This has the potential to either exacerbate or alleviate the winter peak demand, which could reduce strain and investment on the energy infrastructure. However, there is a level of uncertainty about the uptake of these technologies, which makes it difficult to predict future demand profiles and plan infrastructure investments. An overview of potential new technologies within the residential sector is given as follows.

2.6 New Technologies

There are a variety of new technologies within the residential sector which are potentially disruptive to a household’s electricity consumption. Three core disruptions are electrification of other sectors, decentralization of electricity supply with distributed generation and distributed storage, and lastly, digitalization of the electricity sector. Although, it is difficult to predict exactly which technologies will cause disruption to the electricity sector, there is a growing consensus that solar PV systems, EVs, and HESSs will cause the greatest disruption e.g. [47] [48] [49] [50] [51]. An analyse of these three technologies, and Internet of Things (IOT) which allows these technologies to communicate to the electricity sector, are described as follows.

2.6.1 Solar Panels

In 2015 worldwide solar PV capacity was estimated at 231 GW, which is nearly six times the capacity of 2010 [52]. A major driver of this uptake can be associated

¹⁶ Number of homes based on the document: “*Annual Report June 2015/2016*” available at <https://www.eeca.govt.nz/about-eeca/our-programmes/>.

with the financial incentives provided by various governments to combat climate change. From this major uptake, the cost of solar PV has significantly dropped. A report by the Deutsche Bank estimated this drop to be approximately 15% per year over the last 8 years, and a further 40% drop is expected in the next 4-5 years [53].

This decrease in price and incentives from governments, has resulted in solar PV systems being implemented around the world to utilise their economic and environmental benefits; these systems allow the owner to produce their own electricity with zero operating emissions [39]. As opposed to many other countries, incentivising solar PV systems has not been a priority for the New Zealand government. The main contributor to this, is that the country's current generation mix is primarily renewable and the environmental benefits of adding large quantities of solar panels is unclear [39]. This uptake could have a positive impact on the environment by offsetting fossil fuel based generation, or a negative impact by offsetting renewable based generation. Another negative scenario, is solar panels increasing the slope to peak demand (since solar generation does not coincide with peak demand), which could result in additional infrastructure needed to cope with the larger ramp up of power demand.

While New Zealand currently has no financial incentives from the government, there has still been a rapid growth of solar PV systems in individual households. The major reasons for this uptake has been: increased independence from electricity suppliers, insulation from further power price rises, and the chance to test an innovative technology [39]. In 2016, there were over 11,000 installations covering 0.6% of all households [54]. In the same year, six states in Australia already had more than 20% of households with PV systems, with Queensland having the highest percentage at 30.4%¹⁷. This large uptake of household PV systems in Australia is due to government incentives and high electricity prices. Although New Zealand has no government incentives and electricity prices are relatively low, "Grid parity"¹⁸ has still arrived [53], and with a more mature infrastructure to sell excess

¹⁷ Statistics taken from Mapping Australian Photovoltaic installations page at <http://pv-map.apvi.org.au/> installations on December 2016.

¹⁸ Grid Parity is when the energy generated from an alternative energy source has a levelized cost of electricity (LCOE) which is less than or equal to the cost of electricity from the electricity grid.

on site power, solar panel uptake may rapidly increase. Progress towards maturing this infrastructure has been evident in recent years. One such example is in 2016, Vector went in a partnership with Power Ledger for a peer-to-peer platform trail for Aucklanders to buy and sell solar energy [55]. However, with current feed-in tariffs (typically 8 cents/kWh¹⁹) it is evident that consuming solar energy directly at the household level will bring the highest monetary reward. Furthermore, it is expected that feed-in tariffs will likely drop if there is a significant uptake of household solar PV systems [50]. Because if solar PV accounted for a large portion of annual generation, the overall costs of supplying electricity during non-solar generation times would rise [50], discussed in further detail in Section 3.2.2.

2.6.2 Electric Vehicles

The concept of electric automobiles has been present since the early 1800s, with the first prototypes being built in 1891. Although, there was great interest in EVs in the late 1890s and early 1900s, this interest dissolved in the 1930s [56]. This loss in interest was largely due to the Great Depression, which resulted in manufacturers preferring gasoline vehicles: battery costs were high while gasoline prices dropped significantly. However, with current gasoline prices rising, battery costs decreasing, and a rising awareness to environmental concerns, there has been a recent explosion in the demand for EVs [56].

In New Zealand, it is expected an EV will consumes between 1,500 kWh and 2,400 kWh over a year [45]. Without careful consideration, charging of this technology could add substantially more peak load on households and consequently on the electricity infrastructure [45]. The uptake of EVs in New Zealand has been slow, and is estimated to remain slow with an increase from approximately 1,500 in 2015 to 33,000 vehicles in 2020. This slow uptake is expected to only increase residential load by 0.69% in 2020 [45]. However, in 2016, the New Zealand government announced a programme to double the number of EVs every year to reach 64,000 by 2021 [57]. This programme will run a nation-wide information and

¹⁹ 8 cents per kWh is a typical buy back rate from New Zealand energy retailers, as mentioned on “Solar Power Buy Back Rates” webpage at <https://www.mysolarquotes.co.nz>.

promotion campaign over five years to increase the public awareness. This campaign, coupled with falling EV prices, could lead to a larger than expected uptake. Consequently, if the charging of a large fleet of EVs remained uncontrolled there could be significantly more load during peak periods.

2.6.3 Home Energy Storage Systems

Battery technology was first invented over 200 years ago [58]. In the last decade, there has been a wide range of advancements in different battery technology, these include: advanced lead acid, redox-flow, sodium sulphur and lithium ion. The most common technologies used today are small to medium sized batteries used in everyday devices such as phones, laptops, clocks, and vehicles.

The market for batteries has recently shifted with a greater focus on lithium-ion batteries [11]. These batteries have high energy and power densities and high efficiencies (80-90%), making them ideal for consumer electronics, and EVs. These lithium batteries have rapidly decreased in price, through technology improvements and companies scaling-up manufacturing. A notable manufacturing plant is the Gigafactory by Tesla which is estimated to reduce costs by 30% in the first year of production [53]. Using data from a recent Deutsche Bank report on solar panels and energy storage systems [53], as depicted in Figure 2.7, it is apparent that the price of lithium-ion batteries has dropped at approximately 6% each year between 2008-2015 and is expected to drop by 30% in 2017, due to the major upscaling of manufacturing. It is expected that between 2017 and 2024 the price will continue to drop at ~5% to reach Tesla's \$100/kWh goal by 2024.

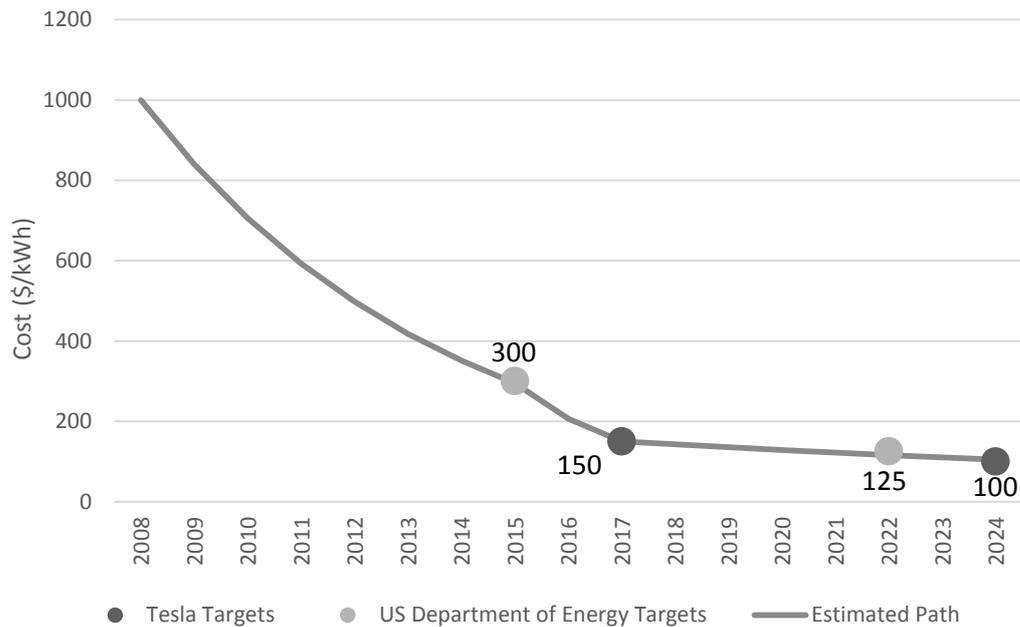


Figure 2.7: Estimated and target battery costs from 2008 – 2024 (targets from [53]).

Large lithium-ion battery factories, like the Gigafactory, have focused on creating batteries for EVs. However, since the battery technology used for EVs can also be used for HESSs, the costs for HESSs are dropping significantly. Although, these battery costs have not reached a global price which makes financial sense for an HESS, they are being widely integrated into households around the world in countries which provide subsidies.

In Australia, where there are government incentives coupled with expensive electricity costs, there has been a large adoption of solar PV and HESS installations, and there could be between 1 to 2 million households with battery installation by 2020 [59]. Although, New Zealand has no government subsidies, a recent high uptake scenario from the Ministry of Business, Innovation and Employment estimates that there could be approximately 400,000 solar PV systems with HESSs installed by 2040 [44].

The installation of HESSs will allow households to reduce electricity costs by storing electricity from the grid when prices are low and storing excess onsite

generation. This stored energy can then be consumed later or be sold to the grid. Selling stored energy could provide retailers with an alternative energy source, which could be used during peak periods when energy prices are expensive. Likewise, these storage units could sell energy at times which reduce the reliance on fossil fuels and help New Zealand to reach its energy goals.

2.6.4 Internet of Things

The Internet of Things (IOT) term was first coined in 1999 and was defined as embedding sensors, control systems, and processors into physical objects which are incapable of transmitting and receiving data, to allow these objects to have network connectivity. These devices are driven to collect data and interface with the physical world. A report by the Organisation for Economic Co-operation and Development (OECD) suggests New Zealand is second in the world for Machine-to-Machine (M2M) devices that use subscriber identity module (SIM) cards [60]. M2M is a subset of IoT and refers to direct communication between devices without human intervention.

New Zealand has a variety of IoT devices with SIM card capabilities such as security systems, vehicle tracking and telematics, however, the majority are Smart Meters (meters in an advanced metering infrastructure system). In 2016 over 1.5 million Smart Meters were installed in New Zealand, with over 1.3 million coming from the residential sector²⁰. Smart Meters are a new technology which connect to a power source and record and transmit accurate energy usage in 30 minute intervals and are capable of load control. These accurate time based readings have allowed: improved energy information through web portals, accurate billing, reduction in network losses, and competition between retailers to provide innovative time-based tariffs [61]. One such retailer is Flick Electric which takes advantage of Smart Meters and invoices its customers based on wholesale costs at each 30-minute interval²¹.

²⁰ Counts taken on December 2016 from the *Metering snapshot* page which is updated regularly at <http://www.emi.ea.govt.nz/>.

²¹ More information on Flick Electric and pricing method can be found at <https://www.flickelectric.co.nz>.

2.7 Summary

Sections one to three of this chapter provided an insight into New Zealand's electricity sector and the challenges this sector is facing, now and in the future. It is evident that New Zealand uses a large amount of renewable energy which sets it apart from many other countries. However, since New Zealand relies predominantly on hydro generation, its electricity supply is vulnerable to the natural environment, in this case the variability of rainfall, which affects security of supply. To monitor and enforce security of supply, Transpower estimates hydro storage levels, the difference between electricity demand and supply in winter months, and the expected surplus generation capacity of the North Island during winter months. A further strategy to ensure security of supply, evident in this chapter, comes from the retailers' side by educating the energy user through innovative tools such as website applications to monitor and manage electricity usage, a variety of different pricing structures, join-up incentives, billing management systems, and rates targeted at EVs. These strategies can help broaden the mix of renewable energy sources and also help with the issue of reliance on rainfall.

The fourth section of this chapter outlined New Zealand's energy strategy. It became evident, that in order to achieve the goals set out in New Zealand's energy strategy, a major shift in the way electricity is generated, distributed and consumed is needed. This could include constructing more renewable generation plants and replacing inefficient fossil-fuelled generation plants. Furthermore, energy sectors which heavily rely on fossil fuels need to move to less CO₂ emitting energy sources e.g. the electrification of the transport sector to utilise renewable generation.

The fifth section of this chapter described New Zealand's electricity consumption. It became evident that the national peak demand causes the price of electricity to rise, incentivises fossil-fuelled generation, and threatens security of supply. Furthermore, it was found that the residential sector has the highest impact on this peak demand, and therefore, demand-side management in households can help benefit the nation significantly by reducing peak demand.

The final section of this chapter analysed available literature to provide insights into the first research question: *which new technologies are available at the household level?* Solar PV systems, EVs, and HESSs were found to be the new technologies that could cause the greatest disruption. Even though these technologies have had a slow uptake in New Zealand so far, this uptake is expected to rapidly increase due to falling costs of these technologies.

The next chapter provides an insight into current research on the impact these technologies could have on New Zealand's electricity industry.

Chapter 3

Related Work

“Climate change is the world’s greatest environmental challenge. It is now plain that the emission of greenhouse gases, associated with industrialization and economic growth... is causing global warming at a rate that is unsustainable”

— Tony Blair

Electricity generation has been a crucial part in the development of New Zealand and continues to be a crucial factor in the country’s economic growth and the well-being of its citizens. Although, New Zealand’s electricity sector is predominantly based on renewable generation, the nation still has a relatively high per capita greenhouse gas emission. The New Zealand government has shown a commitment to reduce the nation’s greenhouse gas emission through ratifying multilateral environmental agreements, and developing national energy strategies e.g. [62] [8]. Many studies have been conducted which give insight into how New Zealand can approximate these commitments, such as how electricity demand can be met with more renewable sources [63] or the impact of upcoming technologies on the electricity system e.g. [64] [65]. Due to the complexity of forecasting the uptake of renewable energy and new technologies, there is a wide variation in studies relating to the future of New Zealand’s electricity system. This chapter focusses on three studies put forward by predominant research organisations within New Zealand.

These organisations include the GREEN Grid research programme, Concept Consulting Group, and the Ministry of Business, Innovation, and Employment (MBIE). Findings of these studies are described as follows.

3.1 Load Profile Impact

The first study discussed, is the paper: *Impacts of new technologies on load profiles*, written by Michael Campbell, Allan Miller, and Neville Watson, as part of the GREEN Grid research programme [49]. This research program is funded by the MBIE and led by Canterbury University in conjunction with the University of Otago. The aim of this program is to model future trends in renewable electricity supply and demand, to ensure New Zealanders have reliable, safe, and affordable renewable energy [66]. An overview of the research from the GREEN Grid research programme can be found at [67]. The paper discussed in this research, as mentioned above, describes the impacts new technologies would have on distribution network loads, experienced in 2015. The technologies observed in this paper include solar photovoltaic (PV) systems, electric vehicles (EVs), and home energy storage systems (HESSs). The impact of these technologies is discussed as follows.

3.1.1 Solar Photovoltaic Systems

This paper models three different sizes of solar PV generation in distribution networks around New Zealand. These sizes include: 8W per capita which was the approximate level in New Zealand in 2015, 80W per capita, and 470W per capita which was the level in Germany in 2015 (the world leader in solar PV generation per capita). Three key findings from this study are outlined as follows.

Firstly, there is a large variability of daily energy generation depending on the day of the year. This is most evident in the Canterbury region with 1W of installed capacity producing 7.7Wh on the 28th of December and on the 18th of August producing over 20 times less energy; 0.36Wh.

Secondly, solar PV generation can have a large effect on peak load during the day if this load occurs during high generation times, an example of this was on the 6th of February on the Orion network, where peak demand was reduced by 52% (with 470W per capita). However, peak load during the day typically occurs when solar PV generation is low causing little to no reduction in daily and annual peak load, as shown in the mean daily columns in Table 3.1.

Thirdly, there is a variance in the mean daily peak reduction and the annual peak reduction, as shown in Table 3.1. This difference is due to New Zealand’s annual peak load occurring in the winter months, when solar PV generation is at its lowest.

Table 3.1: Reduction in peak load using three different levels of PV penetration [49].

Network	8 Watts per capita		80 Watts per capita		470 Watts per capita	
	Mean daily peak (%)	Annual peak (%)	Mean daily peak (%)	Annual peak (%)	Mean daily peak (%)	Annual peak (%)
Orion	0.13	0	1.28	0	7.50	0
Top Energy	0.08	0	0.83	0	4.87	0
NorthPower	0.08	0	0.77	0	4.54	0
Vector	0.25	0.09	2.47	0.88	14.52	5.20
Eastland	0.15	0	1.49	0	8.77	0
Wellington Electricity	0.20	0	2.02	0	11.89	0
Marlborough Lines	0.16	0	1.58	0	9.28	0
Network Tasman	0.20	0.20	1.96	2.10	11.50	12.20
Electricity Ashburton	0.05	0.06	0.49	0.60	2.88	3.60
West Power	0.09	0.10	0.91	1.20	5.32	6.80
Mean	0.139	0.045	1.38	0.478	8.107	2.78

3.1.2 Electric Vehicles

The authors introduce three different levels of EV penetration scenarios modelled on the Orion distribution network. These modelled scenarios provide an insight into the potential impact EVs have on a network's load. The EVs used in these scenarios would typically travel 30 km a day, and had a charger size of 2.3kW. The scenarios and their impact on the Orion distribution network are discussed as follows.

The first scenario assumed all light passenger vehicles were electric and would typically begin charging between 4 and 8pm. This scenario showed that the charging of these EVs would increase the daily energy demand by 14%. Another finding was that since these charging times occurred during typical peak load times the peak load would also increase significantly. One such example was on the 8th of July where peak load was increased by 62%.

The second scenario used a more realistic²² amount of EV penetration. This scenario assumed EVs comprised of 10% of the light vehicle fleet with the same charging method as scenario one²³. This scenario showed a mean increase in daily peak load of 4.6% and a 2.3% increase in daily energy consumption.

The third scenario assumed the same number of EVs as the second scenario, however, charging of EVs would utilise cheaper energy by delaying the mean charge start time to 11pm. This scenario showed that the mean daily peak increased only by 0.97%.

The results from the last two scenarios show that with a realistic EV growth there is minimal effect on a network's peak load, especially if charging is shifted to later times. However, if there is a large number of EVs, there needs to be a clear incentive for these vehicles to be charged at off peak times, otherwise, if left uncontrolled, peak loads could increase significantly, as shown in scenario one.

²² Realistic in this sentence is used to describe a more probable uptake of EV penetration by 2035 than 100%, as mentioned in the first EV penetration scenario.

²³ A 10% EV fleet is still considered high as some work undertaken by Energy Cultures suggest a fleet size of 6% in 20 years being an optimistic scenario if there are no regulatory interventions [99] [100].

3.1.3 Home Energy Storage Systems

A model of HESSs is introduced where the distribution network operators can control the charging and discharging behaviours. This control allows the HESS to be charged at a rate and time which causes minimal effect on peak load, and conversely, discharged at a rate and time which has maximum effect on reducing peak load. The HESS used in this model had a 7kWh capacity, a 92.5% round-trip energy efficiency, and a discharge rate of 2kW. Two different scenarios were discussed in this paper which are explained as follows.

The first scenario assumes 10% of residential sites have an HESS and no solar PV system. The results show there is a large variance in daily peak load reduction. This variance occurred due to the constraints in energy capacity and discharge rate of the HESS. The energy capacity constraints were evident in longer flatter peaks, while the discharge rate constraints were evident in shorter sharper peaks. On average, the HESSs reduced the daily peak load by 7.85% and reduced the annual peak by 5.87%. The extent of annual and daily peak reductions for each distribution network in this scenario is shown in Table **3.1**.

The second scenario assumes the same level of HESSs with a high level of solar PV penetration (470 Watts per capita). In this scenario, it is assumed the HESSs only charge with solar energy, with any excess solar energy being exported to the network. The results show that on average the daily peak load on a distribution network would be reduced by 12.78% and the annual peak load would be reduced by 7.28%, as shown in Table **3.2**.

Table 3.2: Impact of home energy storage systems in 10% of residential ICPs without PV and with a high level of PV (470W per capita) [49].

Network	Mean reduction to daily peak		Reduction of the year's peak load	
	No PV (%)	With High PV (%)	No PV (%)	With High PV (%)
Orion	6.80	11.80	5.90	6.10
Top Energy	9.30	12.10	8.30	8.30
NorthPower	6.40	8.90	5.40	5.60
Vector	6.90	17.90	5.80	6.20
Eastland	8.50	15.20	8.30	8.30
Wellington Electricity	8.30	16.50	6.10	6.10
Marlborough Lines	7.50	12.90	5.50	6.40
Network Tasman	9.80	13.90	5.00	10.50
Electricity Ashburton	3.80	5.10	1.70	3.60
West Power	11.20	13.50	6.70	11.70
Mean	7.85	12.78	5.87	7.28

Overall, three core findings are evident in this paper by the GREEN Grid research programme. Firstly, installing solar PV systems at residential sites without having access to energy storage would reduce mean daily peak load on a distribution network, however, would have little to no impact on the annual peak. Secondly, residential sites with both solar PV and energy storage systems would have smaller annual and daily peak loads, than residential sites with only an HESS. Thirdly, if the charging of EVs is left uncontrolled, there could be a significant increase in peak load.

3.2 Short to Long Term Impacts

The second study discussed is a three-part study from the Concept Consulting Group, authored by Simon Coates, and David Rohan. The Concept Consultant Group provides “advice on energy sector policy, business analysis, restructuring, market design, regulatory issues, energy modelling, market analysis, and technical issues” [68]. Clients of this group include the Electricity Authority, Transpower,

electricity retailers, distribution network owners, and government agencies and ministries. This study presents three reports discussing short to long term greenhouse gas emissions, cost effectiveness, and social impacts related to the uptake of new energy technologies. Findings of these three reports are outlined as follows.

3.2.1 Greenhouse Gas Emissions

The first report looks at how the uptake of new technologies would affect greenhouse gas emissions in New Zealand [69]. The technologies analysed in this report are EVs, solar PV systems, and HESSs. The assumed growth for EVs, solar PV systems, and HESSs started at effectively zero in 2014, and is expected to reach 80%, 60%, and 60% of households by 2040, respectively. The assumed sizes of these technologies are a 4kW rooftop solar PV system, a mid-range EV, and a 7kWh HESS. The considered emissions are from the electricity sector, transport sector, and embodied emissions (emissions incurred in the manufacturing of the technology). The impacts of each technology, discussed as follows, are observed short term (1-3 years), medium term (4-5 years), and long term (15+ years).

Electric vehicles - The uptake of EVs is expected to modestly increase embodied emissions, and emissions in the electricity sector. However, the large amount of tailpipe emissions, reduced in the transport sector, will offset both embodied and electricity sector emissions. The increase of embodied emissions is due to the more emission extensive manufacturing process of an EV in comparison to a gasoline vehicle. The increase of emissions in the electricity sector was examined with two EV charging regimes. The first regime (*smart*) charged EVs at low demand times, while the second regime (*simple*) charged EVs immediately after their journey. The first regime increases the average load, however, since charging is concentrated on off peak times, the peak load is relatively unchanged. Since the second regime charges EVs immediately after their journeys, which may coincide with peak periods, there is typically a much larger increase in peak load. In both regimes, it is expected the added electricity demand from EVs will increase electricity sector emissions in the short term, since a portion of this demand will be

met by existing fossil fuel generation. In the medium term, it is expected electricity sector emissions will modestly increase, as added electricity demand will be met by mainly new power stations, which is expected to be wind and geothermal. The increase of emissions in the electricity sector with the *smart* regime is expected to be lower than with the *simple* regime, as there is less demand at times when fossil-fuel power stations are most likely to operate. The reduced emissions in the Transport sector are expected to offset the added embodied and electricity emissions and significantly reduce New Zealand's net greenhouse gas emissions. Reduction in net greenhouse gas emission is expected to be approximately 1.4 tonnes per year for each EV in the short to medium term, and 1.7 tonnes per year in the long term, as shown in Figure 3.1.

Solar PV - The uptake of solar PV systems is expected to reduce net emissions in the short term by displacing existing fossil-fuelled generation. However, in the medium to long term, it is expected that solar PV systems will substitute construction of other renewable power plants (such as wind and geothermal). This substitution is expected to cause a larger gap between power demand and supply in the winter months, which will require additional peaking plants (presumably fossil-fuelled). For this reason, the net emissions are expected to slightly reduce in the medium term, and increase in the longer term. When assuming a 20-year lifetime, a solar PV system installed in the short, medium, and long term is expected to change net emissions by approximately -12, -0.05, and +0.05 kg CO₂/kWh, respectively. Similarly, on an annual scale, as shown in Figure 3.1, it is expected a solar PV system will reduce emissions in the short to medium term by 0.3 tonnes per year and increase emissions in the long term by 0.25 tonnes per year. These net emission results are also expected to be true in a scenario with a high CO₂ price, as solar PV systems will substitute for a greater number of wind power plants, causing a larger need for peaking plants in winter months, and therefore more emissions.

Home Energy Storage System – There are two scenarios of how HESSs can impact greenhouse gas emissions. The first scenario assumes the HESS is predominantly used to flatten national load and reduce the need for peaking power plants. In this scenario, it is expected that generation from less efficient fossil-fuelled power plants will be shifted to more efficient fossil fuelled power plants in

the short term as they have a cheaper running cost, i.e. from coal to gas fired generation. In the medium to long term, more investment into renewable baseload generation (i.e. wind and geothermal stations) is expected, due to a flatter and more variable load. On an annual scale, as shown in Figure 3.1, these batteries are expected to reduce greenhouse gas emissions by 0.1 tonnes per year, and this value is expected to be consistent, unless there is a widespread uptake of EVs that charge at the same time (reducing the benefits of the HESS). The second scenario assumes the HESSs are used to store excess solar energy. In this scenario, the HESS would be charged during the day when solar PV generation exceeds household demand, reducing the benefits from the previous scenario, as they are no longer used to flatten load. In this scenario, it is possible that embodied emissions exceed the reduction in emissions from the electricity sector, causing an increase in net greenhouse gas emissions.

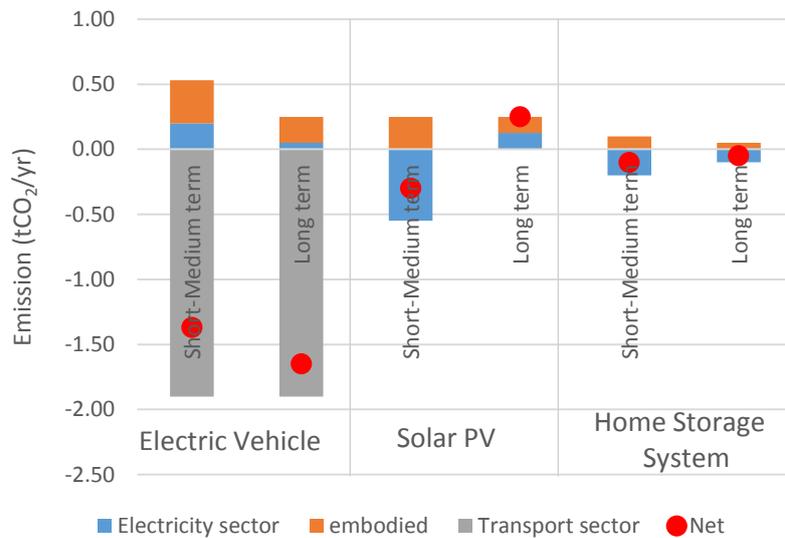


Figure 3.1: Predicted short-term (1-3 years) and long-term (15+ years) annual impacts on greenhouse gas emissions of electric vehicles, solar PV systems, and home energy storage systems [69].

As previously discussed there is a greater reduction in greenhouse gas emission in EVs compared to solar PV systems, and HESSs. This is to be expected as New

Zealand's electricity sector consists predominantly of renewable energy (see Section 2.1.1.), whereas New Zealand's transport sector is predominantly fossil fuelled. This is also true for the household level, where the average household directly causes approximately 7 tonnes of CO₂ per year, with the majority coming from private passenger vehicles (approximately 70%). When comparing the impact of these technologies on greenhouse gas emissions to other countries, the benefits of solar PV systems and household energy storage are relatively low. For example, a country which uses largely coal for electricity generation could benefit from a net reduction of over 4 tonnes of CO₂ per year for an equivalent sized PV system (4kW). However, the benefits of EVs in New Zealand are relatively higher than in other countries that have a lower share of renewable energy. For example, a country that uses predominantly coal for electricity generation might gain a zero-net benefit in emission reduction.

3.2.2 Cost Effectiveness

The second report focuses on the cost effectiveness of new technologies on a consumer and national level [50]. On the consumer level, it looks at whether purchasing new technology would bring economic benefits for the consumer, while on the national level, the focus is on analysing the hidden costs or benefits to society. This report focuses on EVs, solar PV systems, and HESSs. As follows these technologies and their cost effectiveness are described.

Electric vehicles – When comparing lifetime costs, a new mid-range EV has a similar cost to that of a gasoline vehicle, when travelled 10,000 km/year, based on current prices. This similar cost is due to less fuel costs and road user charges of EVs, offsetting their larger upfront costs. With a vehicle travelling 20,000 km or more a year, an EVs lifetime costs would be approximately \$10,000 less than that of an ICE. In the longer term, and assuming EVs upfront costs continue to drop, EVs lifetime costs will also drop making EVs progressively more attractive. On a national level, EVs have the potential to significantly save costs for the nation by reducing greenhouse gas emissions, reducing the need for imported gas, and stabilising electricity demand (allowing for investments into cheaper baseload

generation). However, since these benefits are not fully signalled to the consumer, and the road user charge exemption for EV owners is due to expire (when EVs account for 2% of light vehicle fleet), the uptake of EVs is expected to slow to a suboptimal level. A slower uptake of EVs is expected to cost New Zealand between 300 and 700 million dollars over the next 20 years.

Solar PV - The cost effectiveness of solar PV systems for consumers is very sensitive to factors such as the consumers' electricity usage, the household's location, and the installed solar PV capacity. A simulation was conducted using over 1,000 combinations of these factors and the current costs associated with solar PV. The results of this simulation show that less than 1% of modelled situations were found to be cost effective. Furthermore, the average lifetime cost-benefit for a 2, 4, and 6 kW solar PV system was found to result in a net loss in present value of \$3,300, \$4,900, and \$6,950, respectively. A key reason for this loss, is more electricity from the solar PV system being exported than consumed, resulting in a lower monetary reward. However, if the upfront cost of solar PV systems continues to drop and if electricity tariffs remain the same, it is expected solar PV systems will become cost effective for approximately 40% of modelled situations within 10 years, and almost all situations within 20 years. On a national level, the current electricity tariffs result in a misalignment between the consumers' and the nation's benefit from installing household solar PV systems. This misalignment is a result of energy prices staying relatively unchanged throughout the year, even though, the true cost of energy varies significantly between different seasons. The highest cost of supplying power typically occurs at peak demand periods in the winter months. This higher cost is due to the need for additional electricity generation and network capacity, to supply additional energy demand. Because of these misalignments in costs, consumers may be encouraged to install solar PV systems in situations and orientations which are not cost effective for the nation e.g. orientating a solar PV to capture more summer energy instead of winter energy which is more valuable for the nation. These misalignments could cost New Zealand approximately \$1.8 billion over the next 20 years.

Home Energy Storage Systems - With current electricity tariffs and HESS prices in New Zealand, it is unlikely these systems will be economical for

consumers. The greatest impact HESSs have for consumers, is to store excess generation from solar PV systems. However, the upfront cost is greater than the savings from storing excess generation. On average, a consumer would have a net present loss of \$10,750 when installing a 9kWh HESS with a 4kW solar PV system. On the national level, HESSs can collectively supply electricity during brief periods of critical peak demand. This can benefit the nation by avoiding costs for expensive peak generation and installing additional network capacity. Although hard to quantify, it is probable these costs could be hundreds of millions of dollars. However, since the HESSs are consumer driven and current electricity tariffs provide poor signals for consumers to meet peak demands, these benefits are unlikely to be fully captured. Furthermore, considering the large upfront costs of HESSs, there may be better energy storage options e.g. EVs with vehicle to grid technology.

3.2.3 Social Impacts

The third and final report from this study examines the potential social impacts from the uptake of new technologies in New Zealand [70], specifically whether the uptake of solar PV systems, HESSs, and EVs, shifts any costs to poorer consumers²⁴. One of the main findings is that if electricity tariffs remain the same, it will be likely poorer consumers would be worse off on average. This is because households with solar PV systems pay less for the required infrastructure which creates a shortfall that will be shifted to consumers without solar PV systems. Over 100,000 historical household power usage was analysed with social economic data to estimate the impact of this cost shifting. The results show that over 80% of the poorest consumers would face an average increase of \$100 in their electricity bill per year for the next 15 years, with the highest increase of \$350 or more. This large cost increase would in turn encourage a higher uptake of solar PV, causing a higher economic cost for New Zealand (approximately \$2 billion).

²⁴ In this report, it is assumed that households without solar PV are poorer.

3.3 Investments in the Transmission System

The third study discussed, is the report: *Electricity demand and generation scenarios*, published by the Ministry of Business, Innovation, and Employment in 2016 [51]. In this report scenarios are described, that were created for Transpower and the Commerce Commission, to evaluate future proposals for investments in the transmission network. These scenarios are intended to investigate significant uncertainties in future supply and demand in the electricity sector. These uncertainties include technology costs, price of carbon emissions, price of electricity, demand side participation, and household uptake of new technology (EVs, solar PV systems, and HESSs). The scenario most relevant to this thesis is called the *disruptive* scenario, described as follows.

In the *disruptive* scenario, the cost of new technology continues to fall which leads to a large uptake²⁵, which in turn leads to an increasing electricity demand from the grid. Electricity demand is expected to grow on average by 1.3% per year reaching approximately 54 TWh by 2040, with over 1,600 GWh offset by household solar PV generation. This increase in electricity demand is largely due to the additional demand from charging EVs which is only partially offset by solar energy²⁶. National peak demand is also expected to increase on average by 0.7% per year reaching approximately 7.3 GW by 2040. This peak demand increase is relatively lower than in other scenarios without a large technology uptake e.g. in a scenario without solar PV systems and HESSs, peak demand would be expected to be 490 MW higher in 2040.

This lower peak demand is due to HESSs providing additional energy storage to reduce peak demand, and the additional demand from EVs being partially controllable. This controllability allows the additional demand, during peak

²⁵ In this scenario, it is assumed solar PV systems without HESSs are installed in 81,395 households by 2040, and there are 314,116 households that have both a solar PV and HESS installed. The sizes of these technologies are a 3 kW Solar PV system, and a 6.7 kWh HESS. Similarly, in this scenario electric vehicles are estimated to reach approximately 1.77 million by 2040.

²⁶ In this scenario, it is assumed that 80% of electric vehicle charging occurs between 11pm and 5am, 10% between 5pm and 11pm, and the remaining 10% between 9am and 5pm. This implies that most of the energy demand caused by electric vehicles, occurs outside of solar PV generation times.

periods, to be minimal and charge at low demand periods, causing an overall flatter national electricity demand. This flatter demand is expected to reduce the need for peaking power plants. It also provides an incentive for more baseload power plants, such as geothermal and wind plants, which have a small long run marginal cost (LRMC). The predicted installed capacity of different energy sources, and how much electricity is generated from these sources is shown in Figure 3.2 and Figure 3.3 below.

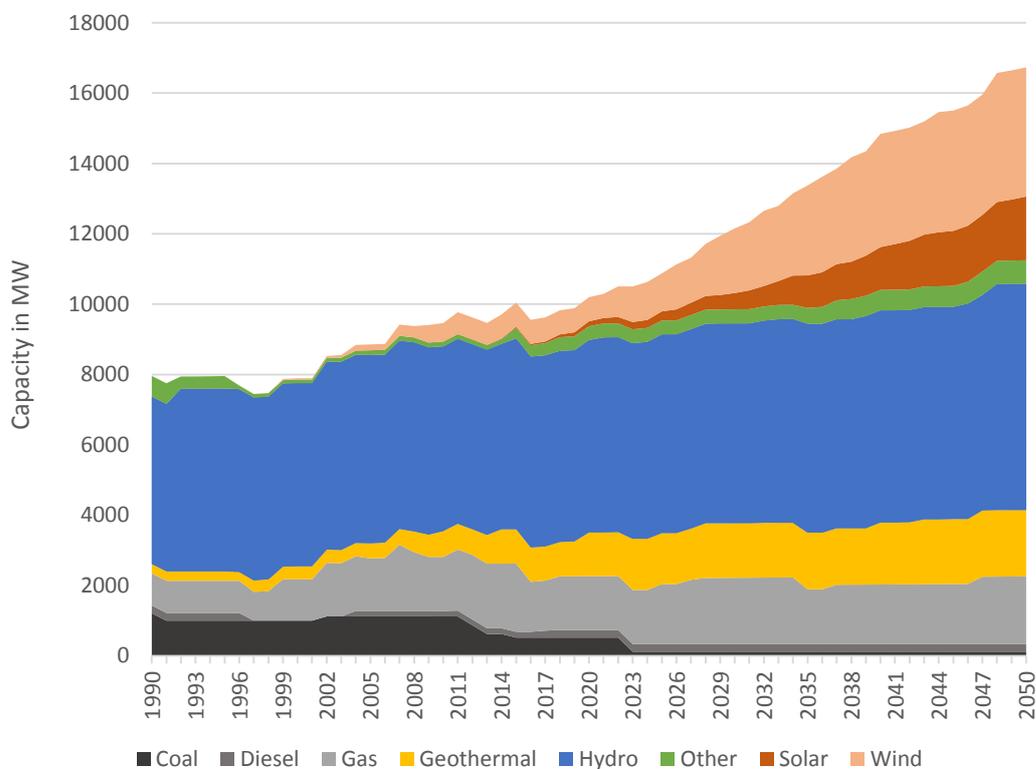


Figure 3.2: Installed electricity generation capacity by fuel type [71].

As shown in Figure 3.2, new power plants, are predominantly renewable with wind, solar PV, and geothermal capacity expected to rise from 680, 40, and 980 in 2016 to 3200, 1200, and 1700 MW, respectively, by 2040. The fossil fuelled capacity shows a reduction in coal capacity which is expected to fall to 120 MW once the two Huntly Rankine units close in the early 2020s. This reduction of coal

capacity can be explained with a shift to more economical gas power plants (an increase of 660 MW between 2016 and 2040) and an overall reduction in the need of peaking plants.

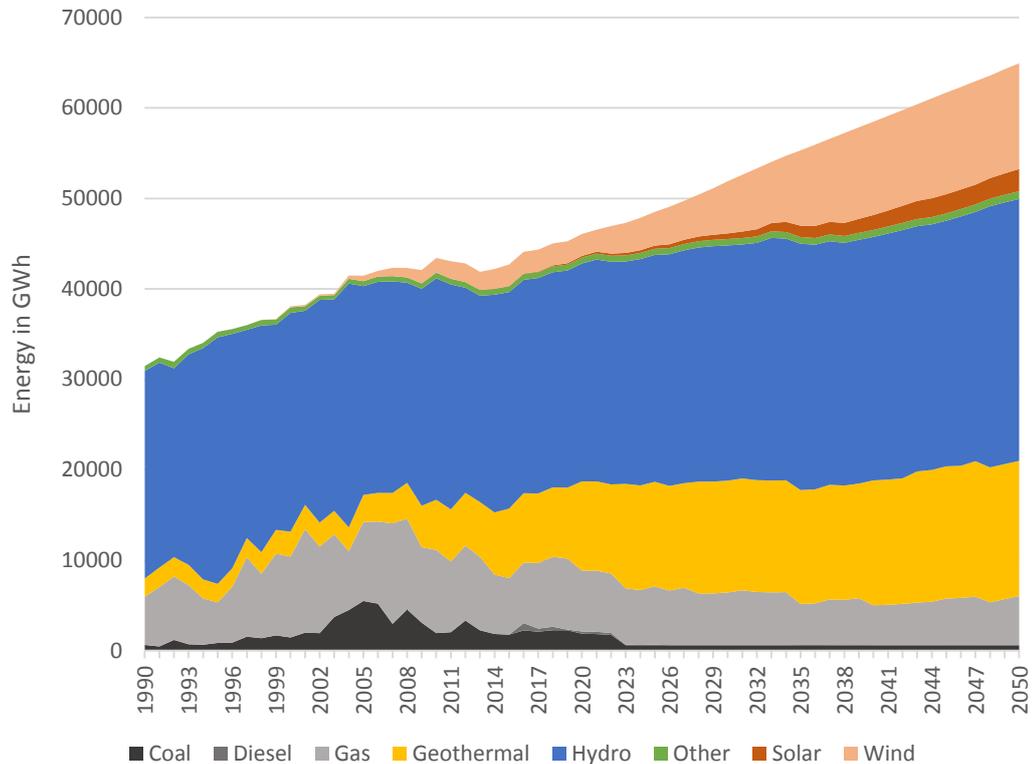


Figure 3.3: Annual electricity generation by fuel type [71].

Although the additional solar and wind capacity increases rapidly with a combined share of 30% in 2040, they only generate 2.8, and 17.6% of total electricity due to their intermittent behaviour, as shown in Figure 3.3. In 2040, most of New Zealand’s generation is expected to be geothermal and hydro (approximately 70%) with fossil fuel generation only consisting of 8.5% of generation. This higher level of renewable generation reduces the country’s electricity generation emissions from 5,228 kt CO₂-e in 2016 to 2,610 kt CO₂-e in 2050, and enables New Zealand to reach over 90% renewable generation by the mid-2030s.

3.4 Summary

This chapter focused on three studies put forward by leading research organisations within New Zealand. These three studies provided an insight into current research on the impact upcoming technologies have on New Zealand's electricity system, now and in the future.

The first study discussed was a paper from the GREEN Grid research programme. This paper analysed the impacts new technologies have on distribution network loads. Three core findings were evident in this paper. Firstly, installing solar PV systems at residential sites would have little to no impact on the network's annual peak load. Secondly, residential sites with solar PV and energy storage systems would have smaller annual and daily peak loads than residential sites with only an HESS. Thirdly, if charging of EVs is left uncontrolled, there can be a significant increase in peak load.

The second study put forward by the Concept Consulting Group, discussed greenhouse gas emissions, cost effectiveness, and social impacts related to the uptake of new energy technologies. This report showed that EVs, when compared to solar PV systems and HESSs, have the greatest impact in reducing the nation's greenhouse gas emissions. Similarly, EVs have the greatest economic benefits. However, if the uptake of EVs remains slow, it is expected to cost New Zealand between 300 and 700 million dollars over the next 20 years. The analysis of solar PV systems, showed that with current electricity tariffs there is a misalignment between the consumers' and the nation's benefit from installing household solar PV systems. These misalignments are due to the fact that households with solar PV systems pay less for the required infrastructure which creates a shortfall that will be shifted to consumers without solar PV systems. This will subsequently lead to a larger uptake of solar PV systems which could prevent the usage of some renewable sources and cause a larger gap between power demand and supply in the winter months. As a consequence, this technology could cost New Zealand approximately \$1.8 billion over the next 20 years. The analysis of HESSs, showed that this technology can benefit the nation by avoiding costs related to supplying peak

demand e.g. peaking power plants and additional network capacity. Although hard to quantify, it is probable these costs could be hundreds of millions of dollars. However, the HESS is most likely to be consumer driven, and with current electricity tariffs these benefits are unlikely to be fully captured.

The third study discussed was a report by the Ministry of Business, Innovation, and Employment, which outlined different electricity demand and generation scenarios. In this report, a simulated scenario was described, where the cost of new technology continued to fall, which led to a large uptake. This scenario showed that the electricity demand is expected to grow on average by 1.3% per year, largely due to the additional demand from EVs. Similarly, the national peak demand is also expected to increase on average by 0.7% per year. However, this peak demand is lower than in other simulated scenarios due to HESSs and EVs being utilised to flatten the national electricity demand. This flatter demand is expected to entice construction of more renewable plants, replacement of current plants with more efficient plants (from coal to gas), and an overall reduction in the need of peaking plants. As a consequence, it is expected CO₂ emissions will be approximately half of the 2016 levels by 2050, and renewable generation will be over 90% by the mid-2030s.

The next chapter describes a web-based simulation tool, that was created as part of this research, to simulate the power output of a solar PV system in New Zealand. This output is needed for the household simulation tool, explained in Chapter 6.

Chapter 4

Solar Panel Simulation

“Every hour the sun beams more energy onto Earth than it needs to satisfy global energy needs for an entire year.”

— National Geographic

The installation of solar panels to capture the sun’s energy is steadily growing in the world. In New Zealand’s residential sector, the most typical installation procedure for solar panels is on the surface of the most north facing roof. This method is space efficient, requires minimal mounting costs and captures a sufficient portion of sunlight. One consequence of this installation procedure, is that the solar panels have a low tilt angle, since the typical New Zealand household has a small roof pitch. This low tilt is suited to provide maximum power in the summer months, however, individuals may favour maximum winter power, maximum annual energy output or a balanced energy output.

This chapter describes the development of a simulation tool named “New Zealand solar panel output tool” (NZSPOT). This tool was created to see the effects of solar panel orientation on power output. The output of this simulation tool provides clarification relating to the power gains and losses, on an hourly scale, using different configurations. This simulation is freely accessible at <http://nzspot.cms.waikato.ac.nz/> and is described in a paper by Joris Suppers and

Mark Apperley [72]. Section one of this chapter describes the calculations used to estimate the sun's position. Section two describes the calculations used to estimate the intensity of radiation coming from the sun. Section three describes the system's effectiveness in transforming irradiance to electrical power. Section four describes the interface of this simulation. The final section presents the findings of this simulation.

4.1 The Sun's Position

The first and arguably most important calculation is accurately calculating the sun's position. Knowing the sun's position at a specific time allows accurate estimations of how much radiation will strike the surface. This is, therefore, essential for NZSPOT as it simulates the power output at an hourly scale. To accurately estimate the sun's position there are seven crucial variables: declination angle (δ), equation of time (EOT), solar time (t_s), hour angle (ω), elevation angle (α), zenith angle (θ_z) and azimuth angle (γ). Each of these variables are described as follows.

4.1.1 Declination Angle

The declination angle (δ) accounts for the earth's fluctuation from its axis of rotation and the plane normal to a line from the centre of the earth and the sun, as shown in Figure 4.1. This angle varies seasonally, and is related to the earth's progress in its orbit around the sun.

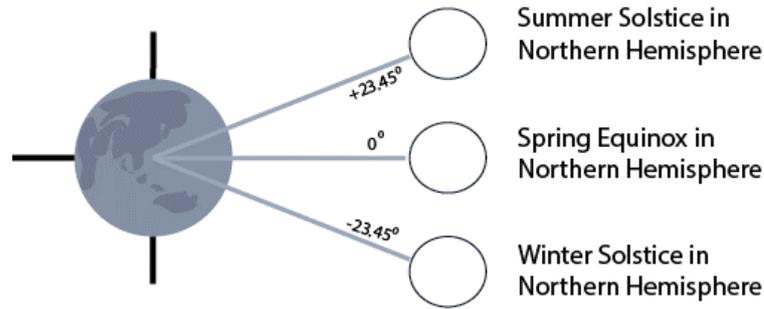


Figure 4.1: The sun's position fluctuates from overhead the earth's equator during the year.

This fluctuation ranges from -23.45° to $+23.45^\circ$ and can be calculated using Equation 4.0 [73].

$$\delta = \sin^{-1}(\sin(23.45^\circ) \sin(\frac{360}{365}(d - 81))) \quad (4.0)$$

Where d is the day of the year e.g. on the 1st of January $d = 1$.

4.1.2 Equation of Time

The equation of time (*EOT*), describes the discrepancy in minutes between true and mean solar time. This discrepancy is caused by the eccentricity of the earth's orbit, and can be calculated using one of the equations below depending on the day of the year (d) [74].

$$\text{For } d = 1 \text{ to } 106 \quad EOT = -14.2 \sin(\frac{\pi(d+7)}{111}) \quad (4.1.0)$$

$$\text{For } d = 107 \text{ to } 166 \quad EOT = 4.0 \sin(\frac{\pi(d-106)}{59}) \quad (4.1.1)$$

$$\text{For } d = 167 \text{ to } 246 \quad EOT = -6.5 \sin(\frac{\pi(d-166)}{80}) \quad (4.1.2)$$

$$\text{For } d = 247 \text{ to } 365 \quad EOT = 16.4 \sin(\frac{\pi(d-247)}{113}) \quad (4.1.3)$$

4.1.3 Solar Time

Solar time (t_s), represents the true time based on the sun's position in the sky. It is the time shown on a sundial, and can be estimated at a specific local time (LT) by using Equation 4.2 [75].

$$t_s = LT + \frac{TC}{60} \quad (4.2)$$

TC in Equation 4.2 represents a time correction factor, in minutes, which accounts for the variation of solar time in certain time zones. This variation can be calculated in three steps. The first step accounts for the longitude variations within a time zone, this is done by subtracting the local standard time meridian ($LSTM$) from longitude (λ). The second step is multiplying the value from the previous step by a factor of four to translate it into minutes, since the earth rotates 1° every 4 minutes. The last step is to add the EOT (see Section 4.1.2 above). These three steps are shown in Equation 4.3 [75].

$$TC = 4(\lambda - LSTM) + EOT \quad (4.3)$$
$$LSTM = 15 \times \Delta T_{GMT}$$

where 15 in LSTM accounts for the earth's spin (approximately 15° per hour), and ΔT_{GMT} is the difference in local time and Greenwich mean time (in hours).

4.1.4 Hour Angle

The hour angle describes the sun's position in the sky at a specific time of day, with solar noon represented as 0° , morning angles represented as negative and the afternoon angles represented as positive, as shown in Figure 4.2.

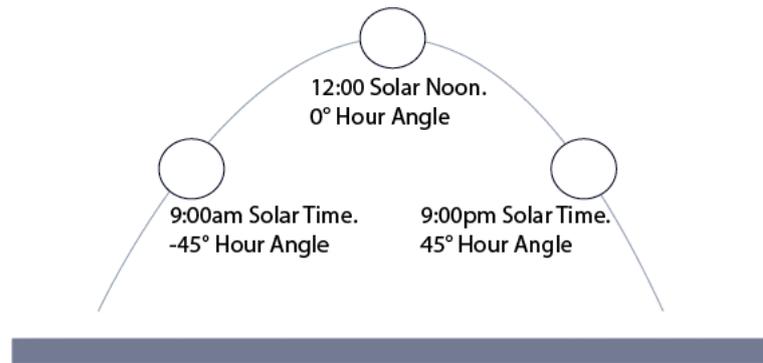


Figure 4.2: The sun's angular position in the sky at different solar times.

This variable is called the hour angle (ω) and can be calculated by subtracting twelve from solar time, and multiplying the result by 15, since the earth spins 15° per hour. This calculation is shown in Equation 4.4.

$$\omega = 15(t_s - 12) \quad (4.4)$$

4.1.5 Elevation Angle

The elevation angle (α) describes the sun's angular height above the horizon, shown in Figure 4.3, and can be calculated from the declination angle (δ), hour angle (ω), and the latitude (φ).

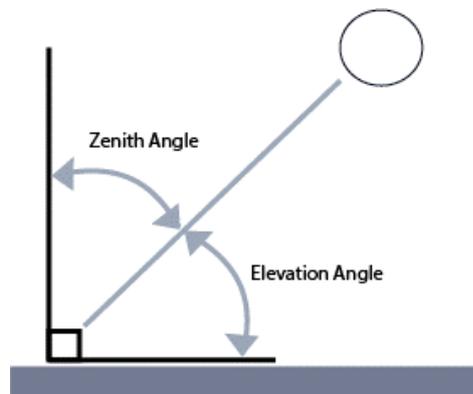


Figure 4.3: The zenith and elevation angles describe the angular height of the sun.

This elevation angle is 0° at sunrise and rises up to an angle depending on the location and time of year, then decreases back to 0° at sunset. This can be calculated by Equation 4.5.

$$\alpha = \sin^{-1}[\sin \delta \sin \varphi + \cos \delta \cos \varphi \cos \omega] \quad (4.5)$$

4.1.6 Zenith Angle

The zenith angle (θ_z), is similar to the elevation angle, as it describes the sun's position in the sky, however, it measures from the vertical axis rather than the horizon (shown in Figure 4.3). The zenith angle can be calculated by subtracting the elevation angle from 90, as shown in Equation 4.6.

$$\theta_z = 90 - \alpha \quad (4.6)$$

4.1.7 Azimuth Angle

The last variable describing the sun's position is the azimuth angle (γ). This angle describes the compass direction of the sun in the sky, with North being 0° , East 90° , South 180° and West being 270° , shown in Figure 4.4.

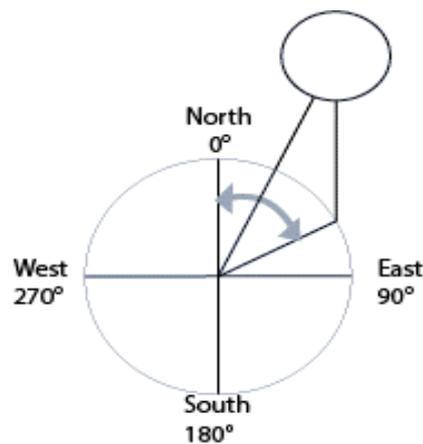


Figure 4.4: Compass direction of the sun in the sky.

The azimuth angle changes during the day, with solar noon being north in the southern hemisphere, and south in the northern hemisphere. This angle can be estimated using the calculation below.

$$\gamma = \cos^{-1} \left[\frac{\sin \delta \cos \varphi \cos \theta_{hr} - \cos \delta \sin \varphi \cos \theta_{hr}}{\cos \alpha} \right] \quad (4.7)$$

These seven variables described are used in NZSPOT to calculate the irradiance impinging on a solar panel's surface at a specific time and location, the irradiance calculations are described as follows.

4.2 Irradiance

Knowing the sun's position, it is possible to estimate the irradiance striking the earth's atmosphere. This irradiance is then absorbed and scattered within the atmosphere and reflected by the earth's surface, as shown in Figure 4.5.

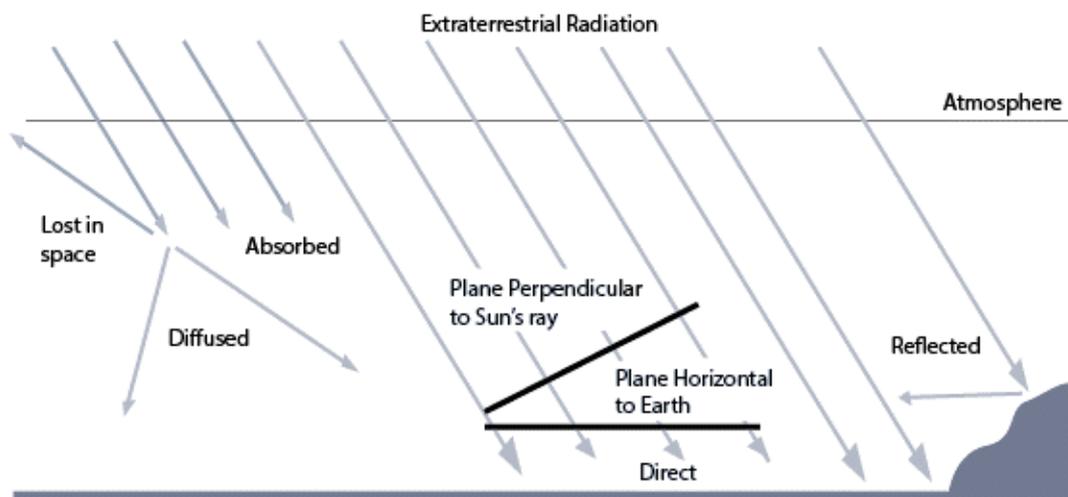


Figure 4.5: The effect of earth's atmosphere on solar radiation.

The National Institute of Water and Atmospheric Research (NIWA), which is a crown-owned company focussing on conducting environmental science, collects data from various weather stations across New Zealand and stores this data in a national climate database called CliFlo²⁷. NZSPOT uses data, collected from ten different weather stations scattered across New Zealand, as shown in Figure 4.6, to accurately calculate the power output of a solar PV system at different locations²⁸. These ten stations are: Kaitaia, Dargaville, Auckland, Hamilton, New Plymouth, Wellington, Nelson, Greymouth, Christchurch, and Invercargill.



Figure 4.6: The ten different weather stations used in NZSPOT provide a good coverage of national weather patterns (Image of New Zealand from www.vectormap.info).

²⁷ More information can be found at <https://cliflo.niwa.co.nz/>.

²⁸ Data was retrieved in 2013 from CliFlo, and consequently the measured data is from 2012.

NZSPOT contains a file with a key and value pair for each of these ten weather stations. The key defines the coordinates of the weather station, while the value is the name of the file, containing the measured values from that weather station. The use of this file with key and value pairs allows updating or adding more weather stations easily. The measured values include: Firstly, the intensity of solar radiation striking a surface which is horizontal to the earth's ground, known as global horizontal irradiance (GHI). Secondly, wind speed (WS). Thirdly, the temperature of air that is shielded from radiation and moisture, known as dry-bulb temperature (Ta). GHI contains both the direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), however, for accurate estimations of power output from solar panels, both DNI and DHI values are needed. To calculate these values, the extraterrestrial irradiance and atmospheric attenuation need to be estimated first.

4.2.1 Extraterrestrial Irradiance

The intensity of solar radiation that strikes the earth's atmosphere varies throughout the year due to the eccentricity of the earth's orbit around the sun. This eccentricity causes the solar irradiance to vary by $\pm 3.4\%$ above the atmosphere, with the highest value when earth is closest to the sun (the perihelion i.e. January 3-5) and lowest value when earth is furthest away from the sun (the aphelion i.e. July 5). The extraterrestrial solar irradiance (E_0) can be estimated with the day of the year (d) and the solar constant (E_{sc}) using Equation 4.8 [76].

$$E_0 = E_{sc} \times \left[1 + 0.033 \cos\left(\frac{360 \times d}{365}\right) \right] \quad (4.8)$$

$$E_{sc} = 1367 \text{ W/m}^2$$

The extraterrestrial irradiance striking a plane horizontal to the earth's surface, can then be estimated by multiplying the extraterrestrial solar irradiance by the cosine of the zenith angle, as shown in Equation 4.9.

$$E_{0h} = E_0 \times \cos(z) \quad (4.9)$$

4.2.2 Atmospheric Attenuation

The intensity of solar radiation that strikes the earth's surface is affected by many factors. One of the main factors is the amount of radiation which is absorbed and diffused within the atmosphere, as shown in Figure 4.5. A variable called the clearness index (K_t) is used to define the ratio between global horizontal radiation (GHI) and extraterrestrial radiation striking a horizontal plane (E_{0h}), as shown in Equation 4.10. Knowing this ratio gives an understanding of how much radiation is lost from absorption and scattering. Another influential factor on atmospheric attenuation, is air mass (AM), which describes the volume of atmosphere sunlight must travel to reach a location. A simple estimation of air mass relative to zenith angle, is shown in Equation 4.11 [74].

$$K_t = \frac{GHI}{E_{0h}} \quad (4.10)$$

$$AM = \frac{1}{\cos(z)} \quad (4.11)$$

With the extraterrestrial irradiance and atmospheric attenuation factors known, the next step is calculating the direct normal irradiance and diffuse normal irradiance, described as follows.

4.2.3 Direct Normal Irradiance

Direct Normal Irradiance (DNI) describes the intensity of solar radiation striking a plane on earth's surface that is perpendicular to the sun's rays. A model produced by Laue [77] estimates the direct normal irradiance based on air mass and a fixed clearness index of 0.7. This clearness index value represents a clear sky, however, with an actual clearness index value calculated from Equation 4.10, this value is substituted for 0.7. The model by Laue, with the substituted clearness index is shown in Equation 4.12.

$$DNI = E_0 \times [(1 - 0.14 \times h) \times Kt^{AM^{0.678}} + 0.14 \times h] \quad (4.12)$$

Where h is the height above sea level in kilometres

4.2.4 Diffuse Horizontal Irradiance

Diffused Horizontal Irradiance (DHI) is the intensity of solar radiation striking a plane horizontal to the earth's surface which has not come from direct sun rays (i.e. scattered and diffused radiation). The DHI can be calculated using GHI, DNI, and the zenith angle, as shown in Equation 4.13 [78].

$$DHI = GHI - DNI \cos(z) \quad (4.13)$$

With the direct normal, diffuse horizontal and global horizontal irradiance known, the next step is to estimate the effectiveness of a solar PV system in transforming this irradiance to electrical power, which is described as follows.

4.3 Power Output

There are many factors to consider when estimating the efficiency of a solar PV system to transform irradiance to AC power. The first factor to consider is the angle of incidence between the sun's position and the surface of the solar panel. With this angle, it is possible to estimate the power output in four stages. Firstly, estimating the irradiance impinging on the solar panel, which is known as the plane of array irradiance (*EPOA*). Secondly, estimating the solar panel and solar cell temperature. Thirdly, estimating the solar panel's power output, and lastly, calculating the conversion efficiency of an inverter in converting DC power to AC. These four are described further as follows.

4.3.1 Angle of Incidence

The initial factor is the angle of incidence (*AOI*) between the sun's position and the solar panel's surface. It can be calculated with the sun's zenith and azimuth angles, and the solar panel's tilt (P_T) and azimuth (P_γ) angles, as shown in Equation 4.14.

$$AOI = \cos^{-1}[\cos(\theta_z) \cos(P_T) + \sin(\theta_z) \sin(P_T) \cos(\gamma - P_\gamma)] \quad (4.14)$$

With the angle of incidence known, the next step is to calculate the irradiance impinging on the surface of the solar panel, which is described as follows.

4.3.2 Plane of Array Irradiance

The irradiance impinging on the surface of a solar panel, known as the plane of array irradiance (E_{POA}), is comprised of beam (E_b), reflected (E_g) and sky-diffuse irradiance (E_d), as shown in Equation 4.15.

The beam irradiance (E_b) striking the surface of the solar panel can simply be calculated by multiplying direct normal irradiance (DNI) by the cosine of the angle of incidence, as shown in Figure 4.7 and Equation 4.16.

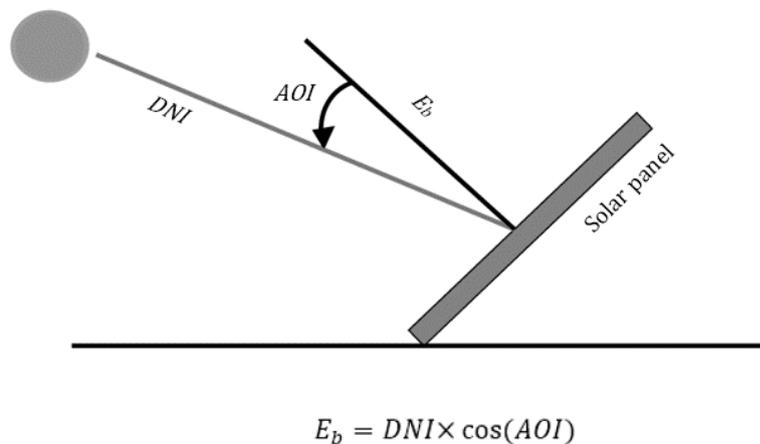


Figure 4.7: How the beam irradiance striking the surface of a solar panel is calculated.

Estimating the diffuse irradiance (E_d) striking a tilted surface is slightly more difficult, and over the years there have been many models developed. These include Klucher's 1979 model [79], Reindl et al's 1990 model [80] and Hay & Davies' 1980 model [81]. The model used in NZSPOT is the Simple Sandia Sky Diffuse Model,

which was developed by David L. King at the Sandia Laboratories [82]. This model, shown in Equation 4.17, uses the solar panel's tilt (P_T), diffuse horizontal irradiance (DHI), global horizontal irradiance (GHI) and the sun's zenith angle (θ_Z). The last component for calculating the $EPOA$, is estimating the amount of reflected irradiance (E_g) from the earth's surface that strikes the solar panel's surface. This can be calculated if the reflectiveness of the ground (albedo) and the tilt of the solar panel are known, as shown in Equation 4.18. This reflectiveness is a scale between 0 and 1, with 0 representing a dark non-reflective surface, while 1 representing a highly reflective surface. NZSPOT assumes an albedo of 0.20 to capture both an urban environment (0.14 - 0.22) and a grass area (0.15 - 0.25) [74].

$$EPOA = E_b + E_d + E_g \quad (4.15)$$

$$E_b = DNI \times \cos(AOI) \quad (4.16)$$

$$E_d = DHI \times \frac{1 + \cos(P_T)}{2} + GHI \times \frac{(0.012\theta_Z - 0.04) \times (1 - \cos(P_T))}{2} \quad (4.17)$$

$$E_g = GHI \times \text{albedo} \times \frac{(1 - \cos(P_T))}{2} \quad (4.18)$$

With the known irradiance impinging on the surface of a solar panel, there are two temperature values which affect the solar PV system's performance. These are the solar panel (module) and solar cell temperatures, which are described as follows.

4.3.3 Module Temperature

The temperature of a solar panel (T_m), also referred to as a module, can change the panel's efficiency in converting irradiance, and is therefore an important factor to consider. This temperature is a function of the air temperature, the incident solar energy, wind speed, and the materials of the module. Sandia Laboratories [74] have established an appropriate function, as shown in Equation 4.19. This equation uses Euler's number (e), plane of array irradiance ($EPOA$), wind speed (WS), ambient air temperature (T_a), and two values (a and b) which depend on the solar panel's

construction, materials and how it is mounted. Sandia Laboratories have tested a diverse range of solar panels and configurations, and have provided a range of values for a and b , and the temperature difference (ΔT) between the solar panel and solar cells at an irradiance level of 1000 W/m^2 , as shown in Table 4.1.

$$T_m = EPOA \times (e^{a+b \times WS}) + T_a \quad (4.19)$$

Table 4.1: Values calculated by Sandia Laboratories for different module types and mounts [74].

Module Type	Mount	a	b	ΔT
Glass/cell/glass	Open rack	-3.47	-.0594	3
Glass/cell/glass	Close roof mount	-2.98	-.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-.0750	3
Glass/cell/polymer sheet	Insulated back	-2.81	-.0455	0
Polymer/thin-film/steel	Open rack	-3.58	-.113	3
22X Linear Concentrator	Tracker	-3.23	-.130	13

4.3.4 Cell Temperature

Another temperature value which needs to be calculated is the temperature of the solar cells (T_c), which differs from the module's temperature depending on the construction and materials of the module, incident irradiance, and weather conditions. To calculate the cells temperature, NZSPOT uses the Sandia Cell Temperature Model, as shown in Equation 4.20. This model uses the solar panel's temperature (T_m), plane of array irradiance ($EPOA$), temperature difference (ΔT) of the solar panel and solar cell, and a reference irradiance (I_r) of 1000 W/m^2 .

$$T_c = T_m + \frac{EPOA}{I_r} \times \Delta T \quad (4.20)$$

4.3.5 Module Power

With irradiance and cell temperature known, it is possible to calculate the maximum power output of the module. This tool uses the Sandia PV Array Performance Model (SAPM) to estimate the maximum power current (I_{mp}), and maximum power voltage (V_{mp}), as shown on the current-voltage curve in Figure 4.6. The SAPM model was developed over twelve years of monitoring, testing, and modelling of solar panels, and has been well validated for flat-plate, concentrator, and large arrays of solar panels [82].

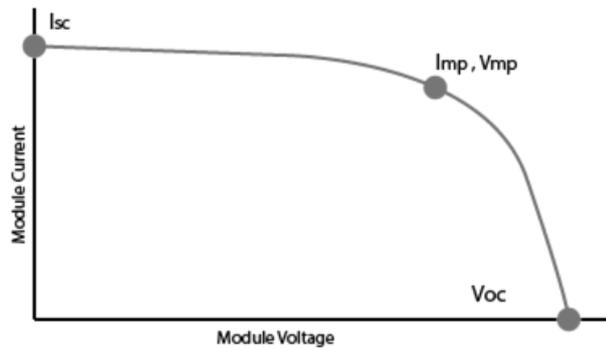


Figure 4.8: Current-voltage (IV) curve for a solar panel showing the maximum power point (point at I_{mp} and V_{mp}).

It is assumed in NZSPOT that a solar PV system has a charge controller which extracts the maximum available power output (i.e. maximum power point tracking [83]). Therefore, the DC power output of a solar PV system (P_{DC}) is the multiplication of maximum power current (I_{mp}), maximum power voltage (V_{mp}), and the number of modules in series (P_s) and parallel (P_p). This is shown in Equation 4.21. This simulation tool also assumes DC and mismatch losses are negligible.

$$P_{DC} = I_{mp} \times V_{mp} \times P_s \times P_p \quad (4.21)$$

4.3.6 Inverter Power

With the DC output of the solar panels known, the next step is calculating the inverter's efficiency in converting this DC power to AC power. This simulation tool uses the Sandia Performance Model for Grid-Connected Photovoltaic Inverters [84] to calculate an inverter's conversion efficiency. This model uses parameters obtained from the manufacturers' specification sheet and measurements taken from field or laboratory studies. This model was validated for a variety of residential and commercial size inverters, with a typical standard error of 0.1% between measured and modelled efficiencies [84].

4.3.7 System Losses

When calculating the power output of a solar PV system, in combination with module and inverter efficiencies, there are a variety of environmental and technical losses to consider. These losses in NZSPOT consist of three main factors. Firstly, soiling, which is dirt and other substances on top of the solar panel. Secondly, shading, which is shadows casted on top of the solar panel's surface. And lastly, electrical losses from manufacturing imperfections and wiring between components.

System losses can range drastically depending on technology, system design, and geographic location. In standard test conditions, system losses can range between 8-38% [85]. NZSPOT assumes a system loss of 14%, this percentage is similar to values used in other reputable solar calculators²⁹.

²⁹ One such example is PVWATTS' solar calculator from the national renewable energy laboratory (NREL), accessible at <http://pvwatts.nrel.gov/>. This calculator also uses the same percentage as the default value (14%).

4.4 User Interface

The user interface of NZSPOT is split into three stages. The user works through each stage, in sequence, to view the estimated power output of a solar PV system depending on its location and configuration.

The first stage is to determine the location of the solar PV system. This is done by presenting the user with an interactive map, allowing the user to easily select their location, as shown in Figure 4.9.

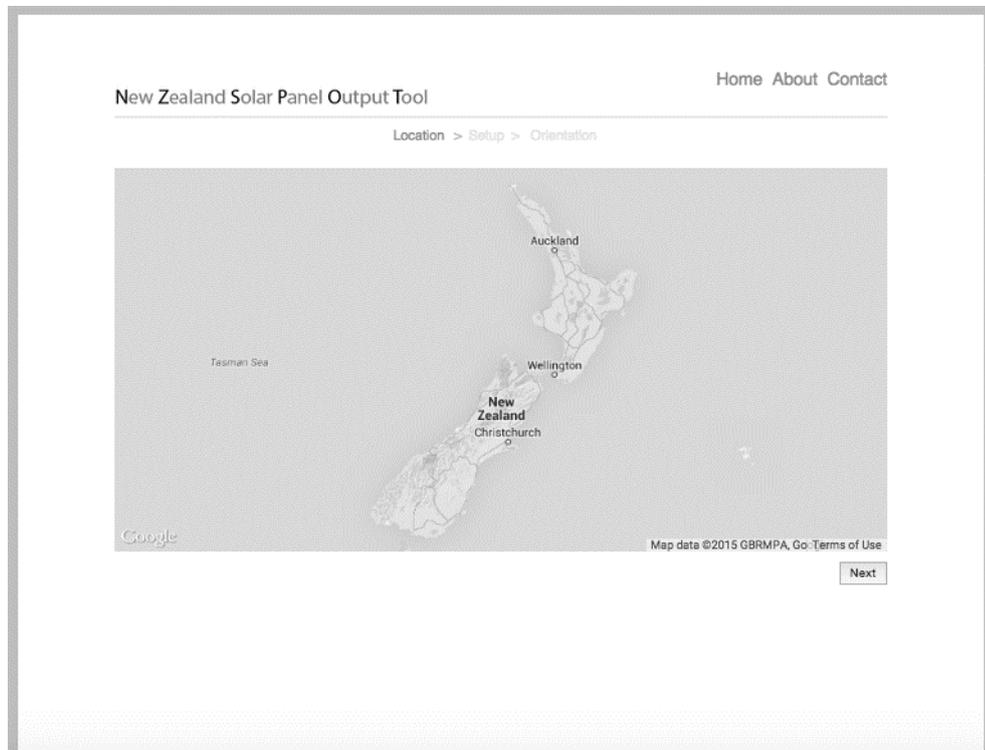


Figure 4.9: The main page of NZSPOT displays a map allowing individuals to select their location.

The second stage is to specify the characteristics of the solar panels and inverter, as shown in Figure 4.10. NZSPOT uses a large database by Sandia Laboratories³⁰ to allow the user to search for specific solar panels and inverters, to extract the needed information for future calculations. Another characteristic of the solar PV system defined in this stage is the number of modules in series (P_s) and parallel (P_p).

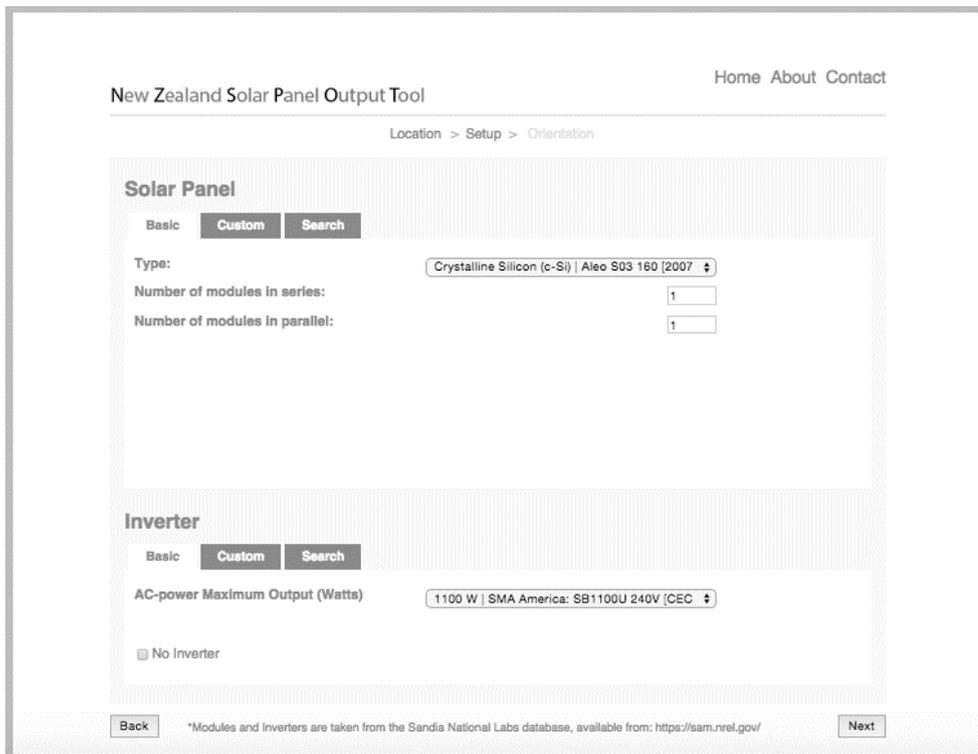


Figure 4.10: Second page of NZSPOT, allowing users to choose their solar panel and inverter setup.

The third and final stage is defining the solar panel's configuration and the type of day the user wants visualised, as shown in Figure 4.11. The configurations the user can select are different tilt and azimuth angles, and different tracking systems. These tracking systems include tilt tracking and azimuth tracking for different

³⁰ Database is available at the National Renewable Energy Laboratory website (<https://sam.nrel.gov/>).

periods of time. With the configuration known, it is possible to calculate the angle of incidence, surface irradiance, module and cell temperature, module performance and lastly inverter performance. The results are then presented to the user in twelve graphs showing the average power output of each month of the year. When the user changes a configuration NZSPOT calculates and presents the power output in real time, allowing immediate comparisons. The user can also change the type of day to show the worst or best day of each month. This change allows the user a better insight into the expected power on a certain day, allowing for better management and planning.

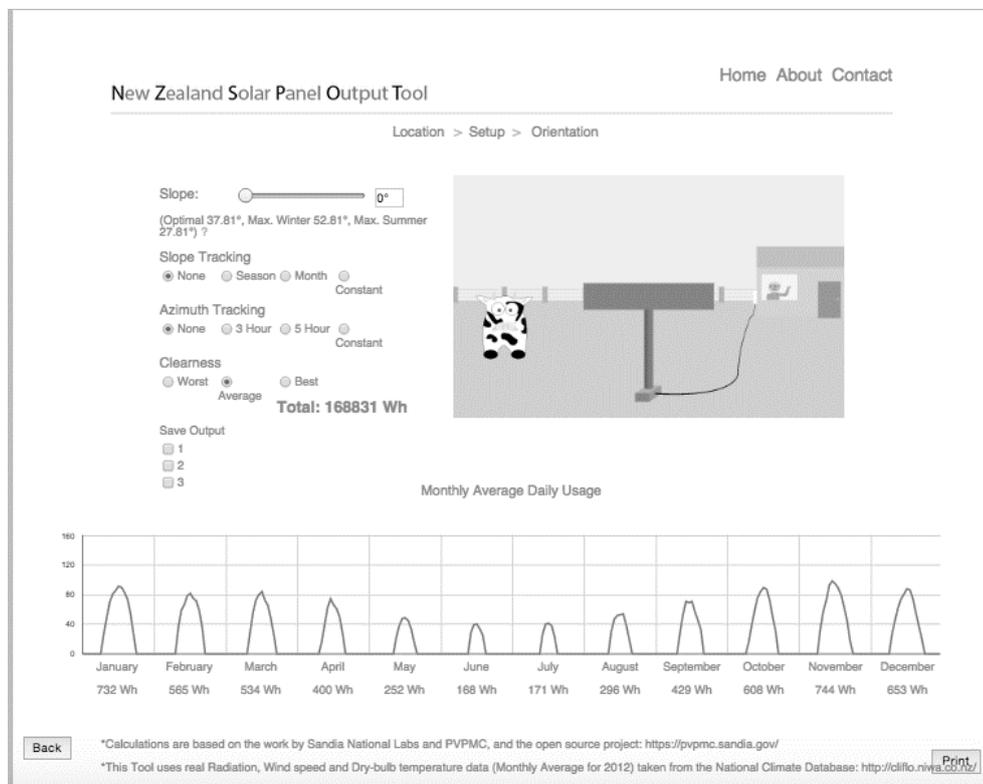


Figure 4.11: The last page of the NZSPOT allows users to see the effects of changing the solar panel’s orientation.

4.5 Findings

The simulation tool was run with different configurations for a solar PV system, then analysed to see how these different configurations affected power output. The solar PV system used in these simulations, as shown in Table 4.2, consists of a 1.5 kW solar panel setup, and an inverter, rated at a maximum of 1.5 kW. The location of the solar PV system, unless specifically stated, is based in Auckland, New Zealand.

Table 4.2: Solar PV system setup used for the results obtained in this chapter.

Module	Mitsubishi PV-UE 125 Watt
In Series	6
In Parallel	2
Inverter	240V HiSEL K Power 1500 Watt
Inverter Efficiency	~95%
System Losses	14%
Location	Auckland (-36.86, 174.76)

The analysis of output from NZSPOT, as shown in Appendix A, offered four core findings which are outlined as follows.

4.5.1 Tilt on Static Solar panels

The optimal tilt angle for a static solar panel, to gain maximum annual output, is typically equal to the latitude where the solar panels are installed. This angle will ensure the smallest annual mean in the angle of incidence. However, not all solar panels are installed with this tilt angle, due to customers' needs and physical restraints. This section will discuss, firstly the tilt angles used in NZSPOT for a static solar PV system, secondly and thirdly, the annual and seasonal output results,

and lastly, the output from NZSPOT compared to the output of other solar calculators.

To gain a better understanding of the effects of changing the solar panel’s tilt angle, NZSPOT was used to simulate a static solar PV system with three different tilt angles. The first angle was equal to the latitude of the installed location, while the other two angles were taken from the Authority on Sustainable Building [86]. The angles retrieved were: -10 degrees from the latitude angle (to give the ideal angle for summer power output), and +15 degrees from the latitude angle (to give the ideal angle for winter power output).

The results from NZSPOT, as displayed in Table 4.3, confirm that having a tilt equal to the latitude angle at the installed location gives the best annual output of 2,118 kWh, followed by the winter angle at 2,100 kW, and lastly, the summer angle with 2,078 kWh. These annual energy values are very similar, with the biggest difference between the latitude (2,118 kWh) and summer (2,078 kWh) tilt angles at only 2%. This small difference shows that the angle of a solar panel has minimal influence on annual energy output.

Table 4.3: Energy output in kWh from a static solar PV system (1.5kW) at different tilt angles in Auckland, New Zealand.

	Latitude Angle	Winter Angle (+15°)	Energy Difference	Summer Angle (-10°)	Energy Difference
Summer	6.67	6.10	-8.56%	6.88	3.15%
Autumn	5.32	5.54	4.14%	5.05	-5.08%
Winter	4.69	5.07	8.10%	4.32	-7.89%
Spring	6.55	6.33	-3.36%	6.54	-0.15%
Annual output	2,117.56	2,100.33	-0.81%	2,078.20	-1.86%

However, on a seasonal scale, the tilt angle has a greater influence on energy output. This is most evident in the winter and summer months, as shown in Figure 4.12 and Table 4.3. A solar PV system at a latitude tilt, on a typical day in the winter season will produce 4.69 kWh, while a solar PV system with a winter tilt will produce 5.07 kWh, and with a summer tilt will produce 4.32 kWh. These results show that the difference in energy output is much greater during the winter season, with the largest difference at 17% between the summer and winter tilts. Similarly, with the summer season favouring the summer tilt with a typical daily output of 6.88 kWh which is 13% more than the winter tilt.

The results produced from NZSPOT provide information on the benefits of installing a static solar PV system at different tilt angles to solar panel owners and installers. This information is useful if the customer wants a desired generation profile. For example, if the customer wants more energy during winter months to power electric heaters, or similarly, wants more energy during summer months to power a pool pump.

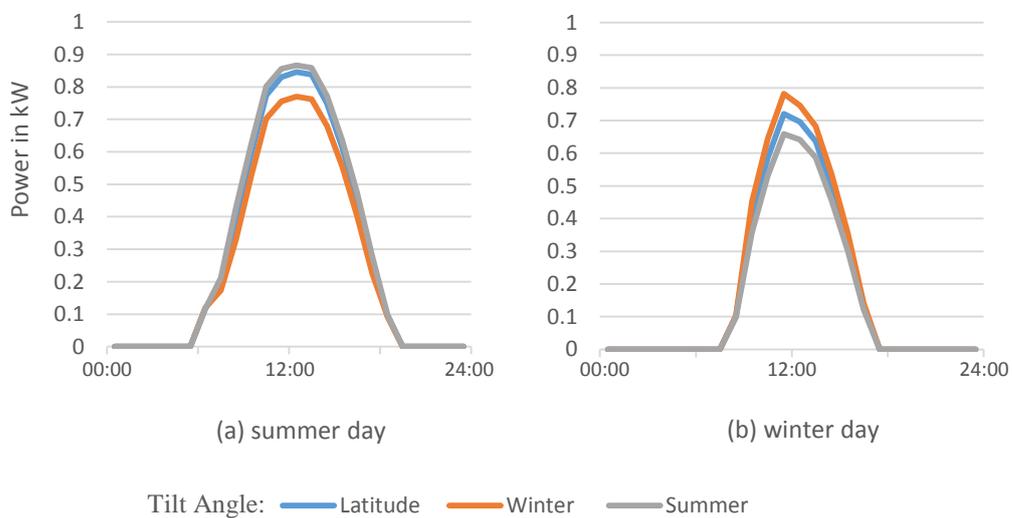


Figure 4.12: Power output for static solar panels at three different tilt angles for a typical (a) summer and (b) winter day.

The energy output, from the static solar panel with a tilt angle equal to the latitude, was compared to the energy output of the solar calculator by EECA and PVWatts using similar configurations, as shown in Table 4.4. The comparison between NZSPOT and EECA monthly outputs show a mean absolute percentage error (MAPE) of 10.31% and a mean percentage error (MPE) of 8.57%. Similarly, with PVWatts monthly output, showing a MAPE of 8.94% and a MPE of 6.21%. The MAPE percentage, shows there is a variance in estimated monthly energy output, however, this variance minimises when combining the month's values, represented with the lower MPE percentage, and an annual output differing by 5.3% and 4.4%, from EECA and PVWatts, respectfully. This variance in output is expected, due to discrepancies in assumptions and weather data, which is also evident when comparing EECA results with PVWatts showing a monthly MAPE of 6%.

Table 4.4: NZSPOT calculated energy output for a 1.5KW solar PV system for a typical day in each month, compared with data from other solar calculators.

Month	NZSPOT	EECA ³¹	PVWATTS ³²
	(kWh)	(kWh)	(kWh)
January	6.7	6	7.2
February	6.7	6.7	6.5
March	5.8	5.9	6.2
April	5.3	4.5	5.3
May	4.9	4.2	4.0
June	4.6	3.7	3.8
July	4.1	4.1	4.0
August	5.4	4.7	4.5
September	6.3	5.4	5.9
October	6.9	6.2	6.0
November	6.5	6.8	6.6
December	6.6	6.9	6.7
Annual output	2,118	2,010	2,028

³¹ The solar calculator by the Energy Efficiency and Conservation Authority (EECA) is accessible at <https://www.energywise.govt.nz/tools/solar-calculator/>.

³² The solar calculator titled PVWATTS is by the National Renewable Energy Laboratory (NREL) and is accessible at <http://pvwatts.nrel.gov/pvwatts.php>.

4.5.2 Location

NZSPOT was used to simulate a solar PV system in 10 different locations in New Zealand, as mentioned in Section 4.2. The results, as shown in Appendix A and Figure 4.13, show that a 1.5kW static solar PV system will produce on average 2012 kWh a year in New Zealand, with the most generation in Nelson (2357 kWh), and the least generation in Christchurch (1656 kWh). These results correlate with the amount of sunshine hours at each location, with Nelson typically receiving more than 2,250 hours a year, and Christchurch only receiving between 2,001–2,250 hours [87]. These results show that even though most cities, out of these ten locations, have the same energy output of approximately 2000 kWh a year, location can still have a significant effect on energy output in New Zealand.

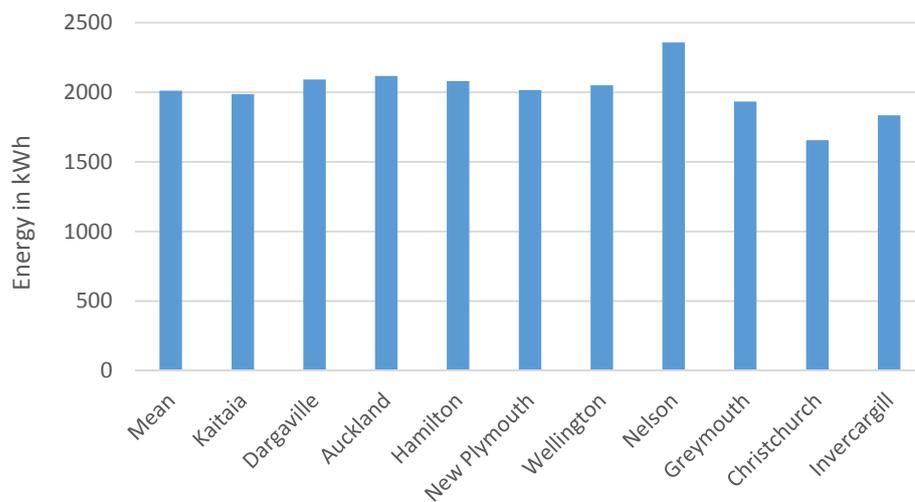


Figure 4.13: Annual energy output of a static solar PV system in different cities with a tilt angle equal to the latitude of the installed location.

4.5.3 Tracking Systems

There are three common types of tracking systems for solar panels. These include tracking the height of the sun (tilt tracking), tracking the direction of the sun (azimuth tracking), or a combination of both (dual tracking). NZSPOT simulated

these different tracking systems to see the effects of including such tracking systems. The results of these simulations by NZSPOT are shown in Table 4.5 and Figure 4.14.

Table 4.5: Seasonal and annual energy output (kWh) for different solar panel tracking systems.

Season	Static	Tilt Tracking		Azimuth Tracking		Dual Tracking	
	Tilt	Seasonal adjustment	Monthly adjustment	2-hourly adjustment	Continuous adjustment		
Typical Day	Summer	6665.617	6983.373	7009.117	8654.033	8813.807	9248.707
	Autumn	5318.303	5484.07	5525.503	5913.813	5969.55	6511.94
	Winter	4693.723	5173.197	5147.67	5068.177	5097.843	5811.95
	Spring	6550.107	6545.857	6655.217	7875.617	8000.18	8414.77
Annual output	2,117,561	2,205,893	2,219,458	2,507,550	2,541,127	2,733,452	

Analysing the results for tilt tracking, shown in Table 4.5, shows that adjusting the tilt every season would result in a 4.2% increase in energy output, similarly, changing the tilt every month would result in a 4.8% increase in energy output.

The second tracking system simulated was azimuth tracking. This tracking system is more focused on following the sun as it rises and sets, and therefore would capture more sunlight hours. The results show that a 2-hour azimuth tracking system (tracking the sun's direction from 11am to 1pm) would give an increase of 18.4%. This is similar to continuous azimuth tracking, which would provide an increase of 20%. This larger increase compared to tilt tracking, is why most single axis tracking follows the sun's direction rather than its height.

The last tracking system simulated was dual tracking. This tracking system follows the sun's height and direction, ensuring that the angle of incidence remains at 0 degrees. The annual output of a dual axis tracking system was approximately

30% more than the static solar PV system and 7.6% greater than the single axis (azimuth) tracking. Dual axis tracking and azimuth tracking (with a tilt angle equal to the location's latitude) provide similar energy output during days with a large sun elevation angle, as shown in the summer graph in Figure 4.14, however, during days with a small elevation angle, particularly in winter months, dual tracking can generate 14% more energy than azimuth tracking.

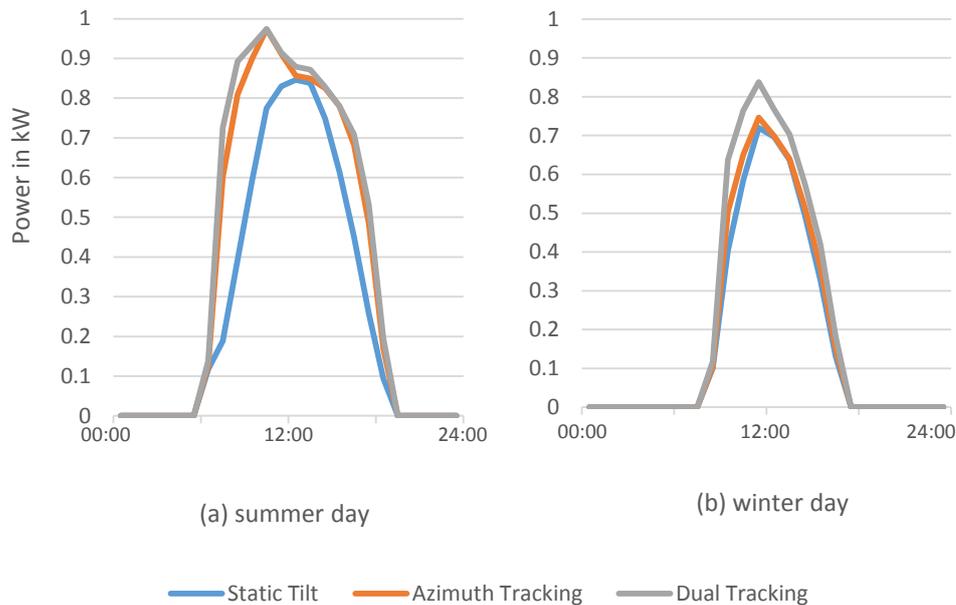


Figure 4.14: Power output for a static, azimuth tracking, and dual tracking solar PV system for an example (a) summer and (b) winter day.

It is apparent from these results that tracking systems can greatly increase energy output, especially azimuth and dual tracking. However, including tracking systems can increase costs and require additional land. The extra land is needed to avoid solar panels from casting shadows on other solar panels, while the cost increase is due to the additional tracking system and the required maintenance costs. A cost comparison of a dual axis tracking and a static solar PV system in New Zealand is described as follows.

4.5.4 Costs

To assess the economic viability of tracking systems in New Zealand, a cost comparison between dual axis tracking and static solar PV systems was performed. These comparisons are based on daily energy output, and do not include maintenance and installation costs. The prices used for the components in these systems were taken from companies within New Zealand. These components, shown in Table 4.6, are solar panels by AA Solar and Sun Power plus, mounting hardware by Solarpv4u, and a dual axis tracker system by Living Systems Solar³³.

Table 4.6: Solar component costs for calculating economic benefits of tracking.

Component	Cost (\$)	Website
Dual axis tracker system for twelve solar panels	3,260.00	http://www.liquidsolar.co.nz/
AAS-200W solar panel	299.00	http://www.aasolar.co.nz/
Mounting for one static solar panel ³⁴	57.38	http://solarpv4u.co.nz

A dual axis tracker system with twelve solar panels, shown in Table 4.6, would cost \$6848.00 in New Zealand. While a static solar PV system with 12 panels would cost \$4276.56. Assuming a dual axis tracker system would give 30% more energy output, as mentioned in Section 4.5.3, adding approximately 30% (4 panels) additional solar panels would give a similar energy output and cost 17% less (\$5702.08).

³³ Prices for the solar panels and mounting hardware were taken in February 2017. Due to a lack of suppliers for dual axis tracker systems in New Zealand, a price retrieved in September 2015 was used. This price appears representable and comparable to prices from companies in other countries.

³⁴ Price for mounting is based on a pitched roof mounting system for 10 panels costing \$573.76.

For dual tracking systems to be competitive on a daily energy output perspective, the system needs to cost less or equal to installing 30% more solar panels. This could happen through two approaches. Firstly, having a cheaper tracking system that costs no more than 30% of the total solar panels. Secondly, having more expensive solar panels integrated on the tracking system. Furthermore, dual axis tracking provides other benefits which are not considered in these comparisons. One such benefit is more power in early and late sunlight hours, as depicted in Figure 4.14, which can also affect the return of investment.

4.6 Summary

This chapter described the development and use of a web-based simulation tool that was created as a part of this research because of a gap in literature on hourly power output of solar panels in a New Zealand setting. The data collected from this simulation tool contributed to answering the second research question: *what are the characteristics and use of these technologies?*

The first three sections of this chapter described the back end of this simulation tool: Firstly, the seven crucial variables in estimating the sun's position: declination angle (δ), equation of time (*EOT*), solar time (*ts*), hour angle (ω), elevation angle (α), zenith angle (θ_z) and azimuth angle (γ). Secondly, the calculations used to estimate the intensity of radiation coming from the sun, and the data collected from weather stations (global horizontal irradiance, wind speed, and dry-bulb temperature). Thirdly, the calculations used to simulate the solar PV system's effectiveness in transforming irradiance to electrical power. These calculations are largely based on the work from the Sandia Laboratories.

The fourth section described the three stages of the interface of this simulation tool, and how the user progresses through these stages. The first stage allows the user to select the location of the solar PV system through an interactive map. The second stage is to specify the characteristics of the solar panels and inverter. The third and final stage is defining the solar panel's configuration and the type of day

the user wants visualised. A novelty of this tool is that the user can see the effects of changing the solar panel's configuration in real-time. A further benefit of this tool, setting it apart from similar tools, is that it provides hourly power output calculated using real data from New Zealand weather stations.

The final section outlines various findings from using this tool to simulate solar panels with different configurations. The first finding was that changing the tilt angle on solar panels has a large impact on the seasonal energy output, however, little impact on annual output. The second finding is that the annual output from a static solar PV system varies greatly at different locations, with an average of approximately 2012kWh, a minimum of 1656kWh (Christchurch), and a maximum of 2357kWh (Nelson). The third finding was that tilt tracking could result in an approximately 5% increase in energy output, while azimuth tracking could provide an increase of 20%. Therefore, most single axis tracking tracks the azimuth angle. The last finding was that dual axis tracking can provide approximately 30% more energy during the year, however, it costs approximately 17% more than adding 30% additional solar panels, which would result in a similar energy output.

The next chapter describes the surveys, conducted as part of this research, to gather household electricity consumption data. It also describes the development and use of a model produced from this data, which generates electricity consumption data for a community of households.

Chapter 5

Household Electricity Consumption

“Without data you’re just another person with an opinion.”

— William Edwards Deming

To gain an accurate understanding of the impacts new technologies can have on a household’s electricity consumption, accurate and representative data on household electricity usage is needed. Due to an absence of detailed electricity usage readings for New Zealand households, studies to gather half-hourly energy usage data were performed. This chapter describes the conducted surveys, the database created from the data collected in one of the surveys, the findings from analysing this data, and a model created to generate household electricity consumption.

5.1 Surveys

Smart meters are devices that record electricity consumption over short periods of time and transmit these readings. In New Zealand, Smart Meters have been widely

adopted by the electricity industry for household installations, and typically record energy usage in 30 minute intervals. In 2016, over 1.3 million residential sites had Smart Meters installed³⁵. In the Waikato region, the distribution company (WEL Networks) owns and maintains the Smart Meters connected to households. In this research, there were two surveys conducted to gain a better understanding of electricity consumption in New Zealand households, as part of these surveys 30-minute energy readings from Smart Meters were acquired. These energy readings were supplied by the distribution company, with the consent of the household dweller in charge of paying for electricity. These energy readings were for the duration of a year, or from when the dweller moved into the household. The material for both surveys is given in Appendix B and C. A description and a short summary of these surveys are discussed as follows.

5.1.1 Preliminary Survey

The *preliminary* survey, titled: *Retrieving and understanding household electricity consumption*, was conducted in 2013 with the intention to investigate which and when appliances were used within households. This knowledge allows a better understanding of the potential demand-side management possibilities within New Zealand homes. The seven participants who took part in this survey, were contacted through email, and consisted of university students and teachers. From this survey, there were five main findings on electricity consumption across the seven households:

1. There was an energy increase of 6 - 40% in winter months, with the lowest increase (6%) coming from a household using a fireplace for space heating, and the largest increase (40%) coming from a household using electricity for space heating.
2. No day in the week showed a significantly different daily energy usage.

³⁵ Counts taken on December 2016 from the “*Metering snapshot*” page which is updated regularly at <http://www.emi.ea.govt.nz/>.

-
3. Peaks in demand that occurred during typical weekdays and weekends³⁶ were identified. Across the seven households, peaks occurred between 7 and 10 am as well as between 4 and 11 pm during weekdays. In the weekend, peaks were less consistent, presumably due to a lack of routine of household members on the weekend, such as waking up at different times, eating out, and going away for the day.
 4. A 30-minute time interval for energy readings was too long to determine which and when appliances were being used.
 5. The data showed a large variability between households' energy usage, therefore, a larger sample size of households would be needed to develop a household energy usage model that is representative for New Zealand households.

5.1.2 In-depth Survey

The *in-depth* survey, titled: *Building a publicly available household electricity consumption database*, was conducted in 2015³⁷, with the intention of gaining more participants, as suggested by the previous survey. The main goals of this survey were to build a free database for fellow researchers and to show how different variables affect household electricity consumption. These variables included: alternative energy sources used within the household, number of occupants, total income and whether the household is in a rural or urban location. There is data for a total of 32 households, but not all for a full year³⁸. There are 16 households for which 12 months data is available, and these have been used to analyse the impact new technologies have on individual households, described in Chapter 7.

The web interface of the database, the findings from the collected data, and the created household model will be described as follows.

³⁶ A peak in this study was considered as a period where energy usage was 20% over the average energy usage.

³⁷ The data for this study was retrieved on November, and consequently the energy readings begin from November 2014 to November 2015.

³⁸ Some household dwellers had been living at the premise for less than a year, therefore, the collected energy readings were from the date the dweller moved into the household.

5.2 Database of Household Consumption

The web interface of the database, as shown in Figure 5.1, is accessible at <http://ei.cms.waikato.ac.nz/> and allows users to compare energy usage of the 32 participating households which participated in the *in-depth* survey. Associated variables for each household are also displayed, these include: if a heat pump is used, number of occupants, household income, if the house is rural or suburban, and which energy sources are used for cooking, water heating, and space heating.



Figure 5.1: Snapshot of the web interface of the database containing collected data from participating households. Currently showing details of 3 households and the average of all households.

This database uses four graphs to provide visual feedback on electricity consumption for selected households. These four graphs, as shown in Figure 5.1, show the average daily energy usage for a weekday and weekend (top left), the energy usage for each month of the year (top right), the mean half hourly energy usage for a typical weekday (bottom left), and similarly, the mean half hourly energy usage for a typical weekend (bottom right). The purpose of this database is to provide fellow researchers with a dataset to help with their research, allow participants to compare their energy usage, and additionally raise energy awareness of the public audience on household energy usage.

5.3 Findings

The data collected from the *in-depth* survey was analysed in two approaches. The first approach was an across house analysis, to study how different seasons and variables affected household energy consumption. This analysis showed that across all houses an average day's usage was 19 kWh, with a summer day typically using 16.6 kWh, and a winter day using approximately 42% more with 23.6 kWh, as shown in Table 5.1.

Table 5.1: Mean daily household energy usage (Wh) for different seasons.

	Spring	Summer	Autumn	Winter	Average
Weekday	16258.41	16310.64	18067.83	22636.73	18318.4
Weekend	17378.41	16867.76	19733.42	24628.63	19652.06
Mean day	16818.41	16589.2	18900.62	23632.68	18985.23

Furthermore, the across house analysis showed that households with a gas energy source typically consumed less electricity, as shown in Figure 5.2.

Households which used mains gas for heating used on average 8 kWh less per day, households which used mains gas for cooking used 7 kWh less on average, and households which used gas for water heating used approximately 6 kWh less. However, since households have many different variables, and some of these might be intertwined (e.g. some houses that used mains gas for heating, used electricity for cooking and water heating), it is difficult to verify which variables affected household consumption. This was further confirmed when the energy usage and geographic variables were run through a data mining program (WEKA), which showed no significant correlation between usage and variables.

The second approach was a within house analysis, to find any patterns and correlations between households' energy usage. This approach produced three findings. Firstly, there were no days during the week that had a significantly different daily energy usage. Secondly, the morning peak for the weekend was typically two hours later than on weekdays; 6:30 am for weekdays and 8:30 am for weekends. Lastly, from the 32 houses, 27 typically used 10% more electricity in the weekend, except for 5 houses which used between 6 and 10% less.

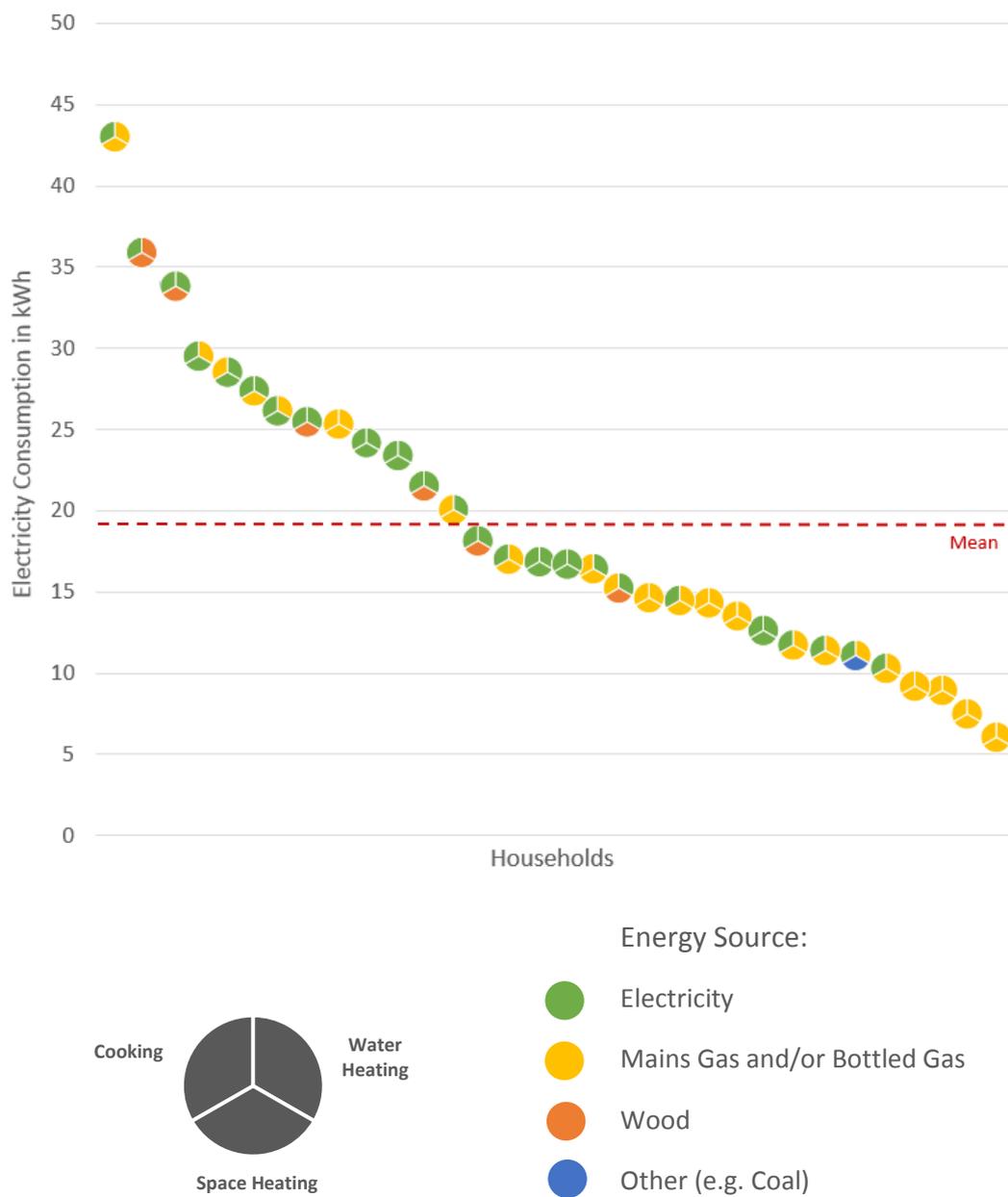


Figure 5.2: Mean daily electricity consumption for each household, with a representation of the energy sources used in the household.

5.4 Household Load Model

There have been many approaches to accurately simulate a household's electricity consumption, as discussed in [88] [89] [90]. The most common approaches involve creating behavioural, regression, or neural network models. This approach typically requires a large sample of either household or individual appliance consumption readings, and extensive knowledge of parameters impacting these readings e.g. number of occupants in a household, appliance behaviour, and weather conditions. These models are typically very accurate when simulating usage on a daily or larger scale, however, due to the complex interplay between consumption and parameters, simulating usage on a sub-daily scale is very complex and typically inaccurate. For example, a regression model presented in [91], which used consumption data from 470 households with extensive appliance and temperature readings, only achieved a R^2 of between 43 and 49% when simulating a demand profile on an hourly scale.

The process of collecting a large sample of household data and conducting in-depth surveys for each household was outside the boundaries of this research, due to time and cost constraints. Therefore, the decision of creating a simple bottom-up model which generates electricity consumption through a sampling process was made. The two main drawbacks of this approach are that (1) the continuity of load between one time interval and the next is not considered, and (2) events may be repeated or not simulated during the day e.g. there may be two or more morning peaks when there is typically only one. These drawbacks may result in a modelled demand profile for an individual household following an unusual and volatile pattern. However, as mentioned in [91][92], if individual demand profiles are aggregated, the inherent variability in electricity consumption is reduced, resulting in an increasingly smoother and representative load shape. Therefore, the drawbacks of this model, do not influence this research as this model is only used to simulate a demand profile of a community of households, discussed in Chapter 8.

This model uses electricity consumption data from thirty households from the *in-depth* survey which had no solar PV systems installed. The consumption data of the selected thirty households was compared with residential consumption from the Electricity Authority (based on the average residential site in Waikato), as shown in Figure 5.3. The comparison shows that on an annual scale there is a minor energy difference of 0.37%, however, on a monthly scale, the difference is larger, with a mean absolute percentage error (MAPE) of 7.44%.

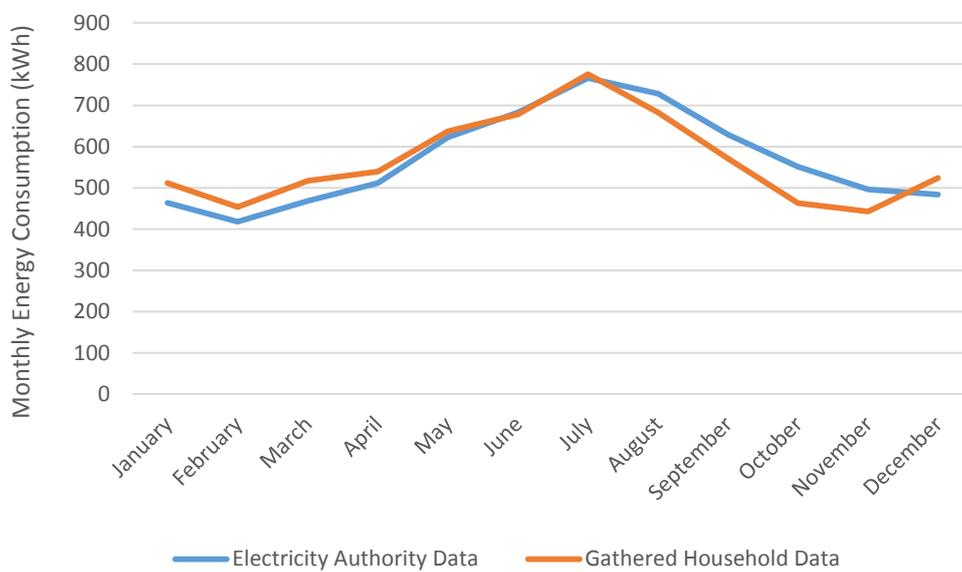


Figure 5.3: Comparison of the average consumption of the thirty households used in the household model with average consumption data from the Electricity Authority³⁹.

Using this sample of households to represent New Zealand households may result in some discrepancies in the impact new technologies have, mainly: If half hour energy values are overestimated there may be an overestimation of possible solar generation being directly consumed by a household. Similarly, if half hour energy values are underestimated there may be an overestimation of the amount of

³⁹ The data from the Electricity Authority is based on the average residential consumption in the Waikato region, retrieved from <https://www.emi.ea.govt.nz/>.

solar generation being exported, and an underestimation of the impact EVs and HESSs have on peak demand (from charging). The remainder of this section will describe the four main components of this model, as shown in Figure 5.4, and an analysis of the modelled consumption.

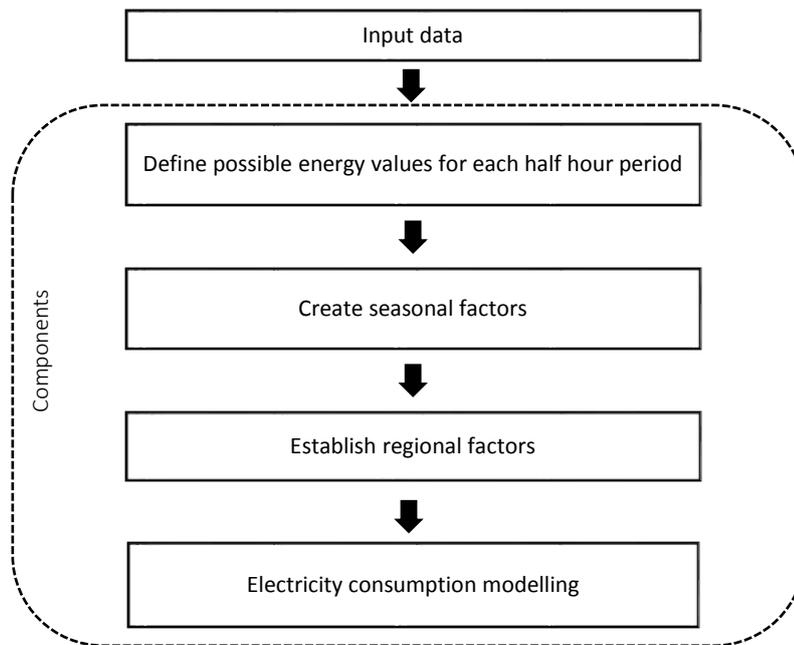


Figure 5.4: Procedure for modelling electricity consumption for a community of households.

5.4.1 Energy Values

In a typical household, the energy usage fluctuates during the day, due to different consumption behaviours throughout the day. This fluctuation is represented in this model by creating a distribution of possible energy values for each half hour period. This distribution of energy values is represented in a two-dimensional matrix (**E**). This matrix contains 48 rows (m), representing each half hour period, and n columns, representing possible energy values for that time-interval. Since weekdays and weekends differed slightly in energy usage, as explained in Chapter 5, two matrices are created, one to represent possible energy values in a weekday, and

conversely, another to represent possible energy values in a weekend. The creation of the matrix (**E**) is done through seven steps, explained as follows.

The first step (1), is the creation of four three-dimensional matrices, one for each season, that hold the measured energy values for each household at each time-interval in that season. These four matrices, as shown in Figure 5.5, are spring (**P**), summer (**S**), autumn (**A**), and winter (**W**). The height in these four matrices represent different times of the day, while the depth represents different households, and the width represents different days of the season. In this instance, there are 48 time-intervals (m), representing half hour periods in a day, and 30 households (h). The width (n) will be taken as the number of weekdays in each season for the weekday seasonal matrices, and similarly, the number of weekend days for the weekend seasonal matrices.

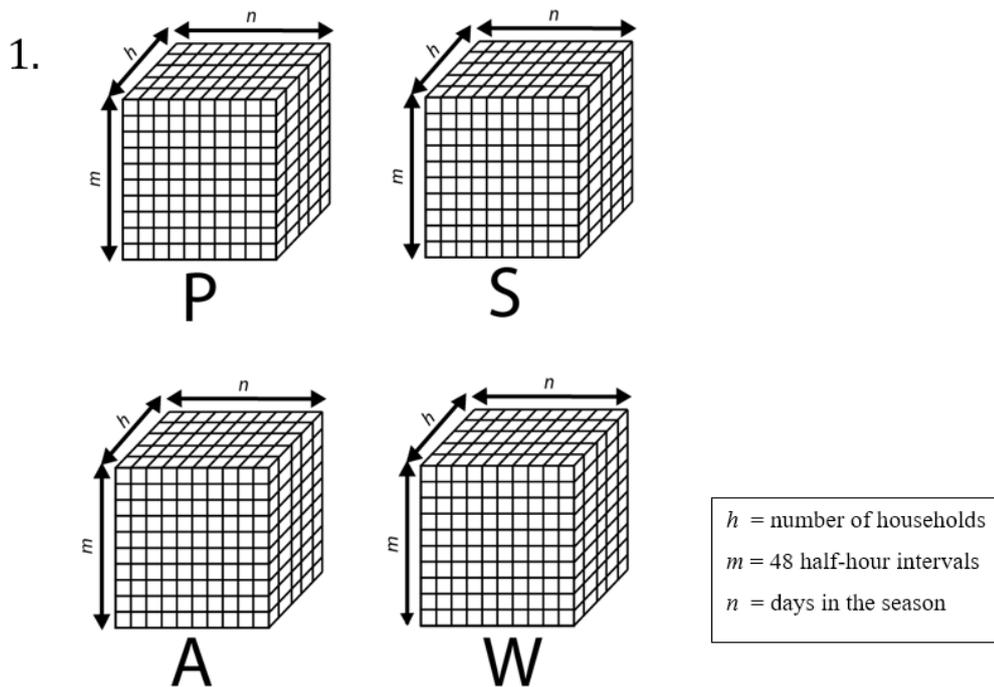


Figure 5.5: A three-dimensional matrix for each season which holds measured energy values for each half hour period (m) from the 30 selected households (h) for all days in that season (n).

The next five steps use the four seasonal matrices to create the two-dimensional matrix (**E**), as mentioned above. These steps are shown in Figure 5.6 and explained as follows.

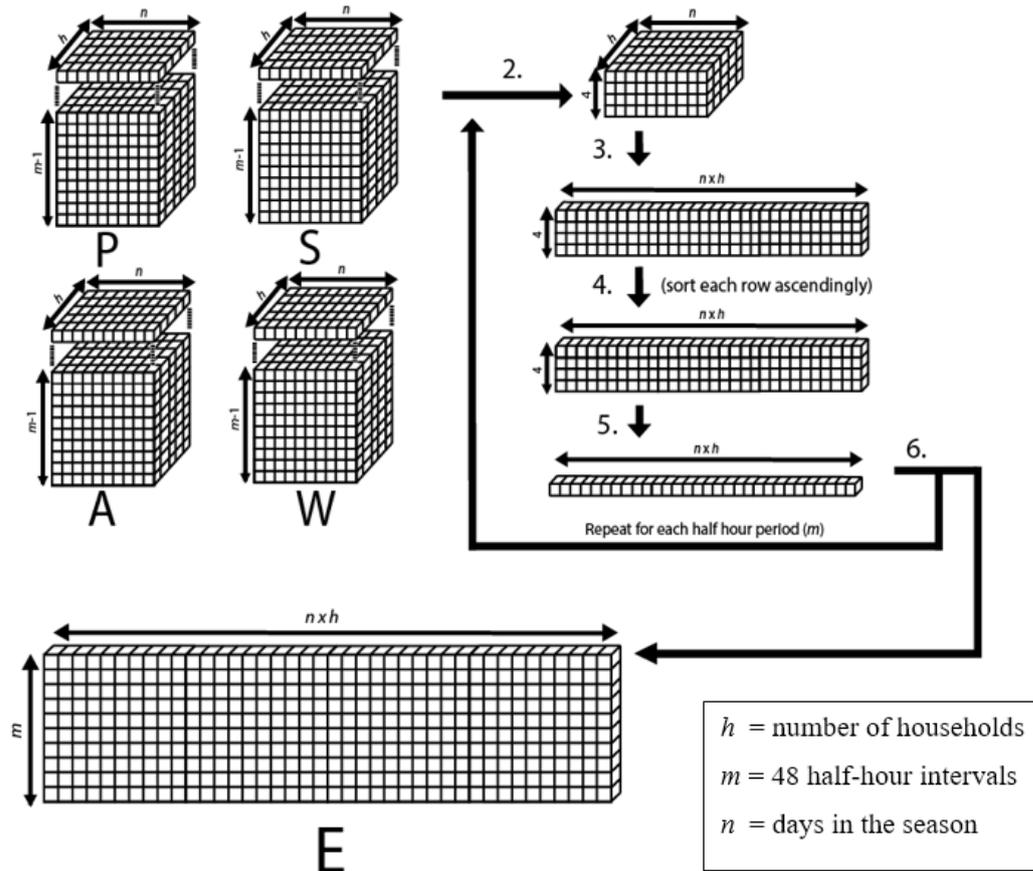


Figure 5.6: The five steps performed to transform the energy values from the seasonal matrices into a sorted two-dimensional matrix.

2. A three-dimensional matrix is created from a layer of each seasonal matrix. This matrix represents all measured energy values for a particular half hour period.
3. The individual household vectors for that half-hour period are concatenated to form a single $h \times n$ length vector for each season.

-
4. Each of these vectors in the two-dimensional matrix is then sorted ascendingly.
 5. A new vector is created which holds the mean of each column of the previous sorted two-dimensional matrix. This vector represents a series, from lowest to highest, of $n \times h$ possible energy values for a half hour period.
 6. Steps 2 to 5 are then repeated for each half hour period, and the created vectors are concatenated to produce matrix **E**.

The result of the previous steps is a two-dimensional matrix (**E**) which contains a distribution of possible energy values for each half hour period. However, due to some seasons differing in size, and accessibility of energy values for some households, not all half hour periods will have the same number of energy values. Therefore, the final step is to reduce the number of columns so that each half hour period has the same number of energy values. The periods that are larger, are reduced through a stochastic process.

The energy values in this matrix (**E**) will serve as the multiplicand energy value for a half hour period, which will be multiplied by a fluctuation factor and a regional factor. These factors are explained in the following sections.

5.4.2 Seasonal Factors

The next component in modelling electricity consumption, is the creation of seasonal factors for each half hour period of a day. These seasonal factors will account for the variations in electricity consumption during different seasons. These factors are created through two steps, explained as follows.

The first step is to create a mean daily load profile for each season. These load profiles are represented in four vectors: spring (**p**), summer (**s**), autumn (**a**), and winter (**w**). These vectors hold 48 values which represent the mean energy usage for each half hour period in that season, as depicted in Figure 5.7.

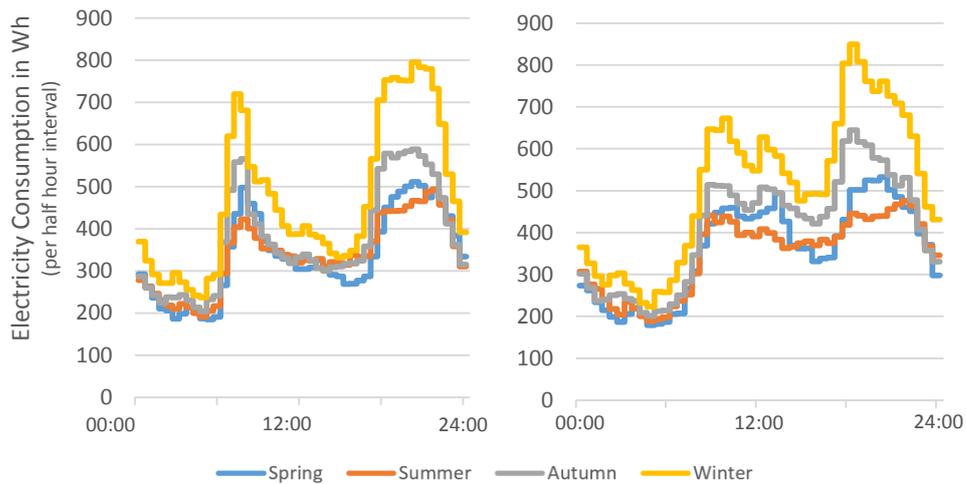


Figure 5.7: Mean daily load profile for a weekday (left) and weekend (right) for different seasons.

The creation of these vectors is done by calculating the mean of each energy value at a half hour period from the corresponding season matrix, as shown in Figure 5.8.

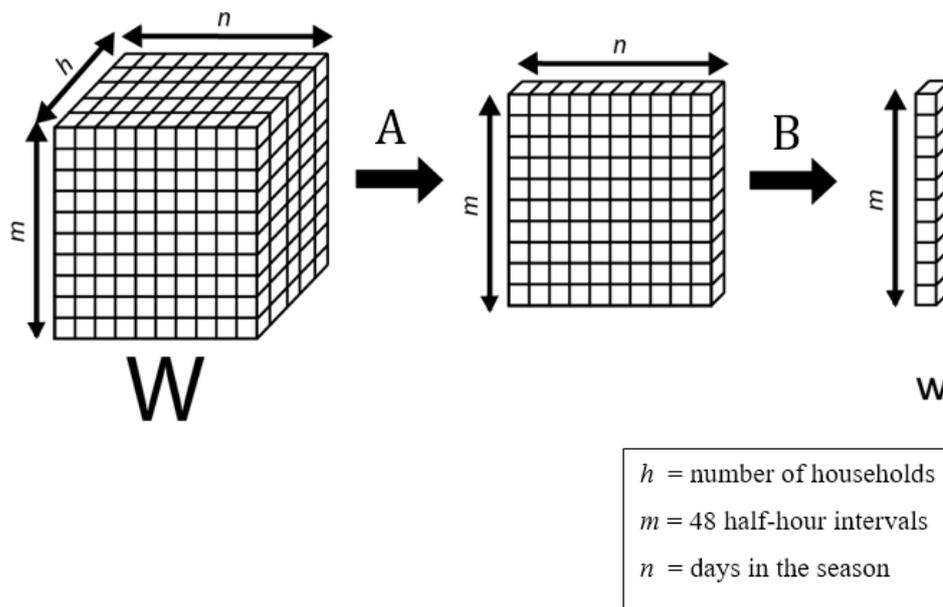


Figure 5.8: The vector representing the average daily usage at half hour intervals for a season (far right) is created by calculating the mean energy usage across all households for each half-hour of each day in the season (A) then the mean across all days in the season for each half-hour (B).

The second step is to create a vector which represents the mean daily load profile of the whole year of all households. This vector is based on the mean of all four seasonal vectors, as shown in Figure 5.9.

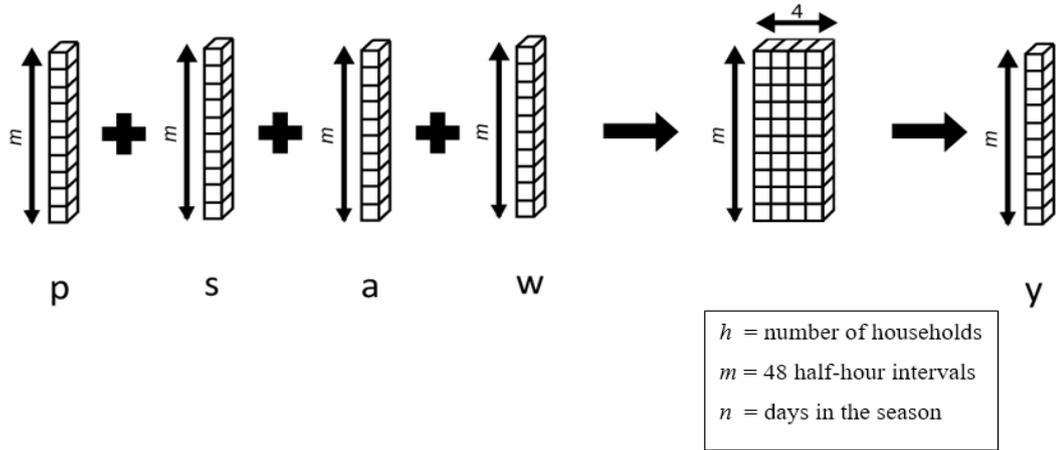


Figure 5.9: The vector representing the mean daily load profile of the whole year of all households (far right) is created by concatenating all of the seasonal vectors then calculating the mean of each half hour period.

The seasonal factor is then calculated from a mean from various seasonal energy values based on the current date, divided by the annual mean value, as shown in Equation 5.1. This process will ensure there is a steady transition in the seasonal factor between different seasons, to prevent an unrealistic rapid change in electricity consumption on the first day of a season.

$$a(x, y) = \begin{cases} \mathbf{p}_x, & y = a \text{ day in spring} \\ \mathbf{s}_x, & y = a \text{ day in summer} \\ \mathbf{a}_x, & y = a \text{ day in autumn} \\ \mathbf{w}_x, & y = a \text{ day in winter} \end{cases} \quad (5.1)$$

$$b(x) = \frac{\sum_{d=1}^{30} a(x, \text{date}_{d-15})}{30}$$

$$\text{season}(x) = \frac{b(x)}{\mathbf{y}_x}$$

Where x represents a half hour period and y represents the day of the year.

5.4.3 Regional Factors

In New Zealand, the location of a region can have a significant impact on energy usage, due to different climates and energy behaviours. This is most evident when observing average annual energy consumption of residential sites in different locations as shown in Table 5.2. For example, a residential site in the West Coast region used 40% less energy in a year than a residential site in the Canterbury region [88]. To account for this regional variance, a multiplier for each region based on the average annual energy consumption of a residential site in that region was created. These energy values were taken from the Electricity Authority and are shown in Table 5.2.

Table 5.2: Residential energy usage in different regions in New Zealand for 2015 [88].

Region	Average annual consumption (kWh)	Multiplier factor ⁴⁰
Waikato	6816	1.00
Northland	6211	0.91
Auckland	7139	1.05
Bay of Plenty	6638	0.97
Gisborne	6312	0.93
Hawke's Bay	7227	1.06
Taranaki	6291	0.92
Manawatu-Wanganui	6429	0.94
Wellington	7093	1.04
Tasman	7278	1.07
Nelson	7016	1.03
Marlborough	7067	1.04
West Coast	6014	0.88
Canterbury	8677	1.27
Otago	8022	1.18
Southland	8561	1.26

⁴⁰ Multiplier factors are based on a region's electricity consumption compared to Waikato's electricity consumption.

The first three components of the household model (Figure 5.4 - half-hourly energy consumption values, seasonal factors, and regional factors) provide the foundation to simulate household energy consumption. The final component, described below, combines these together to calculate energy usage for a community of households.

5.4.4 Electricity Consumption Modelling

The final component of the model is to use the distribution of energy values, fluctuation factor, and the regional multiplier, to generate the energy usage from a community of households. This process is achieved by firstly calculating an energy value for a single half hour period from an individual household. This calculation is done by selecting an energy value from the matrix E through a stochastic process, then multiplying this value by a seasonal factor and a regional factor, as shown in Equation 5.2.

$$household(x,r) = \mathbf{E}_{xr} \times season(x) \times regional\ factor \quad (5.2)$$

Where r is a random number between 1 and $n \times h$ and x is a half hour period.

This calculation is repeated for each household in the simulated network and summed, to represent a load for a community of households for that half hour period, as shown in Equation 5.3.

$$network(x) = \sum_{i=1}^c household(x,r) \quad (5.3)$$

Where r is a random number between 1 and $n \times h$, x is a half hour period, and c is the number of households in the community.

This process is repeated, using the relating weekday and weekend values, for the desired amount of time. For example, to generate a load profile for a day, this process will be repeated 48 times, as shown in Equation 5.4.

$$daily\ load\ profile = (network(1) \ \cdots \ network(48))$$

5.4.5 Output and Verification

This model was used to simulate the energy usage from a variety of different sized household networks, ranging from an individual household to a network of 10,000 households. As shown in Figure 5.10, household energy usage becomes less erratic, on a half hourly scale, when more houses are simulated. Erratic behaviour (i.e. extreme energy fluctuations) occurs in this model in smaller networks of households, as this model does not consider the rate of change in each half hour, as shown in the individual house in Figure 5.10a. There are various modelling techniques that provide a more representative change between electricity consumption, as discussed in [89]. However, this behaviour is acceptable for this research, as the model is intended for larger networks of households, which reduces this behaviour, as shown in the 100 houses graph in Figure 5.10c.

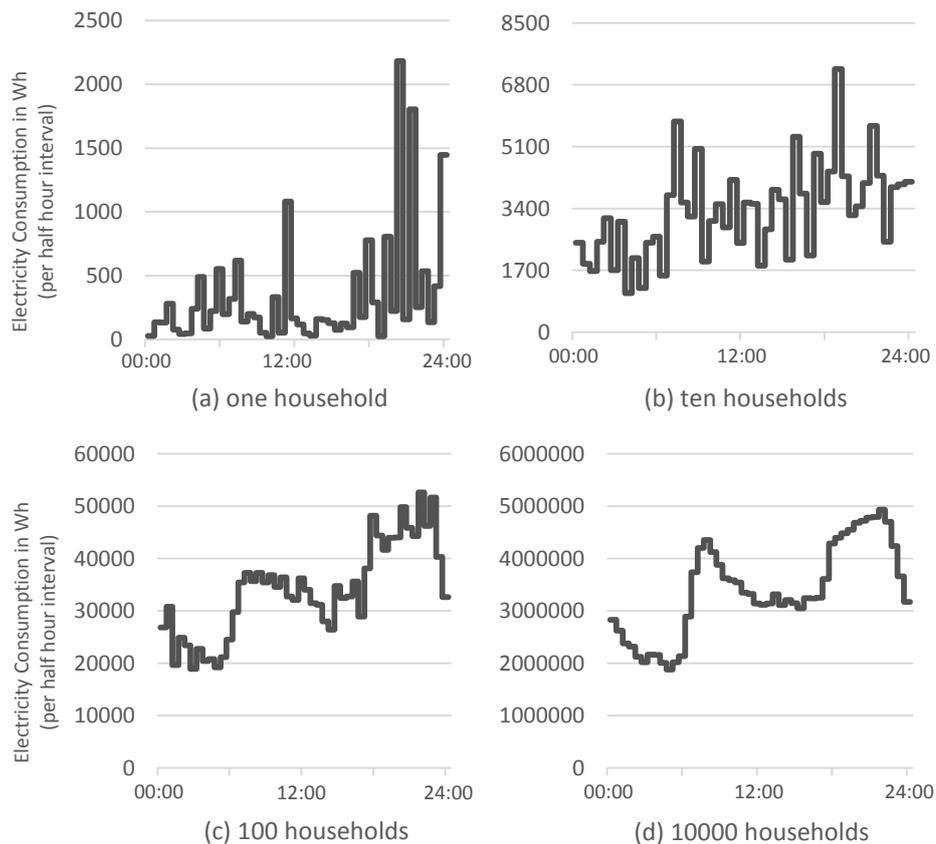


Figure 5.10: Energy usage for a variety of different sized community of households.

A simulation for each region in New Zealand was performed and compared to annual consumption data from the Electricity Authority [88]. The number of households in each region was based on residential consumption data from the Electricity Authority, as shown in Table 5.3. The model's output achieved a mean absolute percentage error (MAPE) of 0.27 with the highest absolute percentage error of 0.61 and lowest of 0.0.

Table 5.3: Electricity Authority consumption data for 2015 [88] compared to simulated consumption.

Region	Estimated residential connections ⁴¹	Simulated consumption (GWh)	Electricity Authority consumption data (GWh)	Energy difference (%)
Waikato	183298	1251.8	1249.4	0.19
Northland	72261	449.1	448.8	0.07
Auckland	513278	3680.5	3664.3	0.44
Bay of Plenty	118274	783.4	785.1	-0.22
Gisborne	15508	98.5	97.9	0.61
Hawke's Bay	65609	474.9	474.2	0.15
Taranaki	48211	302.9	303.3	-0.13
Manawatu-Wanganui	98465	632.1	633	-0.14
Wellington	195077	1385.5	1383.7	0.13
Tasman	19594	143.2	142.6	0.42
Nelson	20674	145.4	145.1	0.21
Marlborough	21235	150.8	150.1	0.47
West Coast	14906	89.6	89.6	0
Canterbury	235986	2046.6	2047.6	-0.05
Otago	94503	761.5	758.1	0.45
Southland	40901	351.9	350.2	0.49

⁴¹ Number of residential connections is based on average annual consumption divided by the regions estimated total consumption.

5.5 Summary

This chapter described two surveys (*preliminary* and *in-depth*), conducted as part of this research, as well as their outcomes including a database and a model to generate household electricity consumption.

The *preliminary* survey was conducted to investigate which and when appliances were used within households. Two main findings were evident: 30-minute energy readings are too broad to determine which and when appliances were being used; and a larger sample of households would be needed to be representative for New Zealand households.

The *in-depth* survey was conducted, to collect electricity consumption data from a larger set of households, as suggested in the *preliminary* survey. A publicly available web interface was created as part of this research with data collected from this survey. This web interface allows the participants from the survey and fellow researchers to compare different household energy usage. Furthermore, an analysis of the data collected from this survey produced five main findings: Firstly, there is no significant correlation between electricity usage and collected household variables. Secondly, there are no days during the week that have a significantly different daily energy usage. Thirdly, the morning peak in the weekend is typically two hours later than on weekdays. Fourthly, most households used 10% more electricity in the weekend. Lastly, an average day's usage was 19 kWh, with a summer day typically using 16.6 kWh, and a winter day using approximately 42% more with 23.6 kWh. A further outcome of the *in-depth* survey was a modelling approach to generate household electricity consumption data. This modelling approach was used to simulate electricity consumption for a community of households.

The next chapter describes the household simulation tool, created as a part of the research, which uses the collected data from *in-depth* survey, and the solar PV data from the solar panel simulation, described in Chapter 4.

Chapter 6

Household Simulation

“A nation that can’t control its energy sources can’t control its future.”

— Barack Obama

Integrating an energy management system (EMS) into a household has the potential to drastically affect the household’s load profile, by learning and accommodating the household’s energy needs in an automatic and autonomous manner [90], which subsequently can have implications on the national electricity infrastructure. As part of this research, a household electricity usage simulation tool (HEUS) was created to simulate the possible impact new energy technology, controlled by a EMS, has on a household’s load profile (accessible at <http://ei.cms.waikato.ac.nz/>). This tool can be utilised to analyse how a household could follow a *Grid-lite* model; a household which in addition to load, storage and renewable generation, has a restricted capacity grid connection [91]. The technologies this tool addresses are electric vehicles (EVs), home energy storage systems (HESSs), and distribution generation systems. This chapter includes six sections related to HEUS: (1) the interface, (2) the charging and discharging strategies of the HESS, (3) a smart battery usage setting, (4) the charging and discharging strategies for EVs, (5) the calculations used to estimate the required energy for EVs before they are

unplugged, and lastly, (6) the calculation steps taken to simulate a household's electricity consumption.

6.1 User Interface

The interface of HEUS consists of seven tabs which the user progresses through. These tabs create an intuitive step by step process which keeps the tool simplistic and makes it easy for the user to define characteristics of a household. The intuitive use and simplicity of these tabs were also valued by the four participants of follow up interviews (as mentioned in Appendix D), who were part of the *in-depth* survey. Participants also valued the insight this tool provided regarding their energy use and implications of the integration of new technologies on their electricity usage as well as potential savings they could gain from different sized technologies. The seven tabs of HEUS are further detailed as follows.

6.1.1 Storage and Generation

The first tab of the HEUS, as shown in Figure 6.1, allows the user to input the energy storage and the distributed generation capabilities of a household.

The energy storage system used in this simulation is defined by five parameters, these include: initial charge, maximum battery capacity, efficiency of converting electricity, maximum charge and discharge rates. For simplicity, the simulation considers that all electricity conversion and storage losses occur during charging of the energy storage system (charge loss).

In this simulation tool, electricity supply from the distributed generation system, for each half hour period (in watt-hours), is defined in the third tab (Section 6.1.3). It is assumed the distributed generation system is grid-tied, and supplying the household with AC power, with all losses pre-considered e.g. inverter losses. In this tab, the amount of electricity supplied by the distributed generation system can be scaled, to easily show the user how different sized systems affect the household's load profile.

click here'. The 'Generation' section has one input field: 'Generation Scaler**' with value 1. Below this field is a footnote: '** Amount to multiply your generation energy e.g. default file has a 1 kWh system so changing the scaler to 2 would make it a 2 kWh system'. On the left side of the form is an illustration of a house with a solar panel on the roof. At the bottom right of the form is an orange 'Next' button."/>

Figure 6.1: First tab of the user interface allows the user to select the household’s energy storage and generation capabilities.

6.1.2 Energy Price

The second tab, shown in Figure 6.2, allows the user to define the price of electricity per kilowatt-hour. This can be on the time of use (i.e. off-peak, peak and shoulder times), or alternatively, they can define the price of energy for each unit of time (defined in Section 6.1.3). Another aspect related to energy cost is the daily charges and any extra charges per kilowatt-hour, which can be added in this tab as well. This is useful if data is taken from real stock market prices and requires additional fees, such as the retail and distribution network costs.

Figure 6.2: Second tab allows the user to define the price of energy and any daily charges.

6.1.3 Household Consumption Data

The third tab, shown in Figure 6.3, allows the user to import a file containing energy usage (Wh), energy price (\$/kWh) and distributed electricity supply (Wh) in half hour intervals, for a desired amount of time.

If a file is not provided, an example file is used. This example file bases the household consumption on the mean of 30 households in Hamilton. The data for these households, provided by WEL Networks, is available at <http://ei.cms.waikato.ac.nz/data>. The price of energy is based on the wholesale spot market prices for the grid exit point HAM0331; this data is freely available at New Zealand’s Electricity Authority website: <http://www.emi.ea.govt.nz/Datasets>. The generation data is from the New Zealand solar panel output tool NZSPOT, accessible at <http://nzspot.cms.waikato.ac.nz>, and is based on a 1kW system (8 x Mitsubishi PV-MF125UE4N 125W) and a 1.1kW inverter with 92% efficiency (SMA America: SB1100U 240V) in Hamilton.

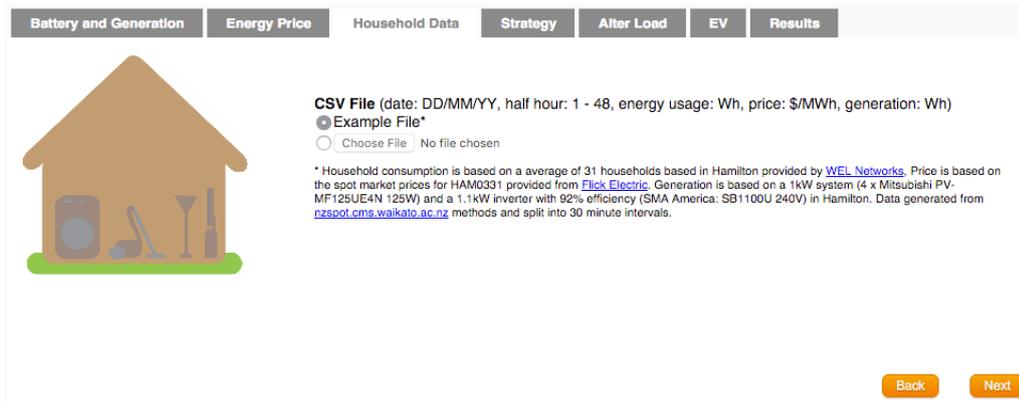


Figure 6.3: Third tab allows user to import a csv file containing a household's energy use, price and generation data.

6.1.4 Charging Strategy

The fourth tab, shown in Figure 6.4, allows the user to define what sort of charging strategy the HESS should use (strategies are explained in more detail in Section 6.2). Depending on the strategy, the user can also: adjust the price at which the HESS should charge and discharge on (*charge price* and *discharge price*), define a value the HESS will try smooth the household's energy usage to (*limit*), and define a value the household energy usage should not exceed (*maxlimit*). The *limit* can be set to one of six different values, these include: (1) The moving average of all previous values, (2) the average of the previous week, (3) the average of the previous month, (4) a user defined value, (5) 20% below the previous week's average, (6) 80% below the previous week's average, and lastly (7) double the previous week's average. Another setting the user can choose is to enable *smart battery usage* for certain months, which allows the *limit* to be automatically adjusted, and the HESS to charge to full capacity within a certain timeframe.

Figure 6.4: Strategy tab allows the user to define the home energy storage system’s energy behaviour.

6.1.5 Load Management

The fifth tab, shown in Figure 6.5, allows the user to simulate load management, this includes shifting and adding load. This feature allows the tool to simulate the effects of load management on energy usage e.g. what are the cost savings when postponing loads to off peak hours.

Figure 6.5: Alter load tab allows the user to perform load management.

6.1.6 Electric Vehicles

On the sixth tab, shown in Figure 6.6, the number of EVs associated with the household, and their energy capacity, as well as charge and discharge rates are specified. Further, the user can choose what sort of charging strategy the EV should use (strategies are explained in more detail in Section 6.3). The time the EV is plugged in and out from the household can be defined by the user to be at any given half hour period in a day, similarly, the amount of energy required before the EV is unplugged can be specified here. In addition, the user can allow the tool to estimate these values, based on real data taken from the New Zealand Household Travel Survey [92] (explained in more detail in Section 6.4).

Battery and Generation | Energy Price | Household Data | Strategy | Alter Load | EV | Results

Electric Vehicle Charging Strategy:

Use the EV like a Home battery and try have enough energy for the next trip by plug out.

Max Capacity:
Charge/Discharge:

Days

- Monday
- Tuesday
- Wednesday
- Thursday
- Friday
- Saturday
- Sunday

Electric Vehicles

Time to plug out: (1-48) Time to plug in: (1-48) Needed Energy: (Wh)
OR Generate Times and Needed Energy

EV: 1 Plug Out: 18 Plug In: 40 Needed Energy: 8000
EV: 2 Plug Out: 18 Plug In: 40 Needed Energy: 8000

Figure 6.6: The sixth tab allows the user to define electric vehicles and how they interact with the household.

6.1.7 Results

The last tab, shown in Figure 6.7, displays the results of simulating an electricity management system within a household, using the defined characteristics from previous tabs. These results are divided into text and graphical feedback. The text feedback is split into two sections. The first section shows a comparison of energy usage with and without the HESS, distributed generation system, and EV(s). The second section of the text feedback shows: how often energy usage has exceeded

maxlimit, the amount of generation energy that was wasted (either sent back to the grid or spilled), the daily charges, the cost savings when including the defined technologies, and finally, when the EV(s) were unable to reach the desired energy requirement (shown in the bottom right textbox in Figure 6.7).

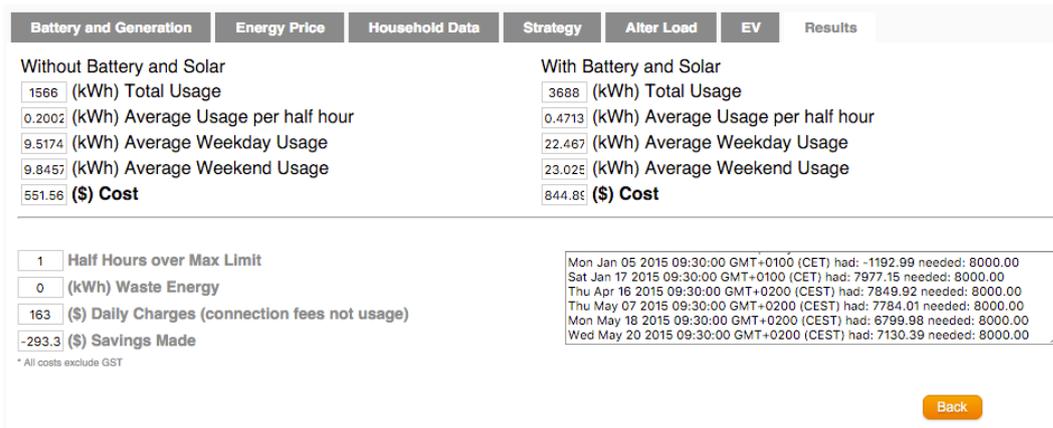


Figure 6.7: Last tab of HEUS displays the results of the simulation tool.

The graphical feedback section of the results tab provides charts to the user which give feedback on different energy aspects of their predefined EMS at different times during the year. These charts provide information on: household load, grid load, current energy capacity of the HESS and any connected EVs, the price of energy, and lastly, the amount of energy generated from the distributed generation system. Charts to visually represent data were chosen as they allow the user to easily see and compare the results of the simulation, as shown in Figure 6.8.

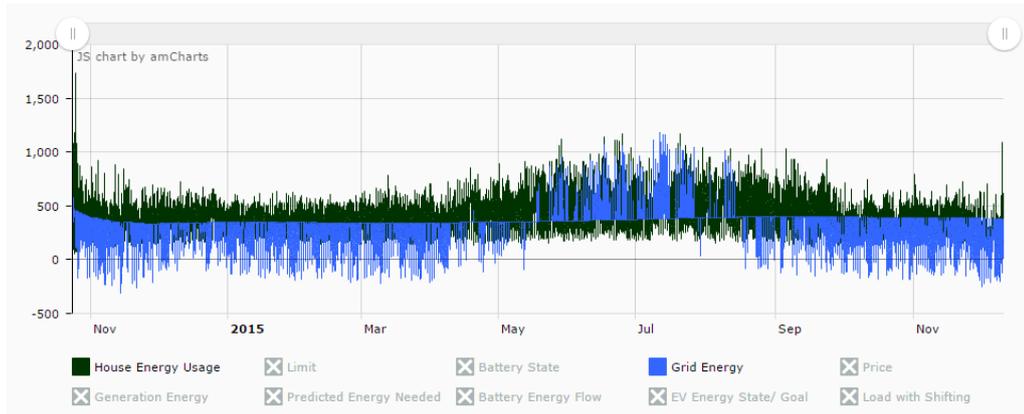


Figure 6.8: Two charts comparing grid load (Wh) over a period of one year, showing the original load (black) and the new load (blue) when considering the defined technologies.

The seven tabs of HEUS, described above, provide a simplistic interface for the user to simulate and understand how certain characteristics affect electricity consumption. The remaining sections of this chapter are related to the back-end aspect of this tool, specifically, charging and discharging strategies of the HESS and EVs, calculations used to estimate the required energy for EVs, and lastly, calculations used to simulate electricity consumption.

6.2 Energy Storage Strategies

In HEUS, there are three different strategies available to decide when to charge and discharge the HESS; called *co-op*, *saver* and *hybrid*. These strategies are described in further detail as follows.

The *co-op* strategy focuses on using the HESS to smooth grid load, as shown in Figure 6.9a. This smoothing is achieved by charging the battery when household load is below *limit* (a value defined by the user or automatically calculated, described in Section 6.1.4) and discharging when household load is above *limit*. Furthermore, in this strategy, solar energy is prioritised to reduce household load to *limit* (if load is above *limit*), then charge the HESS to full capacity, and only then reduce further household load. By maintaining a constant and predictable load, this strategy improves energy efficiency, allowing for greater adoption of baseload generation (which is typically cheaper and emits less fossil fuels).

The *saver* strategy focuses on using the HESS for a financial gain, as shown in Figure 6.9c. This is achieved by charging the HESS when energy prices are low and discharging the HESS when energy prices are high. When an energy price is considered high or low is defined by the user in HEUS, as mentioned in Section 6.1.4. In this strategy energy generated from the solar PV system will be used in a more typical manner; reducing household load before charging the HESS. As a result, the household will typically achieve the greatest energy savings from solar energy.

The *hybrid* strategy is a combination of both the *co-op* and *saver* strategy, as shown in Figure 6.9b. In this strategy, the HESS discharges energy to reduce load that is above *limit*, and charges only when energy prices are low. Energy from the solar PV system is prioritised in the same manner as in the *co-op* strategy; reduce load to *limit* and store the rest.

Along with these three strategies, a *smart battery usage* setting can be applied to change the HESS's energy behaviour, described as follows.

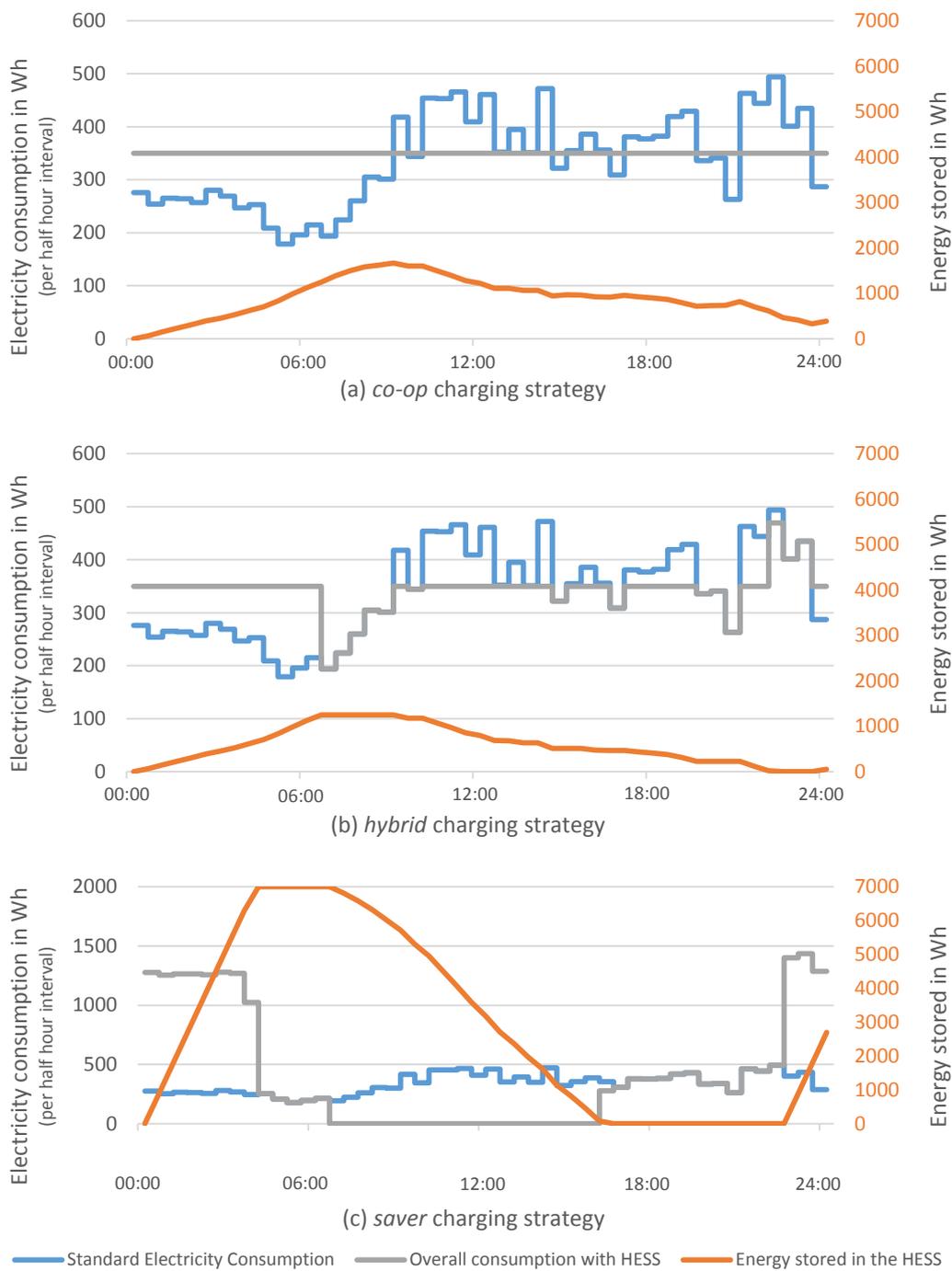


Figure 6.9: Example day showing the impact of different home energy storage system charging strategies on electricity consumption.⁴²

⁴² These examples are assuming: the *limit* is 350Wh (half hour), the electricity price is high between 7am and 11pm and low between 11pm and 7am, and the HESS has a maximum storage capacity of 7kWh, a maximum charge and discharge rate of 2kW, and a battery efficiency of 90%.

6.2.1 Smart Battery Usage

The *smart battery usage* setting allows the user to further manipulate the HESS's energy behaviour through two methods.

The first method adjusts the *limit* automatically to ensure the grid load remains smooth, this is possible in both the *co-op* and *hybrid* strategy. In the *co-op* strategy, the tool predicts the energy usage within *lookahead* hours, and calculates if it is possible to smooth load with the current *limit*. If it is not possible, the *limit* is increased evenly within *lookahead* hours, to ensure load can be smoothed. In the *hybrid* strategy, the HESS only charges when energy is below *charge price*, allowing for fewer charge times. Therefore, to distribute the charge load across more charge times, the *charge price* along with the *limit* are increased. Both values are increased within *lookahead* hours by a value which ensures load remains relatively smooth and the HESS charges at a relatively low energy price.

The second method charges the HESS to full capacity within three different timeframes. Firstly, within *lookahead* hours, which ensures there will always be stored energy, even when household load is high. Secondly, before the next peak, which ensures there is available energy in the HESS to reduce the next peak load. Thirdly, at a user specified timeframe, utilising low energy prices. However, if the solar PV system is relatively large, this third approach can lead to more exported solar energy; since the HESS becomes too full to store solar energy.

Another operation the EMS needs to consider is how to charge connected EVs, this operation is described as follows.

6.3 Electric Vehicle Storage Strategies

When plugging an EV into the household's electricity circuit, there is the possibility to configure how the EV interacts with this circuit. In this simulation, there are three different interaction strategies based on the strategies discussed in a paper by Monigatti *et al.* [93]. This paper describes a simulation model that explores the possibility of extending reliance on non-dispatchable energy sources (with a focus on wind generation) by utilising EVs as grid storage. The three strategies used from this paper are *slow*, *greedy* and *co-op*.

In the *slow* strategy, as shown in Figure 6.10a, it is assumed the plug-out time of the EV is known, and the EV will charge at a constant rate until it is unplugged. This rate is calculated by distributing the required energy (for its next trips) evenly until the EV is unplugged.

In the *greedy* strategy, as shown in Figure 6.11a, the EV charges at its full charge rate as soon as it is plugged into the household, until it has the required energy for its next trips.

In the *co-op* strategy, as shown in Figure 6.10b, the EV will behave similarly to an HESS, by charging and discharging to smooth future peaks, while ensuring it has enough energy stored before it is unplugged for its next trips (the plug-out time is also known in this strategy). Furthermore, it is assumed that the EV is connected to a system which communicates to the grid and can provide demand response services such as throttling the charging of the vehicle and/or discharging energy from the vehicle to the grid, this is often referred to as vehicle-to-grid or V2G.

Another strategy used in this research is named *saver*, as shown in Figure 6.11b. This strategy is similar to the *greedy* strategy; however, it only charges at a low electricity price.

The times the EV plugs into and out of the household, and the amount of energy needed for its trips can be user defined, as mentioned in Section 6.1.6, or calculated automatically, which is described as follows (Section 6.4).

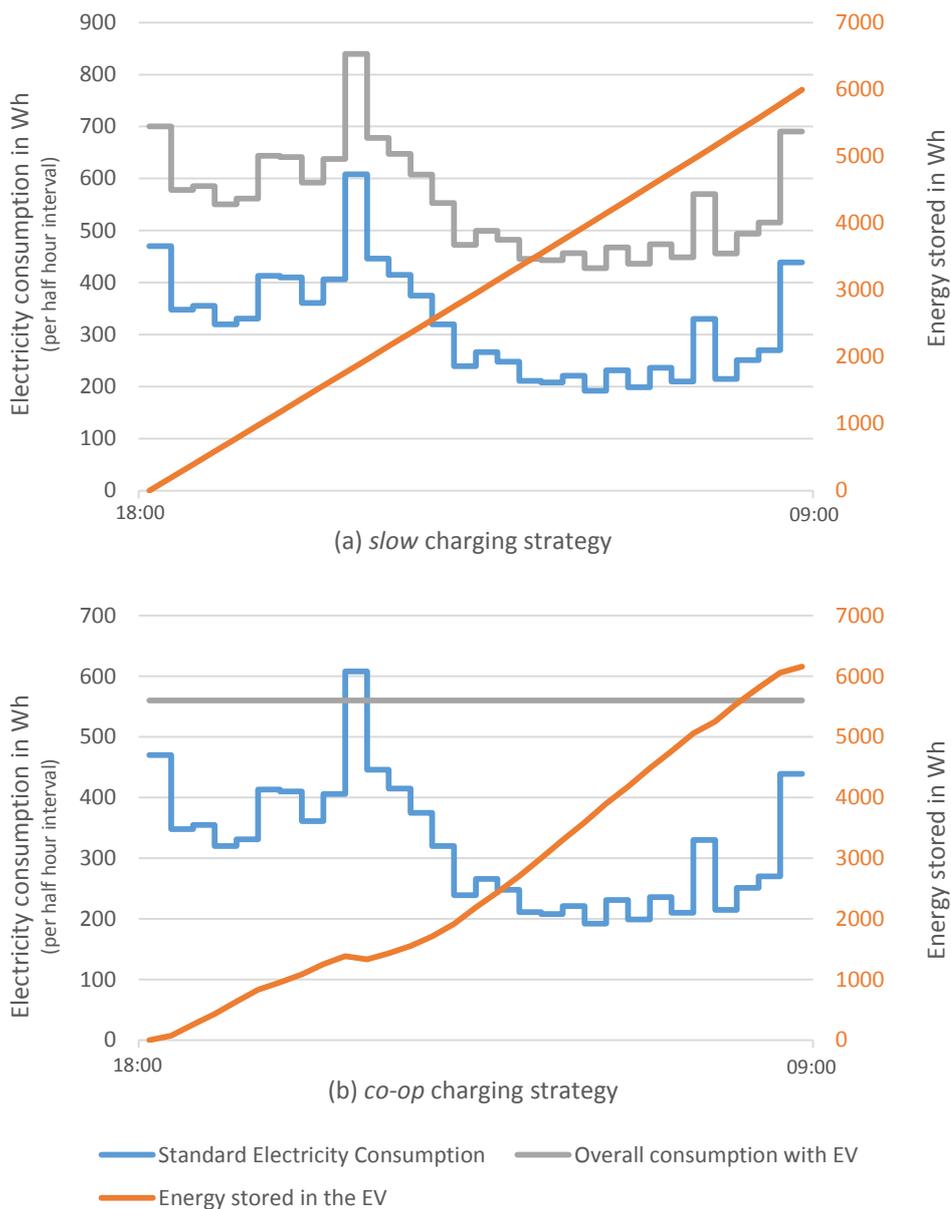


Figure 6.10: Example of *slow* and *co-op* EV charging strategy with a plug-in time of 6pm, plug-out time of 9am, and an energy requirement of 6kWh before it is unplugged.⁴³

⁴³ These examples are assuming: the *limit* is 560Wh (half hour), the electricity price is high between 7am and 11pm and low between 11pm and 7am, and the EV has a maximum storage capacity of 50kWh, a maximum charge and discharge rate of 5kW, and a battery efficiency of 85%.

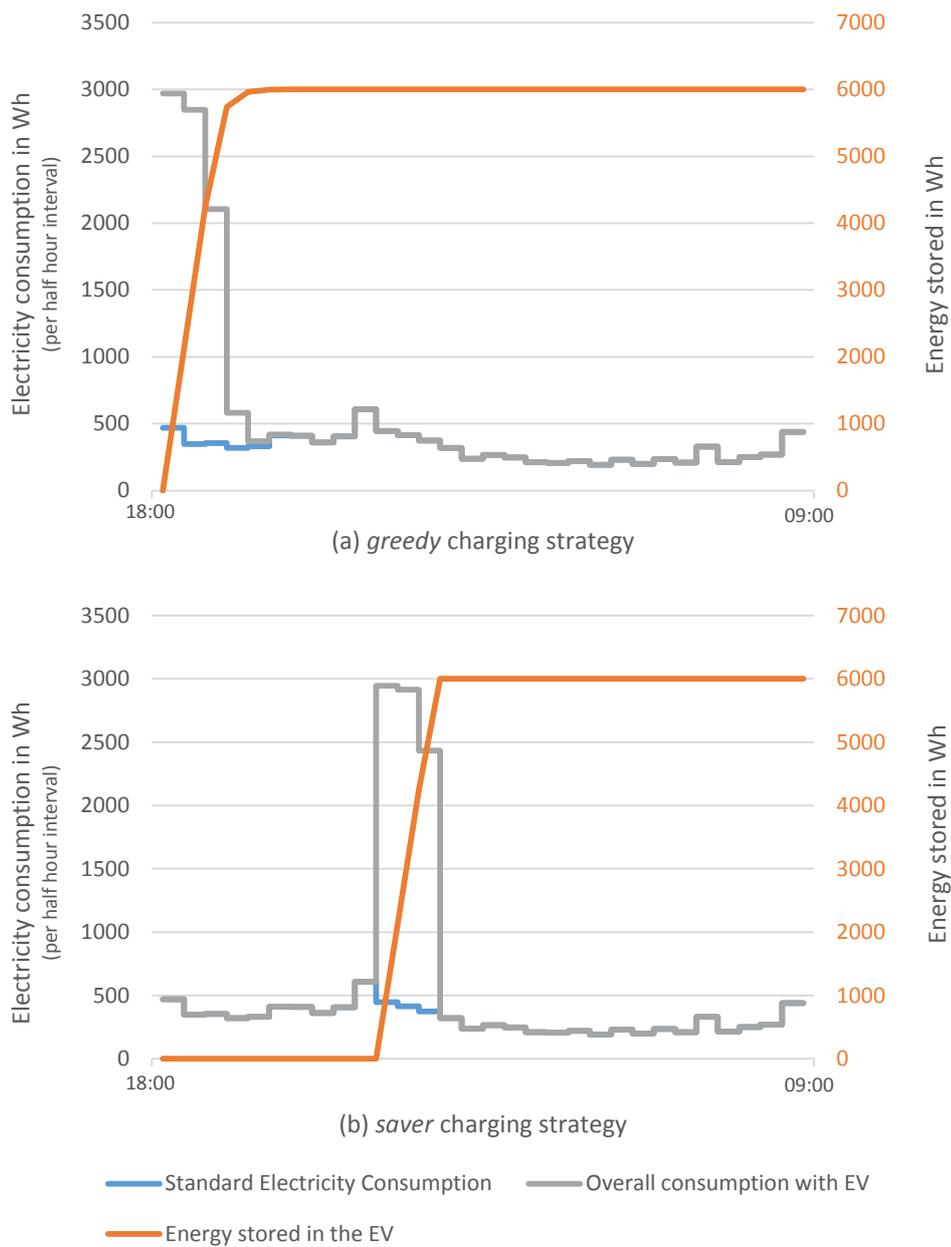


Figure 6.11: Example of *greedy* and *saver* EV charging strategy with a plug-in time of 6pm, plug-out time of 9am, and an energy requirement of 6kWh before it is unplugged.⁴³

6.4 Electric Vehicle Travel Patterns

To simulate an EV's travel behaviour, this simulation uses data from the New Zealand Household Travel Survey [92]. This survey invited people from more than 4600 households to record their travel data over a two-day period, which included their personal vehicle usage. With this vehicle usage data, the simulation tool calculates an EV's travel times, travel distances, and the energy required to travel these distances. These calculations and an analysis of the distance the EV travels are discussed as follows.

6.4.1 Travel Times

In this simulation tool, it is assumed the EV will be used 22 times within a week, as this is the average number of trips New Zealanders make in their cars each week [92]. It is also assumed that there are at least two trips a day, and that the EV unplugs from the household at the start of the earliest trip, and reconnects into the household at the end of the last trip (beginning at a half hour period). This simulation tool estimates when each trip starts through a random selection on a cumulative probability of travel times, which is based on the number of trip legs occurring at a given hour of the week, as shown in Figure 6.12.

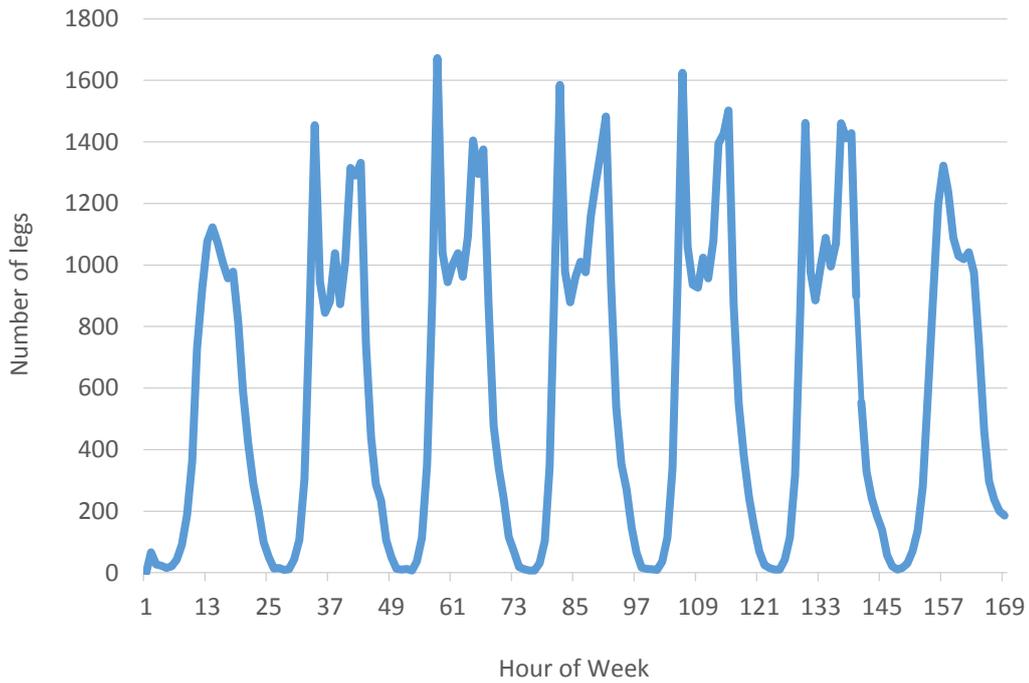


Figure 6.12: Trip legs by hour of week (data from [92]).

6.4.2 Travel Distances

In the previous section the start of each trip made by the EV was calculated, the next step is to estimate the distance the vehicle will travel on these trips.

The estimate of the trip distance is based on the *Behaviour Model* discussed in [93], and is calculated by (i) obtaining the average trip length for the given start time, as shown in Figure 6.13, and (ii) multiplying that by a random selection from the normalised distribution of daily distances travelled by vehicles in the survey, as shown in Figure 6.14.

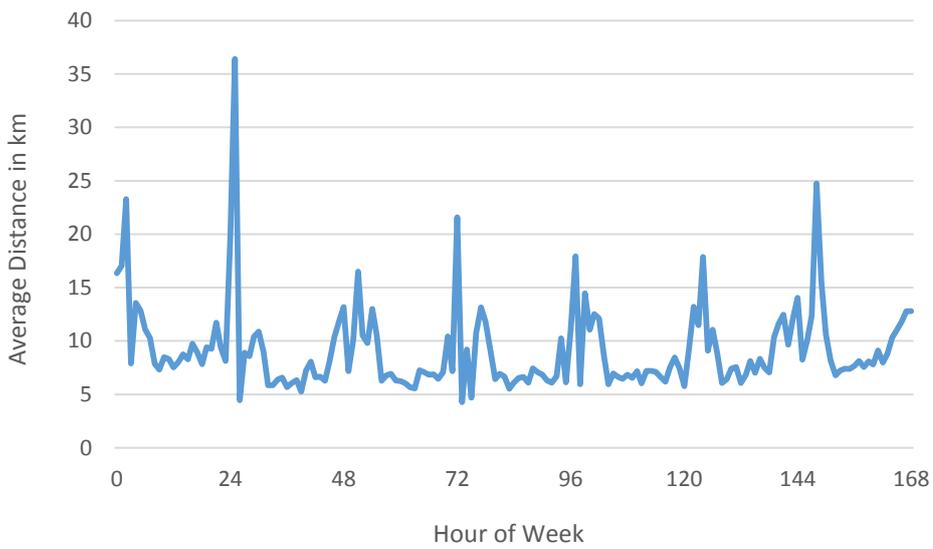


Figure 6.13: Average trip distance for each hour of the week (data from [92]).

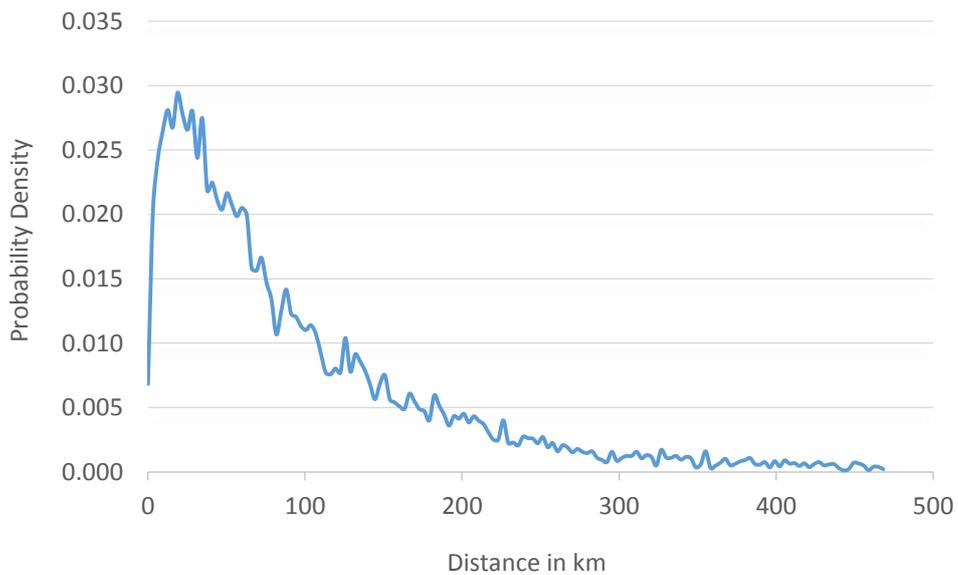


Figure 6.14: Distribution of daily distances travelled per vehicle (data from [92]).

6.4.3 Energy Consumption

In this simulation, it is assumed the EV has a battery-to-wheel efficiency of 200 Wh/km (values typically range from 100 to 200 Wh/km) [94] [95]. The energy required for the EV is, therefore, calculated by multiplying the battery-to-wheel efficiency by the distances of next trips. If the energy required is over its maximum battery capacity, it is assumed the vehicle receives any further energy at another location e.g. at a charging station.

6.4.4 Annual Travel Distance

When running this calculation for 100 different EVs, the annual travel distance ranges between 11,086 km and 13,617 km with a mean of 12,442 km, as shown in Figure 6.15. When comparing these results to data from the New Zealand Ministry of Transport, the distance is comparable to the mean travel distance of a new to 15-year-old light passenger vehicle [96], which seems representative for EVs in New Zealand.

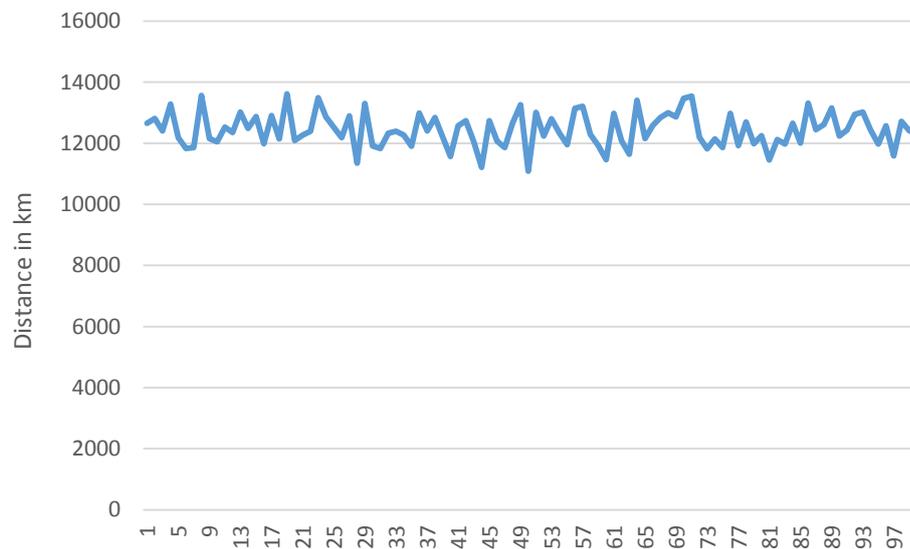


Figure 6.15: Annual distance travelled from 100 different simulated electric vehicles.

6.5 Calculations

The created simulation tool uses a variety of different calculation steps to simulate a household's electricity usage for each time-period. The calculations used in each step depend on the selected strategy for the HESS and the selected strategy for the connected EVs. The six calculation steps, as shown in Figure 6.16, are explained as follows, with the exact calculations given in Appendix E.

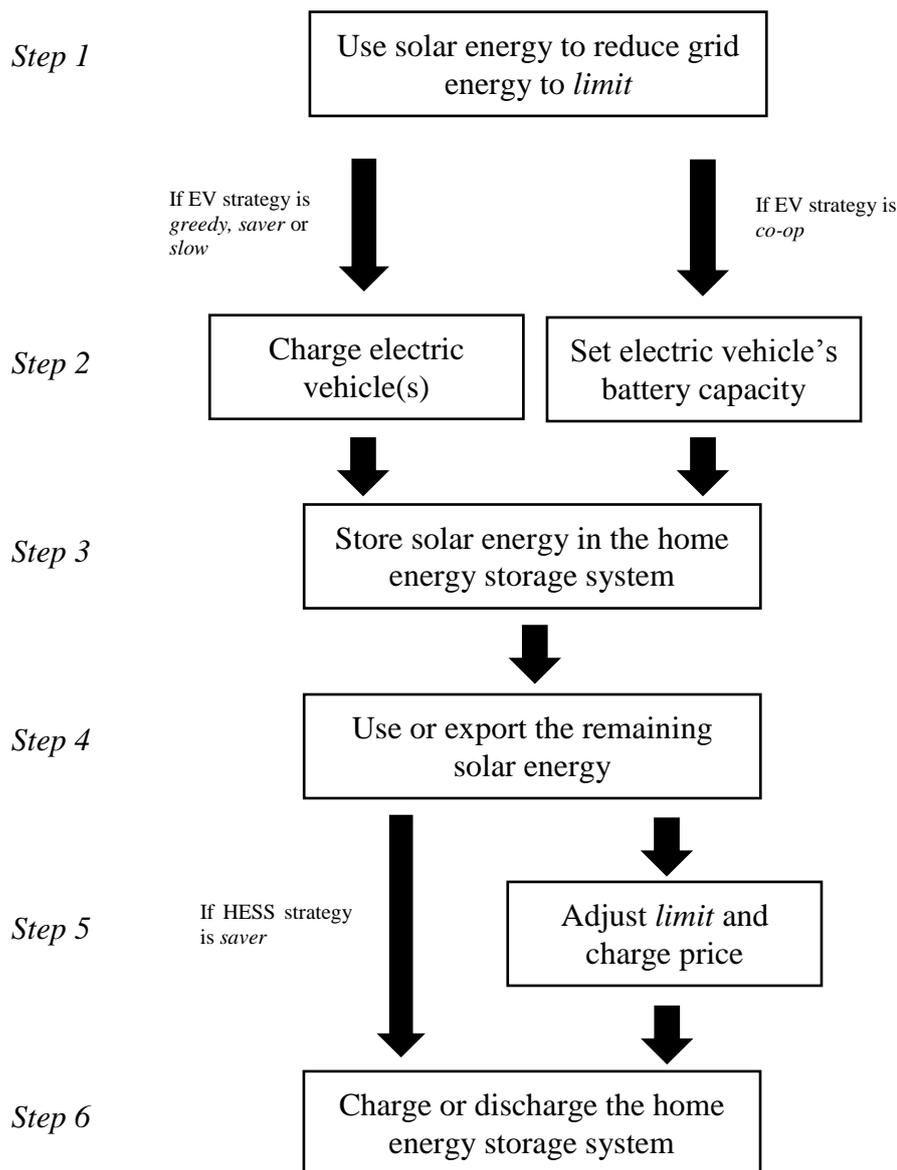


Figure 6.16: The different steps used in HEUS to calculate electricity usage of a household for each time-period.

In the first calculation step, the generated energy from the solar PV system is used to reduce household load to the specified *limit*. If the HESS is set to *saver* strategy, the *limit* is set to 0. If there is not enough energy generated to reduce energy usage to *limit*, all generated energy is consumed. If household load is less than *limit*, solar energy will be used in the following steps.

The calculations used in the second step depend on the EV's charging strategy. If the EV is in a *greedy* or *slow* charge strategy, the second step is to store the remaining generation into the EV, and to charge the EV to its specified goal capacity (as explained in Section 6.3). If the EV strategy is set to *co-op*, the second step is to add the EV's energy capacity to the HESS, when the EV gets plugged in. Similarly, the EV's energy capacity is removed from the HESS when it is unplugged. The amount of energy removed, depends on how much energy is needed by the HESS to reduce further peaks, and the required energy for the EV, with preference given to the latter.

In the third step, the remaining generated energy is stored in the HESS. If the EV is in a *co-op* strategy, the generated energy will also be stored in the EV. This is because the EV is considered part of the HESS.

In the fourth step, any remaining generated energy is exported to the grid or used to reduce household load, with preference given to the latter.

The fifth step is only taken if the home strategy is not set to *saver*. This step's purpose is to adjust the *limit* and *charge price* accordingly, so that the HESS is able to smooth future load. The *limit* is adjusted by predicting how much energy is needed to reduce peaks within *lookahead* hours. This prediction is based on the energy usage of the same period in the previous week and the previous fortnight. If the EVs are in a *co-op* strategy setting, the *limit* and *charge price* are also adjusted accordingly, so that the EV's capacity does not go below a threshold where it cannot charge to its required capacity.

The last calculation step is to charge or discharge the HESS. The amount the HESS charges or discharges is dependent on its current charging strategy and the current household load, as explained in Section 6.2.

6.6 Summary

This chapter described a household simulation tool, created as part of this research. This tool simulates the possible impact new technologies can have on electricity consumption on a half hourly basis. The simulated technologies: EVs, HESSs, and distribution generation systems, were decided upon through the literature review in Chapter 2 as they were suggested to be most disruptive.

Sections one to three outlined the interface of the simulation tool and the charging strategies of HESSs and EVs. The interface of this tool allows the user to alter the characteristics of a technology to see how electricity consumption is impacted on a half hourly basis. The charging strategies of the HESS can be set to follow three possible behaviours: bring maximum savings to the consumer (*saver*), smooth electricity consumption from the grid (*co-op*), or a combination of both (hybrid). The charging strategies of the EVs can be set to follow a behaviour where the technology has vehicle-to-grid capabilities and is utilised to smooth electricity consumption (*co-op*), or where there are no vehicle-to-grid capabilities and the EVs charge at a specific charge rate and time to reach its goal capacity (*slow*, *greedy*, and *saver*).

Sections four and five described the procedure the simulation tool follows to simulate an EV's travel behaviour in New Zealand. The simulated distance using this procedure is approximately 12,500 km which is comparable to the mean travel distance of a new to 15-year-old light passenger vehicle

The next three chapters will describe the results from the household simulation tool, specifically, the impact new technologies have on a household level (Chapter 7), community of households (Chapter 8), and on the national level (Chapter 9).

Chapter 7

Results of Household Simulation

“The role of the market place is to be an instrument of environmental change and policy making. We are all consumers with a great potential for change. Environmental protection begins at home.”

— Noel Brown

Within the last century there has been a vast number of technological advancements for the household which brings comfort and security to its dwellers. Although these technologies have been largely purchased by the dweller for self-interest, with careful consideration these technologies can also benefit the public. For example, the purchase of hot water cylinders with ripple control provides benefits such as access to hot water and typically a cheaper electricity price (to warm the water) for the dwellers, additionally, for the public this technology provides a controllable load that can minimise network strain and costs during peak demand times.

This chapter analyses the impact solar PV systems, home energy storage systems (HESSs), and electric vehicles (EVs) have on a household’s electricity consumption by using the household electricity usage simulation tool (HEUS). This

analysis provides a greater understanding of how these technologies will behave at a household level, and the potential impact these behaviours have on the community and the nation, which is explained in Chapter 8 and 9, respectively. The household data used in HEUS was derived from 16 households, part of the *in-depth* household survey, as described in Section 5.1.2. These 16 households had no solar PV system installed and had a full year of data available. The solar PV power output is simulated using NZSPOT, described in Chapter 4, and is based on a solar PV system installed in Hamilton, New Zealand, the same location as the houses. The EV's travel patterns is simulated using the methods described in Section 6.4, exploiting actual private vehicle usage data [92]. The electricity prices are based on real electricity prices available for households in Hamilton, New Zealand, as shown in Table 7.1.

Table 7.1: Electricity prices based on real values from a New Zealand energy retailer⁴⁴.

Daily fixed charge	33.33 cents/day
Variable day (7am-11pm)	28.73 cents/kWh
Variable night (11pm-7am)	24.72 cents/kWh

The analysis of the results from HEUS are split into three main sections. These three sections focus on the impact of: (1) a solar PV system, (2) an HESS, and (3) an EV, on the selected 16 households, discussed as follows.

⁴⁴ Based on electricity prices, retrieved on July 2017, from the “eSaver Classic Plan” for Hamilton by Genesis Energy at <https://www.genesisenergy.co.nz/>.

7.1 Solar PV System

Installing a solar PV system in a household provides an alternative energy source for its dwellers and can have a significant impact on the household's grid load and energy costs. To understand this impact, a 1.5, 3, and 4 kW solar PV system was simulated for each of the 16 households. The solar PV system characteristics, including size and price, are based on real values and costs in New Zealand, as shown in Table 7.2. Furthermore, it is assumed the solar PV system is grid-tied and capable of injecting power into the grid.

Table 7.2: Solar PV system assumptions.

Solar PV tilt	37.79°
Solar panels	8 x Mitsubishi PV-UE 125 Watt
Inverter	240V HiSEL K Power 1500 Watt
Inverter efficiency	~95%
System losses	14%
Installed location	Hamilton, New Zealand
Solar PV system cost ⁴⁵	\$6,000 (1.5 kW) \$9,000 (3 kW) \$12,000 (4 kW)
Solar PV degradation rate	2% per year
Feed-In tariff	8 cents per kWh ¹⁹
Inverter replacement cost	\$0.4 per W
Inverter replacement year	15
Operation and maintenance cost ⁴⁶ (\$/kW/year)	30
Azimuth angle	0°

⁴⁵ Based on the installed solar PV system costs produced by the Energy Efficiency and Conservation Authority in the solar calculator at <https://www.energywise.govt.nz/tools/solar-calculator/>.

⁴⁶ Based on the fixed operation and maintenance costs for a solar PV system less than 10 kW (\$21 USD) produced by the National Renewable Energy Laboratory <http://www.nrel.gov/>. (July 2017)

The results from HEUS when simulating a solar PV system in the 16 households, produced three main findings, relating to the amount of solar energy being consumed, the impact solar energy has on grid load, and the cost savings a solar PV system brings to a household. These three findings are explained as follows.

7.1.1 Solar Energy

Typically, solar panels include a 25-year warranty period e.g. [97]. During this period, it is expected a 1.5, 3, and 4 kW solar PV system will generate 46, 92, and 122 MWh of energy, respectively. Although, the average household load is much larger at approximately 180 MWh, only a portion of the energy generated from the solar PV system, when used on its own (e.g. with no distributed storage), is typically consumed, as shown in Figure 7.1. This can be explained by a typically low household demand during solar PV generation times. Therefore, households with a higher electricity demand during generation times consume more solar energy, and conversely, households with a low electricity demand during generation times consume less solar energy. This is evident in the simulation results, shown in Table 7.3, where the household that consumed the most electricity (*high-user* household) consumed almost all the generated solar energy, while the household that consumed the least amount of electricity (*low-user* household) used over 60% less solar energy than the *high-user* household.

Table 7.3: Solar energy generated and consumed by households in a 25-year period.

		Solar PV system size (kW)		
		1.5	3	4
Solar Energy Consumed (%)	<i>high-user</i> household	99.7	94.2	86.2
	mean of all households	70.9	52.7	45.1
	<i>low-user</i> household	35.6	21.3	17.0
Solar Energy Generation (kWh)		45801	91603	121833

Furthermore, the results show that for most households a 4kW solar PV system only slightly increased the household’s self-consumption, with an overall mean increase of 12%. This low percentage can be explained with the fact that households only typically utilise the additional generated energy during the start and end of generation times, as shown in Figure 7.1.

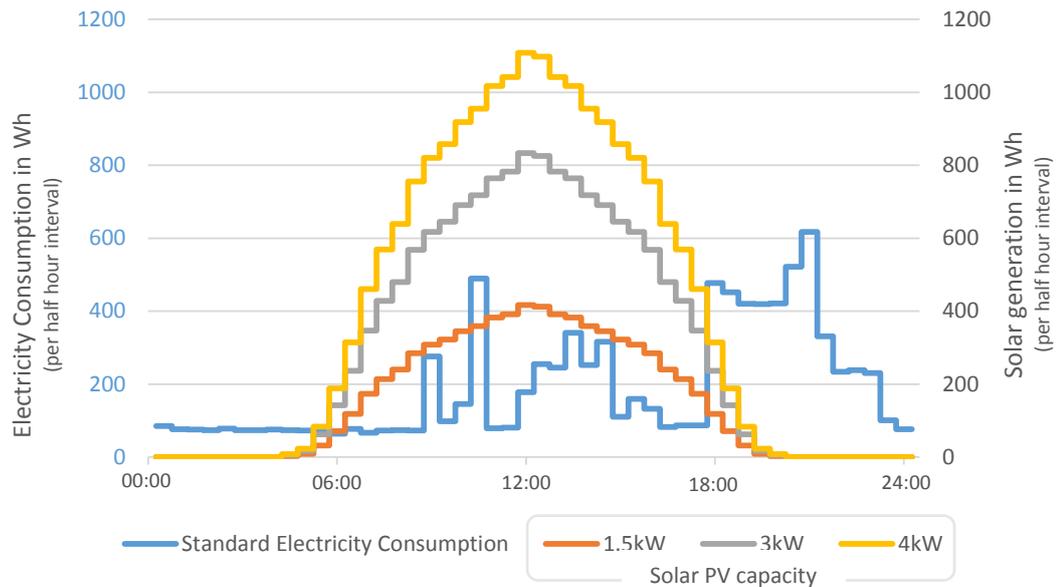


Figure 7.1: Example household demand and energy generated from different sized solar PV systems on a typical day.⁴⁷

7.1.2 Grid Energy

A household which has access to distributed generation has the potential to significantly reduce its energy consumption from the grid. On an annual term, installing a 1.5, 3, and 4 kW solar PV system in these 16 households resulted in a mean reduction of 21, 29, and 33 % of total energy from the grid. Furthermore, if excess solar energy is exported to the grid, it is evident from the results shown in Table 7.3, that most households will export a significant portion of the energy

⁴⁷ Standard Electricity Consumption refers to the actual household load without any technologies (i.e. solar PV system, HESS, or an electric vehicle).

generated from a solar PV system. This can be problematic for the nation if there is a large uptake of this technology, as it would require further infrastructure to allow bi-directional flow of electricity between households, and would increase costs of supplying electricity during non-solar generation times, as mentioned in Section 2.6.1. Overall, the reduction in load and the export of excess solar energy causes the standard deviation of electricity consumption over the period of a year⁴⁸ to increase by 13.97, 19.11, and 18.10 % with a 1.5, 3, and 4 kW solar PV system, respectively.

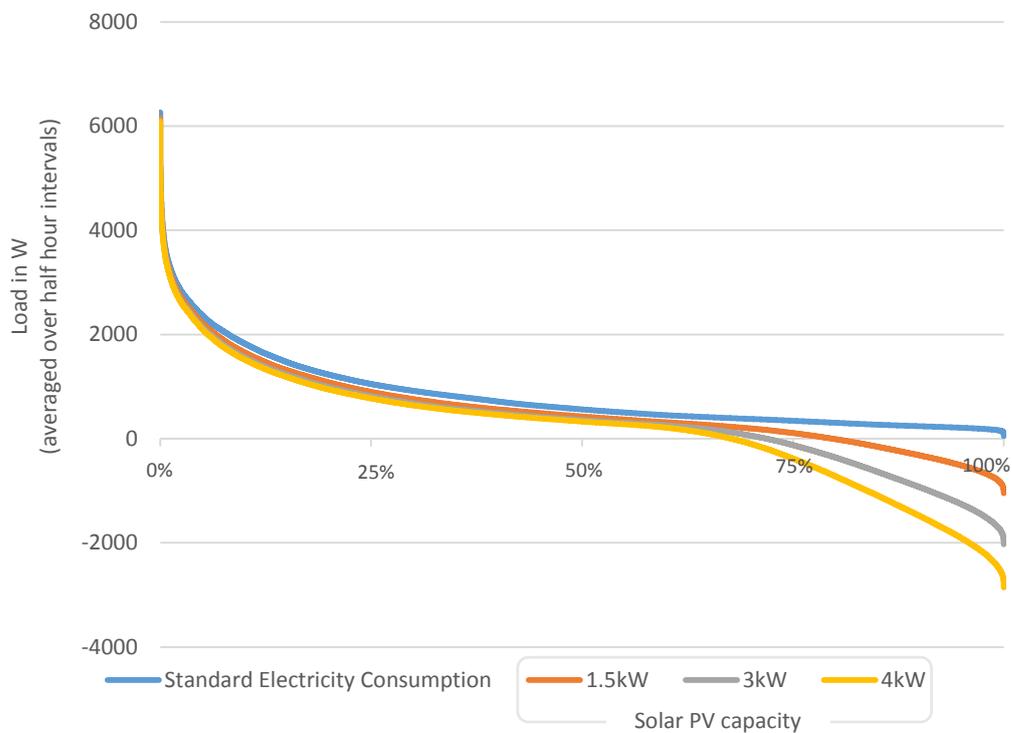


Figure 7.2: Mean annual load duration curves of all households with and without a solar PV system.

⁴⁸ The change in standard deviation of electricity consumption over the period of a year will be referred to as the “Standard Deviation Change” from this point forward. A positive value represents there is an increase in the standard deviation, while a negative value represents there is a decrease in the standard deviation.

In addition, since 54% of daily peaks and 62% of annual peaks across the 16 households, occur outside sunlight hours, as shown in Figure 7.3, a solar PV system has little impact on reducing peak energy demand. The results from HEUS show that a 1.5, 3, and 4 kW solar PV system is able to reduce the daily peak demand of the selected 16 households, on average by 6.66, 10.05, and 11.73 %, while the annual peak can be reduced by only 1.4, 2.29, 2.86 %, respectively.

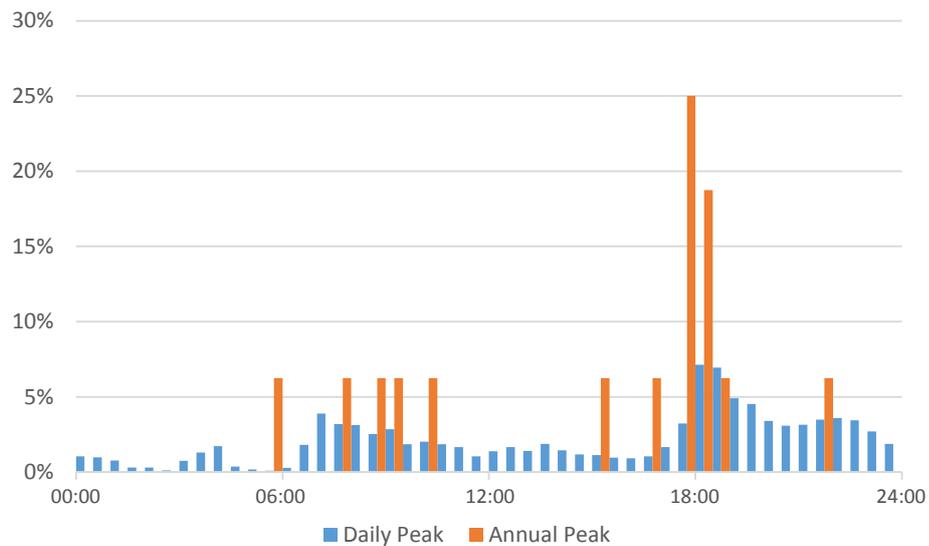


Figure 7.3: The percentage of daily and annual peaks occurring at a specific time of day, based on data from the 16-household set.

7.1.3 Value to Consumers

To achieve a net gain from a 1.5, 3, and 4 kW solar PV system, the gross savings need to be greater than \$7725, \$12450 and \$16600, respectively, to cover upfront, inverter replacement, and maintenance costs. To achieve this level of gross savings in 25 years, with realistic electricity prices as shown in Table 7.1, approximately 27, 43, and 58 MWh of solar energy needs to be consumed, which is approximately half of the total energy generated by a 1.5, 3, and 4 kW solar PV system, respectively. The results from simulating the selected households with a solar PV system, as shown in Figure 7.4, show that most of the households consumed more

than half of the generated solar energy, resulting in a mean net gain of \$2651, \$4856, and \$4489 for a 1.5, 3, and 4 kW solar PV system, respectively. The *high-user* household achieved the greatest net gain of \$5381, \$12736, and \$14886. Similarly, the *low-user* household had the lowest net value, being the only household having a net loss. This net loss is due to the relatively high level of exported solar energy, which at 8 cents per kWh does not cover the solar PV system’s costs¹⁹. This is also evident with a 4kW solar PV system, resulting in a lower mean net gain on most households in comparison to a 3kW solar PV system. Furthermore, this exported value is likely to decrease if electricity prices change, to reflect the true costs of exporting solar energy, as discussed in Section 3.2.2.

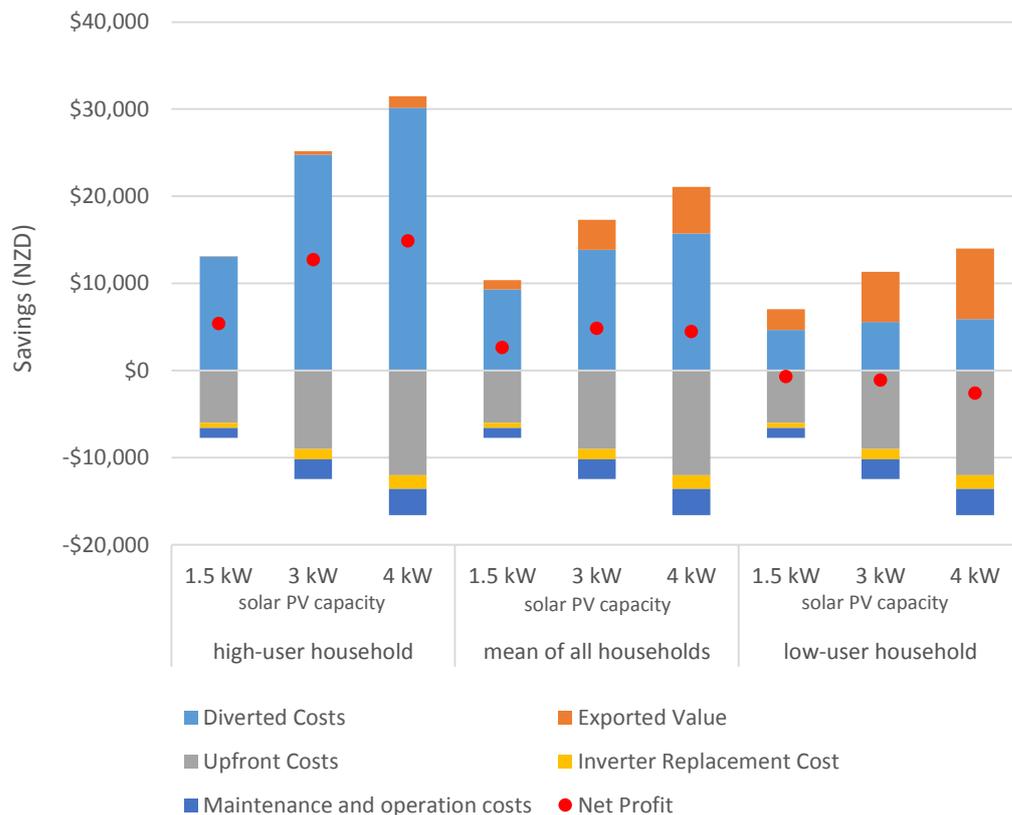


Figure 7.4: Costs and savings over a 25-year period for different sized solar PV systems on the representative households from the 16-household set.

7.2 Home Energy Storage System

Integrating an HESS in the household has the potential to significantly alter the household's load profile; by storing solar energy, storing grid electricity, and displacing grid energy. To understand the extent of this impact, an HESS was simulated in the 16 households. The HESS is based on the Tesla Powerwall 2 AC⁴⁹, the characteristics of which are shown in Table 7.4. The degradation rate is based on the warranty given to these systems in Australia and New Zealand⁵⁰. There are three charging strategies used by the HESS, as explained in Section 7.2. Firstly *co-op*, which focuses on smoothing load, secondly *saver*, which charges and discharges for optimal savings, and lastly *hybrid*, which is a combination of both.

Table 7.4: Home energy storage system assumptions, based on the Tesla Powerwall 2 AC⁴⁹.

Storage (kWh)	13.5
Efficiency	90%
Storage warranty period	10
Storage degradation rate (%)	3
Discharge and charge rate	5 kW
Cost	10,100
Installation	2,250

⁴⁹ Characteristics on the Tesla Powerwall 2 AC were retrieved from the “Powerwall” webpage at <https://www.tesla.com/>. (November 2017)

⁵⁰ Degradation rate was calculated based on the warranty (70% of their rated capacity after 10 years) from the “Tesla Powerwall Warranty (Australia and New Zealand)” document, available at <https://www.tesla.com/>. (November 2017)

Two scenarios were used in analysing the impact of the HESS; one with and one without an installed solar PV system. The findings from these scenarios are discussed as follows.

7.2.1 Storage without a Solar PV System

The first scenario, which simulated a household with an HESS and no solar PV system, resulted in two main findings, which were related to the change in grid load and the amount of cost savings achieved, as explained in further detail below.

Grid Load - When using a *co-op* or *hybrid* charging strategy, the HESS causes a mean reduction in daily peak demand by 54.5 and 34.6 %, and similarly, a mean annual peak demand reduction by 11.6 and 8.8 %, respectively. This reduction in peak demand can help reduce network stress and smooth demand in the electricity infrastructure, which would reduce system costs and incentivise renewable generation. However, current electricity prices do not incentivise households to have a smooth load, therefore, it is more likely the HESS will follow the *saver* strategy to gain maximum savings. In this strategy, the mean daily peak demand is increased by 200% and similarly, the annual peak demand is increased by 55%. This large increase is a result of the HESS charging at its maximum charge rate without regards to the current household demand. This charging behaviour causes grid load to significantly fluctuate, which is evident from a standard deviation change of 133%, whereas using the *co-op* or *hybrid* strategy would lead to a standard deviation change of -55 and -34%, respectively, as depicted in Figure 7.5.

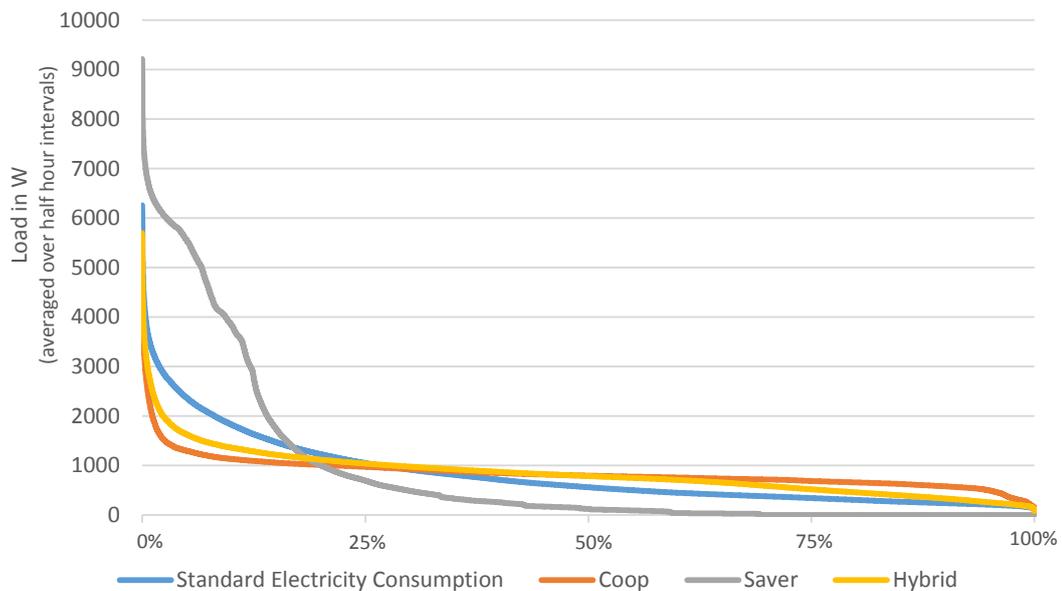


Figure 7.5: Mean annual load duration curves of all households with a home energy storage system for each of the three investigated strategies.

Cost Savings – If we assume the HESS does one full cycle daily for 10 years, an HESS with 13.5 kWh capacity has the potential to displace⁵¹ 42623 kWh of energy⁵². To cover the costs of the HESS, each kilowatt hour displaced by the HESS needs to give a net gain of at least 28.98 cents. If we consider the electricity prices from Table 7.1, each kilowatt hour that is displaced by the HESS would result in a saving of approximately 1.263 cents⁵³. With these savings, the maximum gross gain that could be achieved, is \$538 in 10 years. This gross gain will result in a significant net loss when considering the cost of the HESS. This net loss is likely true for all electricity prices in New Zealand, as there are currently no electricity tariffs available which could provide the required savings for each displaced

⁵¹ A displaced load here refers to energy delivered to the household from the HESS, and consumed from the grid at some other time.

⁵² Assuming a 3% degradation every year and a charge loss of 10% with 0% discharge loss. Although there is expected to be a discharge loss, all rated losses are calculated during charging for this simulation.

⁵³ To displace 1 kWh the battery needs to charge just over 1.1 kWh to account for efficiency losses. This costs 27.46 cents at 24.72 cents per kWh and when displacing electricity at 28.73 cents per kWh the savings is 1.263 cents.

kilowatt hour⁵⁴. This net loss is also apparent in the simulated scenarios, shown in Figure 7.6. When the HESS follows the *saver* strategy, there is a mean gross gain of \$457, while with the *co-op* and *hybrid* strategy there is a mean gross loss of \$322 and \$9, respectively. This loss occurs as a result of the HESS discharging during lower electricity prices, and additionally in the *co-op* strategy, the HESS also charges during high electricity prices.

These results show that the gross savings of an HESS are significantly lower than its current upfront costs, which will likely prevent a major uptake of this technology. Furthermore, if there is a large uptake of HESSs and electricity tariffs remain the same, it is likely the HESS will follow the *saver* strategy. However, if the uptake reaches a level where this technology is disruptive to the grid, it is likely electricity tariffs will change, which could negate the achieved savings when following the *saver* strategy.

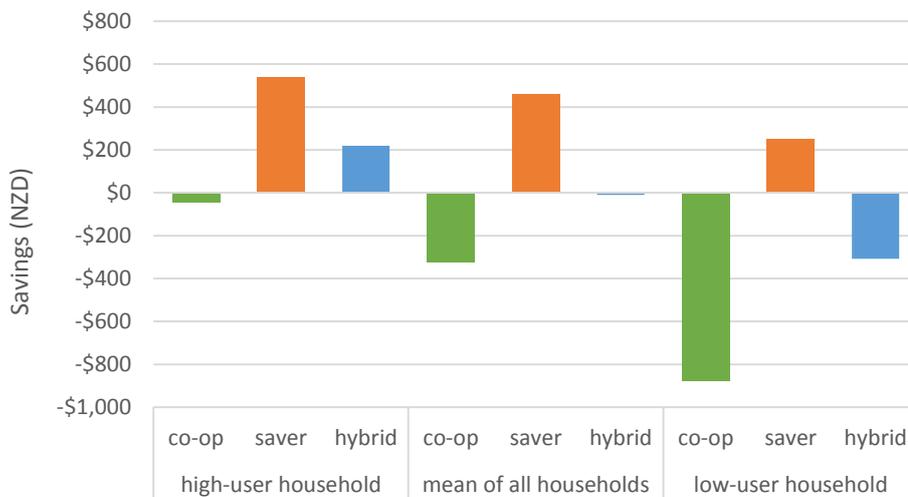


Figure 7.6: Gross savings from selected households when using a home energy storage system.

⁵⁴ There would need to be a difference in charging and discharging price of 31.867 cents to gain the 28.97 cents of savings. This difference was not found in an extensive search on electricity tariffs from New Zealand retailers.

7.2.2 Storage with a Solar PV System

In the second scenario, a combination of a solar PV system and an HESS was simulated. The HESS was used to store solar energy during low electricity prices, and excess solar energy during high electricity prices. Three main findings were evident in this scenario, which are related to the amount of generated electricity stored in the HESS, the change in grid load, and the amount of achieved cost savings, as explained in further detail below.

Stored solar energy – With a 1.5 kW solar PV system, 13 out of the 16 households could store all excess solar energy with the remaining 3 storing over 98% of excess solar energy. With a 3 and 4 kW solar PV system, households typically stored 94 and 87 % of excess solar energy, respectively. Not being able to store all excess solar energy is a result of limitations in the HESS's charge rate and/or its capacity.

Grid load – With an HESS and a 1.5, 3 and 4 kW solar PV system the mean reduction for selected households, in annual energy consumption, is 32, 57, and 67 %, respectively. This reduction is 10, 27, and 34 % more than if there is no HESS and only a solar PV system. The daily peak load in this scenario is also reduced by a mean of 15, 41, and 53 %. However, the greatest reductions in peak load occurs during non-winter months when solar PV generation is high, as shown in Figure 7.7. Consequently, with the annual peak occurring in winter months, there is only a slight reduction in annual peak load of 2.8, 7.2, and 9.1 %, for a 1.5, 3, and 4 kW solar PV system.

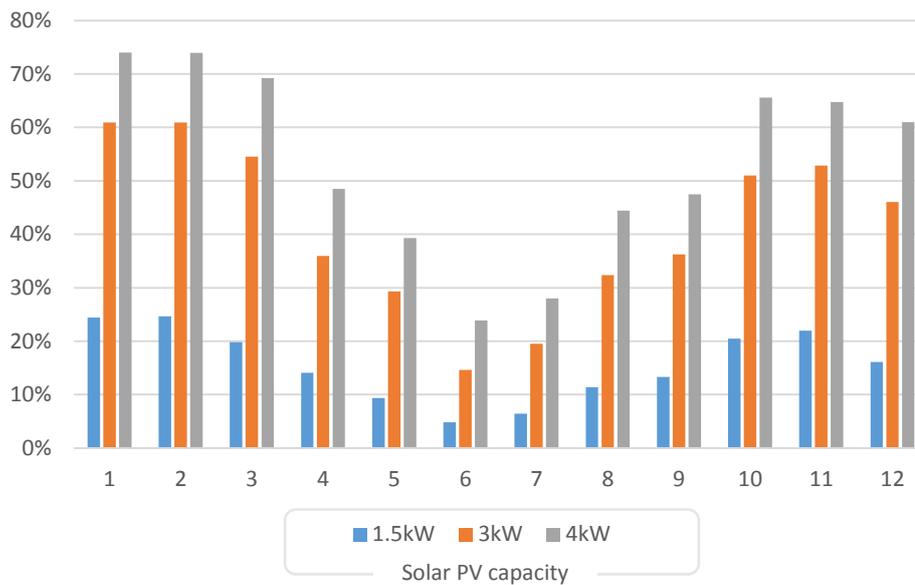


Figure 7.7: Mean daily peak reduction for each month of the year for all 16 households with a solar PV system and a home energy storage system.

Cost Savings – Storing excess solar energy in an HESS has the potential to increase the household’s self-consumption. This storage of solar energy instead of grid energy can yield significantly greater savings, since solar energy has a cost of 8 cents per kWh, whereas grid energy has a cost of 24.72 or 28.73 cents per kWh⁵⁵. This lower energy cost results in a savings of 19.8 or 15.8 cents per kWh, which is much larger than 1.263 cents per kWh when charging from the grid. The results of the simulated scenario show that a household with an HESS, which stores excess energy from a 1.5, 3, and 4 kW solar PV system, achieves a mean cost savings that is \$1524, \$4220, and \$5650 larger than a household without an HESS. However, these savings do not cover the HESS’s costs. In this scenario, since the HESS only charges with excess solar energy, the HESS only utilises 13, 36, and 48 % of its battery capacity (with a 1.5, 3, and 4 kW solar PV system, respectively). If the HESS also charged during off peak times, there could be potential added savings of \$470, \$347, and \$281. With these added savings, the gross gain from the added

⁵⁵ The 8 cents per kWh is what the household would receive in this simulation if it exported a kWh of solar energy.

HESS is still significantly less than its upfront costs, which means that these 16 households would be better off financially without an HESS. However, with the price of this technology steadily decreasing, and with government incentives, this technology could be financially viable in the near future. One such example, is Australia which provides such government incentives, which is expected to result in 1 to 2 million households installing an HESS by 2020 [59].

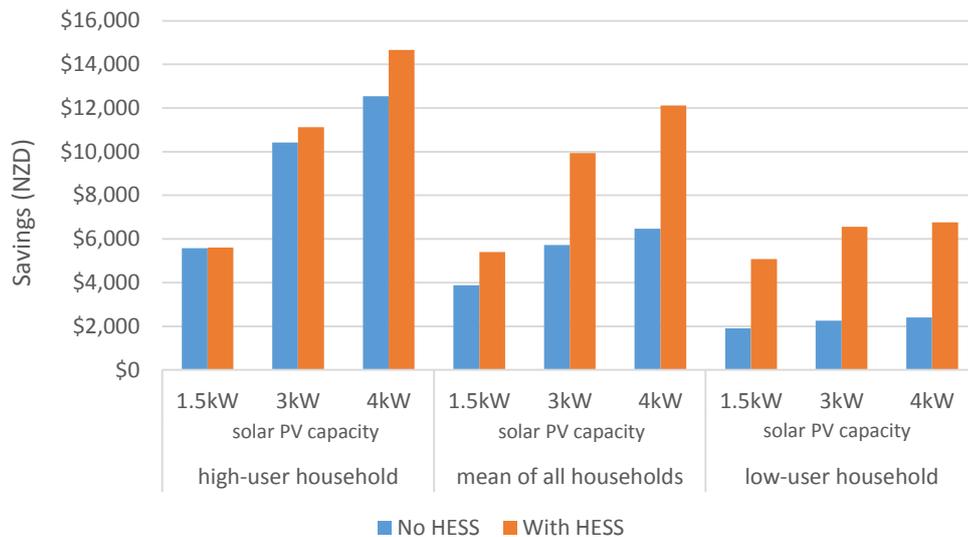


Figure 7.8: 10-year savings from solar energy consumption with and without a home energy storage system in the 16 households. These savings do not include the potential savings from exporting solar energy.

7.3 Electric vehicles

Another simulation performed by HEUS is the inclusion of an EV in the 16 households. The characteristics of the EV are based on a mid-range electric vehicle with a medium battery-to-wheel efficiency level, as shown in Table 7.5.

Table 7.5: Electric vehicle assumptions are based on a mid-range electric vehicle, with typical characteristics [93] [94] [95].

Maximum battery capacity	50 kWh
Charge loss	15%
Maximum discharge and charge rate	5 kW
Battery-to-wheel efficiency	0.2 kWh/km
Petrol Costs ⁵⁶	\$2/L
Petrol battery-to-wheel efficiency ⁵⁷	0.06L/km

In this simulation, the EV followed four different charging strategies, as explained in Section 6.3. These strategies are *greedy*, which charges at maximum charge rate until it has reached its goal capacity, *saver*, which charges at maximum charge rate at a low electricity price (between 11pm and 7am in this simulation) until it has reached its goal capacity, *slow*, which splits the needed energy evenly until the vehicle is unplugged, and *co-op*, which uses the EV’s battery to smooth household load while ensuring it reaches its goal capacity before it is unplugged (this strategy assumes the household has vehicle-to-grid technology). The results of this simulation are related to how the EV impacts household grid load, the added energy costs and potential savings when using an EV, how an EV performs in a household with a solar PV system, and the benefits of adding all three technologies in a household. These results are explained in further detail as follows.

⁵⁶ Petrol cost is an approximate value based on the 91 octane petrol prices in New Zealand in 2017 (<http://www.aa.co.nz>).

⁵⁷ The efficiency is based on the fuel consumption of a 1300-1599cc vehicle made in 2015-2016. Retrieved from “2016 New Zealand Vehicle Fleet Annual Spreadsheet” at <http://www.transport.govt.nz/>.

7.3.1 Grid Energy

An EV increases a household's energy demand by approximately 40%⁵⁸. This added demand has the potential to significantly alter the household's load profile, as shown in Figure 7.9. When an EV follows a *greedy* or *saver* charging strategy, almost all the EV's charging occurs within an hour, this behaviour causes a substantial increase in electricity consumption for a short period of time, resulting in a standard deviation change of almost 100%, as shown in Figure 7.9. The *slow* and *co-op* charging strategy distributes the added energy demand from the EV, resulting in a small standard deviation change of 22.6 and 6.4 %. From a peak demand perspective, the *co-op* and *slow* strategy increases the daily peak demand by 21 and 29 % and increases the annual peak by 34 and 45 %. While the *greedy* strategy increases daily peak demand by 186% and annual peak demand by 70.8%, in the *saver* strategy, the EV increases daily peak demand by 97.5%, and annual peak by 46.2%. This slightly lower peak increase, when compared to the *greedy* strategy, is a result of charging the EV when standard electricity consumption is typically low, i.e. between 11pm and 7am.

⁵⁸ When assuming the vehicle travels 12500km a year, as mentioned in Section 6.4, which will require approximately 2941 kWh of energy, when considering 85% battery. This demand is 40.7% of the mean annual household energy demand of the selected 16 households (7217 kWh).

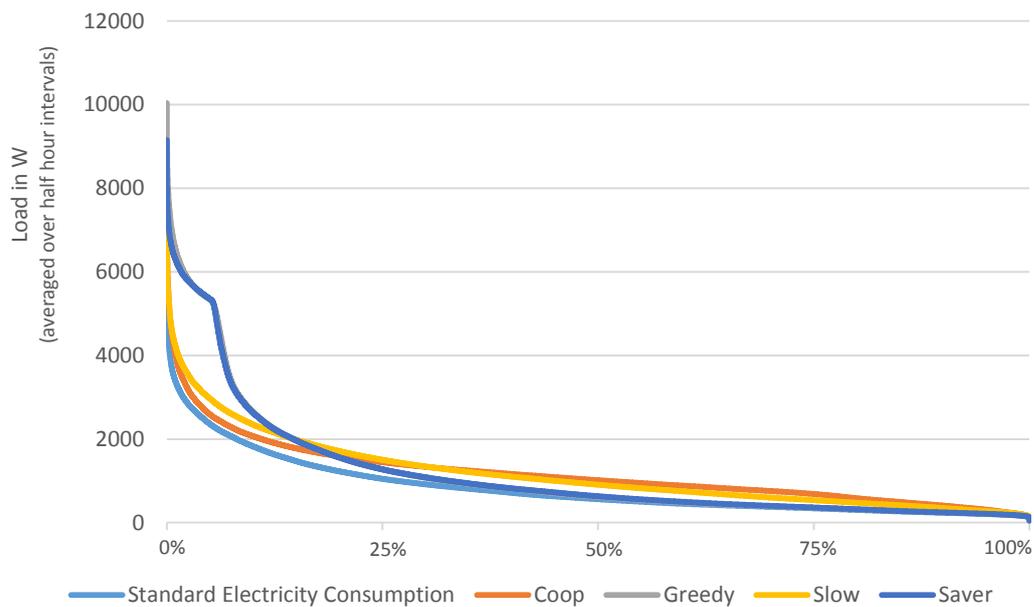


Figure 7.9: Mean annual load duration curves of all households with the addition of an electric vehicle following different charging strategies.

7.3.2 Value to Consumers

An EV which travels 12,500 km a year will require approximately 2941 kWh. When charging at 28.73 or 24.72 cents per kWh, the prices selected for this simulation, this would cost between \$727 and \$845 per year. In comparison, the petrol costs for an equivalent internal combustion engine vehicle would amount to approximately \$1500. The savings using an EV, would therefore be between \$773 and \$655 per year, depending on the time the EV is charged.

The results from simulating an EV in the selected 16 households show similar energy costs, as shown in Table 7.6. An EV in the *greedy* strategy adds the highest energy costs to the household, since the vehicle is charging at its maximum charge rate as soon as it is plugged in, which is typically when the electricity prices are high. *Slow* and *co-op* strategies in comparison have a lower energy cost since some of the vehicles' charging occurs at times of low electricity prices. However, with the *co-op* strategy also discharging during low electricity prices to smooth load, the added energy costs are slightly higher in this strategy. The *saver* strategy achieves

the lowest energy cost since almost all of the charging occurs at the lowest electricity price.

Table 7.6: Mean annual energy costs of an electric vehicle⁵⁹.

	Distance Travelled (km)	Added Energy Costs (\$)	Cost for each km (cents/km)	Petrol Equivalent cost (\$)
<i>co-op</i>	12502	796	6.37	1500
<i>greedy</i>	12469	816	6.54	1496
<i>slow</i>	12382	775	6.26	1486
<i>saver</i>	12440	725	5.83	1493

The results from the simulation show that an EV's fuel costs amount to approximately half of the fuel costs of an equivalent internal combustion vehicle, when using the electricity prices in Table 7.1. If we consider the capital cost premium of an EV to be \$12,000⁶⁰, it would take over 15 years for a net gain. This long period could significantly deter investment into this technology. However, these results do not consider other financial benefits, such as lower maintenance costs and lower road user charges. Furthermore, with an electricity tariff that has a lower off-peak electricity price, the EV's fuel costs could be substantially lower e.g. using the off-peak Wellington electricity price of 13.65 cents/kWh⁶¹, the fuel costs for an EV would be approximately \$400 per year.

⁵⁹ Based on the mean of 10 runs, due to the variation each run can have on electric vehicle behaviour, as explained in Section 6.4.4.

⁶⁰ This price is the estimated capital cost premium of a mid-range electric vehicle by Concept Consulting [50].

⁶¹ eSaver Classic Plan Variable Night price available at <https://www.genesisenergy.co.nz>.

7.3.3 Electric Vehicle with a Solar PV System

An EV charging in a household with a solar PV system has the potential to utilise solar energy, which could significantly reduce the need for grid energy and as a result save energy costs. To test the extent of this impact, an EV was simulated in the selected 16 households with different sized solar PV systems and with two different charging scenarios, over a 25-year period. The first scenario (*saver*) assumed the EV would charge during the cheapest period, while the second scenario (*co-op*) utilised the EV's battery to smooth household load while assuring there is enough stored energy to meet the energy requirements for the next trips. In the second scenario, solar energy is used to smooth grid load before charging the EV, while in the second scenario, solar energy is prioritised to reduce all grid load before charging an EV, as it yields more savings⁶². The findings from both scenarios are explained as follows.

Grid Load – An EV's energy demand for a year is approximately 2941 kWh. Without a solar PV system, this demand is entirely met with grid energy, which increases the household's annual energy demand by approximately 40%. With a solar PV system, solar energy is used to reduce household demand and charge the EV. In the *co-op* strategy, the added annual grid load is 1621, 742, and 235 kWh, while in the *saver* strategy the added grid load is 1509, 610 and 115 kWh, with a 1.5, 3, and 4 kW solar PV system, respectively⁶³. On a half hourly scale the EV's charging behaviour has a major effect on the household's load profile. In the *co-op* strategy, the EV is successful in distributing load, resulting in a standard deviation change of 21.37, 42.44, and 61.08%, with a 1.5, 3, and 4 kW solar PV system, respectively. In the *saver* strategy, since the EV charges at its maximum charge rate during cheaper electricity prices, there is a large spike in demand, as shown in Figure 7.10. These large spikes result in a standard deviation change of 100, 112, and 120%, with a 1.5, 3, and 4 kW solar PV system, respectively. These results

⁶² Diverting a kWh of grid load with solar energy will save 28.73 cents, whereas, the savings will be less when charging an electric vehicle, since charging of an electric vehicle is typically done during cheaper prices (24.72 cents/kWh).

⁶³ These values also include the household demand which is diverted from solar PV energy.

show that the load profile within the *saver* scenario is significantly more fluctuant than a *co-op* scenario and a scenario without a solar PV system and an EV.

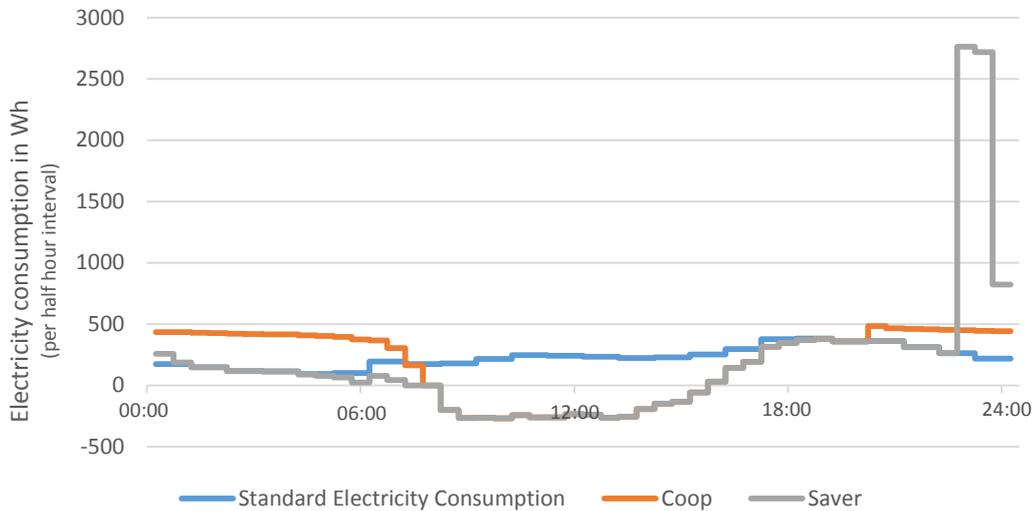


Figure 7.10: Example household load profile on a typical day with a solar PV system and an electric vehicle in a *co-op* and *saver* charging strategy.

Peak Demand – An EV following the *co-op* strategy distributes its charging and utilises stored energy, to smooth the household’s electricity consumption from the grid. This behaviour results in a small increase in daily peak demand with a 1.5 kW system (approximately 7%), and a reduction in daily peak demand with a 3 and 4 kW system (approximately 8.8 and 15.7%, respectively). Using a 4kW solar PV system in combination with an EV, results in a reduction of peak demand of up to 4% greater than without an EV. This greater reduction is a result of the capability of the EV to store and distribute solar energy. Furthermore, if there is an unpredictably high electricity consumption before the EV is unplugged, the EV could charge during this high consumption period. This behaviour can result in a larger peak demand, which is shown in the simulation through a mean increase in annual peak demand of 29, 24, and 24 % with a 1.5, 3, and 4 kW solar PV system, respectively. In the *saver* strategy, the daily peak increases by approximately 150%, and annual peak by approximately 50%, since the EV is not used to smooth grid load.

Exported Energy - It is expected that EVs can utilise excess solar energy, however, since these vehicles are typically unplugged from the household during periods of high generation times, the EV only utilises a small portion of solar energy. The simulation results show that adding an EV to a household with a 1.5, 3, and 4 kW solar PV system, would result in the household exporting only approximately 6.2, 10.7 and 12.6% less solar energy than a household without an EV. Similarly, the amount of solar energy stored in the EV only equates to 4.5, 15.8 and 24.8 % of its energy needs.

Cost Savings – A household with an EV in the *co-op* strategy and a 1.5, 3, and 4kW solar PV system, will have an added energy cost of approximately \$9804, \$3671 and \$193, over a 25-year period, while in the *saver* strategy, these added energy costs are lower, at \$8066 and \$1886, for a 1.5 and 3 kW solar PV system. With a 4kW solar PV system, however, it is expected that there is a net gain of \$1427. Although, adding an EV to a household results in an overall higher electricity bill, the savings diverted from fuel costs offset the expenses, resulting in significantly higher net savings, as shown in Figure 7.11.

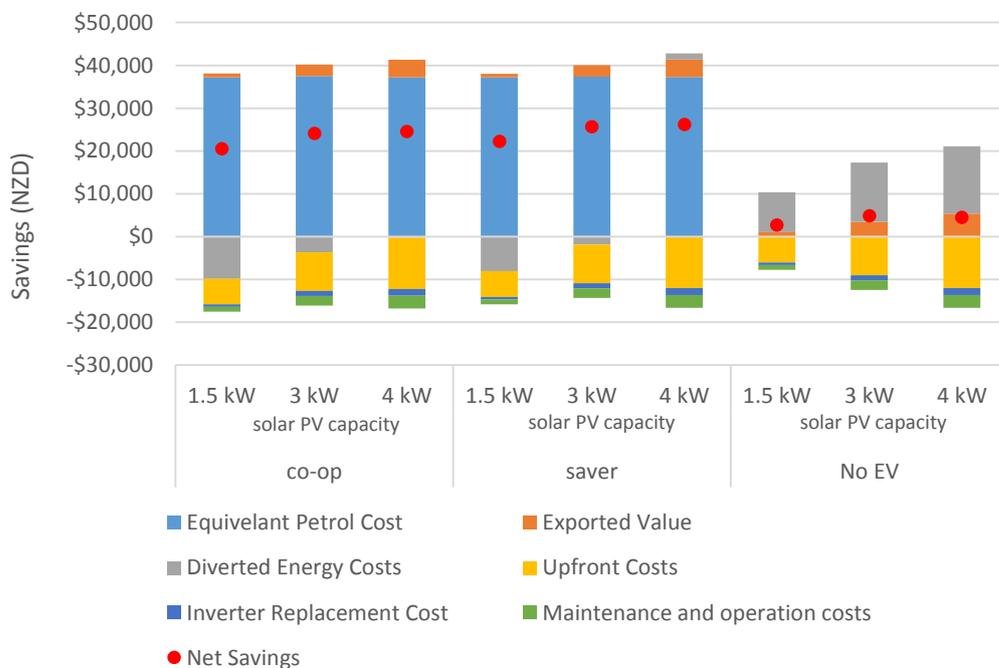


Figure 7.11: Costs and savings related to a household with a solar PV system and an electric vehicle during a 25-year period.

7.3.4 Electric Vehicle with Distributed Storage and Generation

A household with all three technologies (an EV, solar PV system, and HESS) has the potential to significantly impact the household's grid load and energy costs; by utilising distributed generation and distributed storage (from the HESS and the EV). To test the extent of this impact, 16 selected households were simulated with different sized solar panel systems, an HESS, and an EV. Two different scenarios were simulated, explained as follows.

The first scenario assumes the technologies are prioritised to smooth household load, rather than save costs. This is achieved by simulating the EV and HESS to follow the *co-op* strategy. The results, as shown in Figure 7.13, make evident that with a 1.5 kW solar PV system, the HESS and EV could reduce household fluctuations, which is evident through a standard deviation change of approximately -28%. However, as shown in Figure 7.12, fluctuations still occurred when the HESS and EV could not store anymore solar energy, due to capacity and charging restraints or an unplugged EV. These fluctuations are more frequent in households with a larger solar PV system, which is shown by simulating a 4kW solar PV system, resulting in a standard deviation change of 28%. Similarly, this scenario shows that if these technologies were used to smooth load, the daily peak demand in a household would be expected to drop by 37, 50, and 53 %, and annual peak demand by 2, 5, and 15 %, with a 1.5, 3, and 4 kW solar PV system, respectively. However, when comparing the savings for these technologies over a 10-year period⁶⁴ (approximately \$11821, \$15835, and \$17824), with the technology costs such as the cost of the HESS (\$12350), the cost of a solar PV system for 10 years (\$3090, \$4980, \$6640)⁶⁵, and the premium costs for an EV, it is evident that there is a significant net loss.

⁶⁴ 10 years was chosen as this is the warranty given for the HESS.

⁶⁵ An estimated 10-year cost of a 1.5, 3, and 4 kW solar PV system, based on the prices shown in Table 7.2.

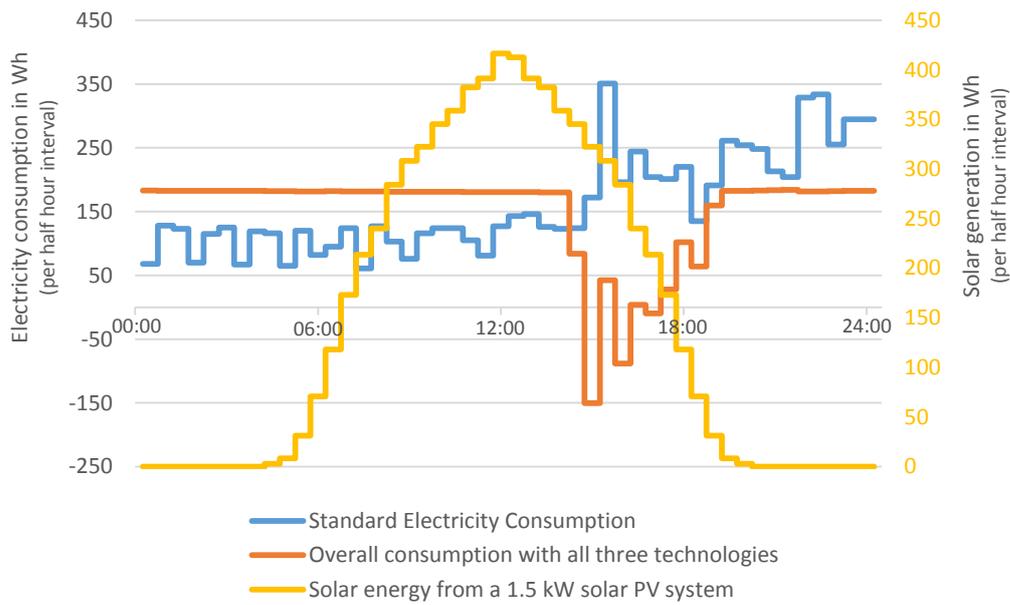


Figure 7.12: Example of fluctuation in grid load due to the home energy storage system being at full capacity.

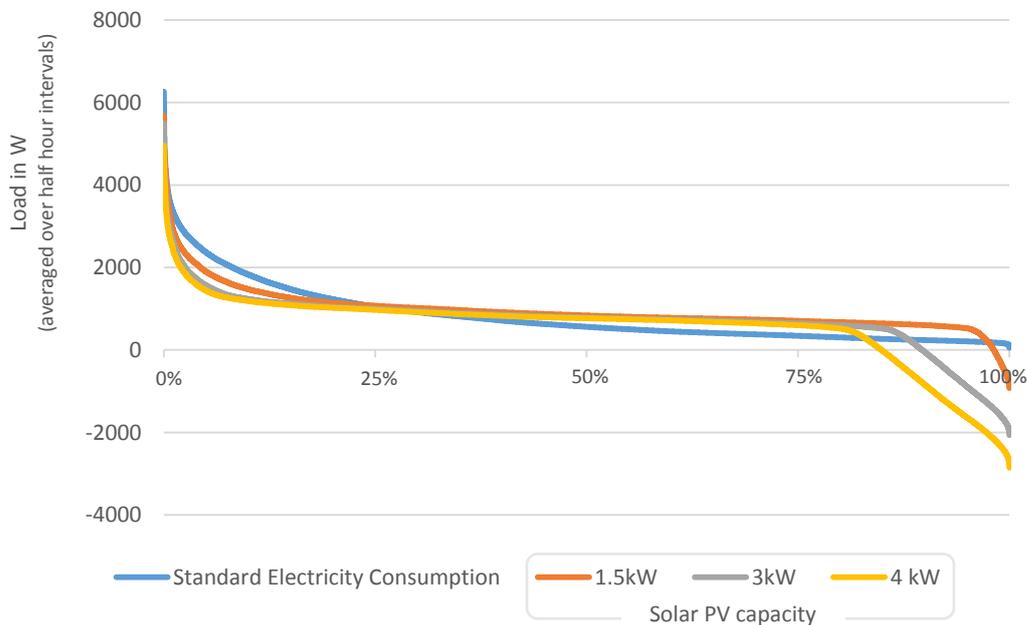


Figure 7.13: Mean annual load duration curves of all households with a home energy storage system and an electric vehicle following the *co-op* charging strategy, with various sized solar PV systems.

The second simulated scenario, assumes that the technologies are used to achieve the greatest cost savings. This is achieved by simulating the EV and HESS to follow the *saver* strategy. Since these technologies are consumer driven, it is more likely households adopt this scenario. In this scenario, the net value after a 10-year period is approximately -\$1905, \$986, and \$2093, with a 1.5, 3, and 4 kW solar PV system, respectively. This low net value is due to the HESS providing an additional \$1268, \$2679, and \$3513 in gross savings, however the upfront costs of this technology is significantly higher. Another finding from this simulation was that the HESS brought little to no benefit for the EV, as the HESS would prioritise reducing household load over charging the EV, as it yields approximately 3.6 cents⁶⁶ more savings per kWh. There are cases where the HESS could be used to charge EVs, such as if the HESS needed to discharge additional capacity to avoid excess solar energy being exported to the grid. However, the HESS would typically use all of its stored energy before the solar PV system began generating energy.

7.4 Summary

This chapter discussed how the adoption of solar PV systems, HESSs and EVs can impact a household's electricity consumption.

The first section of this chapter discussed the benefits and limitations of including a solar PV system in a household. It became evident that only a portion of the generated energy from a solar PV system is typically consumed by the majority of simulated households, because of a relatively low energy demand during solar generation times. In addition, the household's self-consumption was not increased with more solar PV capacity for the majority of households, since additionally generated energy was typically only utilised during the start and end of generation times. Thus, solar PV systems are of more value to households with a high level of self-consumption. Furthermore, the results show that self-consumption

⁶⁶ A kWh of stored energy will displace approximately 900 watts of household load saving 25.857 cents at 28.73 cents per kWh whereas charging an electric vehicle will divert 900 watts at charging at 24.72 cents per kWh saving only 22.248 cents which is 3.6 cents less.

results in a large drop in electricity consumption from the grid during midday, and little to no reduction in peak demand, since peaks typically occur in the afternoon.

In the second section of this chapter, the inclusion of an HESS and its capacity to store solar energy, grid electricity and displace grid energy was discussed. Two scenarios were simulated with the inclusion of an HESS in a household: with and without solar PV. It became evident that in a household without solar PV, an HESS which follows the *co-op* or *hybrid* charging strategy can reduce daily peak demand significantly (by 54 or 34 %) and annual peak demand (by 11 or 8 %). However, households are not currently incentivised to follow the *co-op* or *hybrid* charging strategy and, therefore, it is more likely for them to use a *saver* strategy. Using a *saver* strategy could increase the mean daily and annual demand (by 200 and 55 %), and cause an overall more fluctuant load profile. In the second simulated scenario, where the HESS was simulated in a household with solar PV, it became evident, that excess solar energy could be fully or mostly stored in the HESS. However, only storing solar energy results in the HESS utilising less than half of its battery capacity.

The third section analysed the impact of an EV on the household's electricity demand. The EV followed four different charging strategies in the simulation: *greedy*, *saver*, *slow* and *co-op*. It became evident that EVs increase a household's energy demand by approximately 40%. When using the *greedy* and *saver* strategy, significant fluctuations were visible, as well as a significant daily and annual increase of peak demand. The *co-op* and *slow* strategy show less fluctuations and an overall smoother load. Regarding the value of EVs to consumers, it became evident that the fuel cost of the EV is approximately half of an internal combustion vehicle, with the highest energy costs attributed to the *greedy* strategy and the lowest costs attributed to the *saver* strategy. Using an EV in a scenario with solar PV showed that only a small portion of excess solar energy can be used by the EV, since the vehicle is typically unplugged during high generation times. Using an EV in a scenario with solar PV and an HESS in the *co-op* setting, benefitted the household load by decreasing overall fluctuations in electricity demand. Furthermore, the HESS brought no benefit for the EV in the *saver* strategy as the HESS prioritised reducing household load rather than charging the EV, as this

yields more savings. Regarding the value to consumers, it was evident that even if all three observed technologies are prioritised to achieve maximum cost savings, the current upfront cost of the HESS results in an overall net loss.

Chapter 8

Community Simulation

“Real, sustainable community change requires the initiative and engagement of community members”

— Helene D. Gayle

Throughout human history the behaviour of members inside a community has had the potential to either benefit or harm that community. This could be in the form of political engagement such as a petition towards heritage preservation, in form of social engagement such as supporting marginalised groups in the community, or technological engagement such as community members adopting disruptive technologies.

This chapter analyses how households that integrate new technologies can impact a community of households; specifically, the community’s electricity consumption. The technologies analysed are solar PV systems, home energy storage systems (HESSs), and electric vehicles (EVs), as they were suggested to be most disruptive in Section 2.6. To understand the extent of this impact, different adoption levels of these technologies were simulated on electricity consumption of a community of households. This simulation was achieved using the household electricity usage simulation tool (HEUS) with electricity consumption data produced from the household modelling approach described in Section 5.4. The

simulated community consisted of 100 households, while the different adoption levels of each technology was 10, 50, and 100 %. These adoption levels represent scenarios where 10%, half, or all households in the community have these technologies. The number of households (100) represents a medium size block of households in Hamilton, New Zealand ⁶⁷. The electricity prices are based on real electricity prices available for these households, as shown in Table 7.1. The analysis of the simulation results is split into three main sections which focus on each of the technologies, and are described as follows.

8.1 Solar PV Systems

The results of Chapter 7 suggest that solar PV systems are economically viable for most households⁶⁸. It also becomes evident that this technology has a relatively high upfront cost, which has been a barrier preventing a major uptake. However, this cost is steadily decreasing which can lead to a larger uptake as more households install a solar PV system. The results from Chapter 7 also show that for an individual household the installation of a solar PV system has minimal impact on reducing its daily and peak demand, and causes a larger fluctuation in grid electricity consumption. This section provides insight into the impact on a community's electricity consumption when installing solar PV systems at 10, 50, and 100 % of households in that community. The solar PV system simulated for each household has a 3kW capacity⁶⁹, with the characteristics shown in Table 7.2. Two main findings were evident from these simulations, related to the level of solar energy typically consumed within the community, and how solar PV systems alter the community's electricity consumption. These two findings are explained as follows.

⁶⁷ Based on an analysis of *meshblocks* in Hamilton, New Zealand from the 2013 Census meshblock dataset (available at www.stats.govt.nz).

⁶⁸ Based on the results from Chapter 7, where 15 of 16 households had a net gain with a solar PV system in a 25-year period.

⁶⁹ The 3kW solar PV system was shown in Chapter 7 to have the greatest mean savings for individual households.

8.1.1 Solar Energy

The results from the simulations, as shown in Table 8.1, make evident that if only a small share of households install a solar PV system, any generated energy which is not consumed directly by the household, can be distributed within the community. However, if there is a larger uptake, there are periods where this technology will generate more energy than the community can consume. This is shown in the 50 and 100 % adoption levels, where approximately 12 and 41 %, respectively, of the generated energy is not consumed within the community. If this community has no energy storage capabilities, any excess generated energy is likely to be exported to the grid.

Table 8.1: Solar energy generated and exported, and grid electricity consumed in a community of 100 households.

	Percentage of households with a solar PV system		
	10%	50%	100%
Energy generated (MWh)	40	202	405
Exported energy (MWh)	0	23	168
Grid energy (MWh)	643	505	446
Daily peak demand change (%)	-0.37	-0.64	-0.74
Annual peak demand change (%)	0	0	0
Standard deviation change (%)	3.92	58.68	161.40

8.1.2 Grid Energy

Due to the intermittent and non-dispatchable behaviour of solar energy, only electricity consumption during generation times can be directly reduced. This restriction in reducing electricity consumption can have negative consequences, particularly with larger numbers of solar PV systems, as it creates a large dip in

electricity consumption during solar generation times, as shown in Figure 8.1. Additionally, since daily peak demand typically occurs in the afternoon, solar PV systems have little impact on reducing peak demand. This is shown in the simulated scenarios with 10, 50, and 100 % adoption levels where no reduction in daily peak demand could be observed for approximately 300 days of the year. Similarly, an overall mean reduction in the daily peak demand of only 0.39, 0.68, and 0.79 % with 10, 50, and 100% adoption levels, respectively, was evident. Furthermore, there was no reduction in annual peak demand, and very little reduction (<5%) of the highest 1000 peak demand half-hour periods of the year, as shown in Figure 8.2. These dips in electricity consumption and no change in peak demand result in a significantly different load profile, as shown in Figure 8.2. These results make evident that the inclusion of solar PV technology has no impact in reducing the infrastructure needed to supply electricity to the simulated community, as there is no change in peak demand. Furthermore, additional infrastructure could be required to export excess solar energy out of the community.

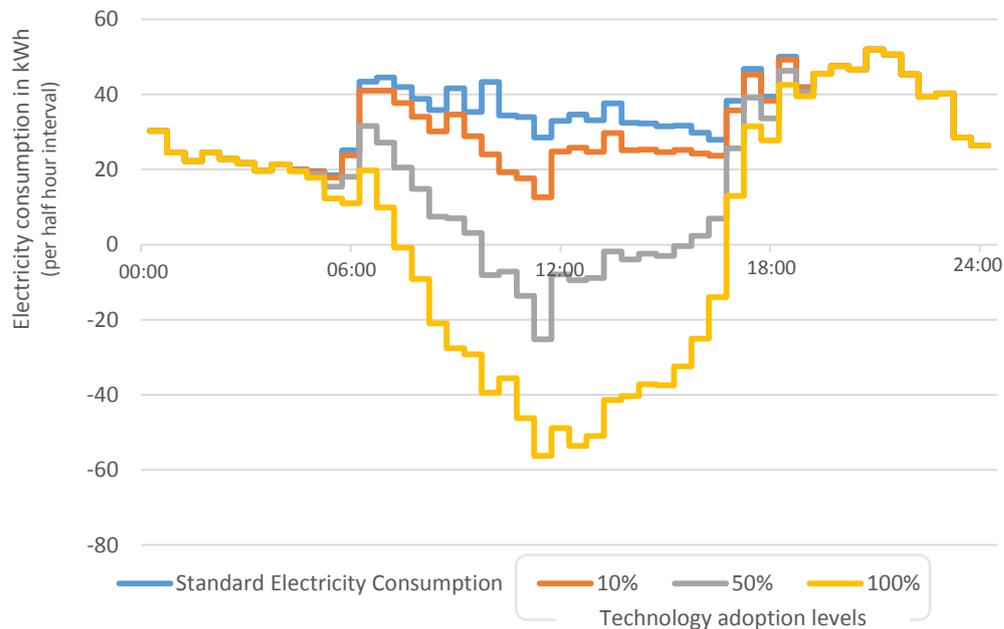


Figure 8.1: Grid load profile for a random day in the year of a community of households for different adoption levels of solar PV.

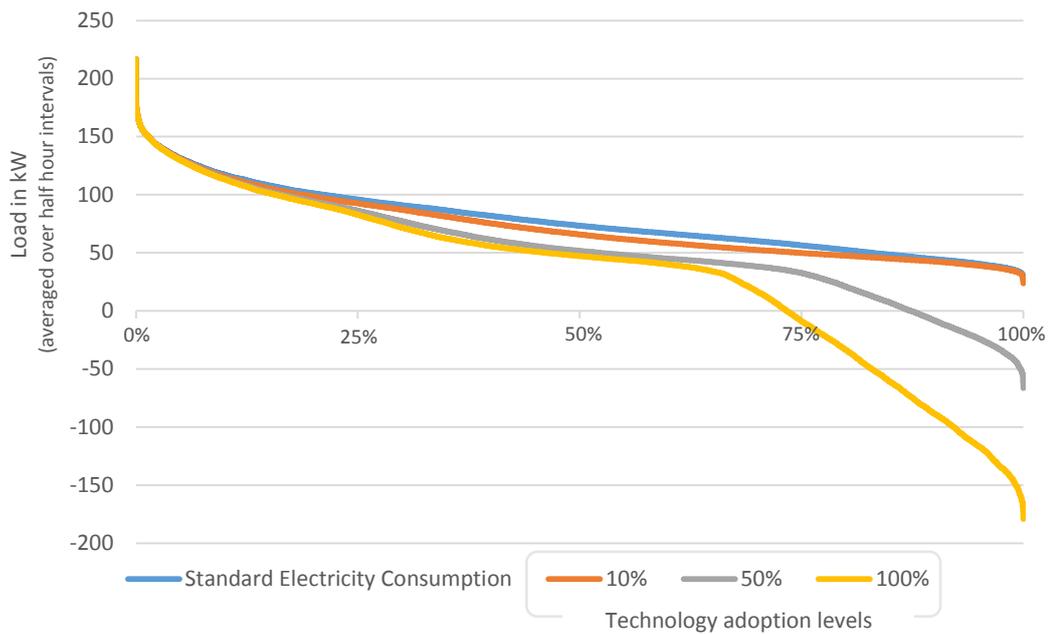


Figure 8.2: Annual load duration curves for a community of households for three different levels of installed solar PV.

8.2 Home Energy Storage Systems

The installation of energy storage in a community of households allows that community to utilise excess solar energy and store grid electricity for future consumption. This has the potential to significantly alter how the community consumes and supplies electricity from and to the grid. This section describes the results from simulating HESSs in a community of households using the HEUS simulation tool. The HESSs are based on the Tesla Powerwall 2 AC, as described in Table 7.4. Two different scenarios were simulated; a scenario without solar PV, and a scenario with varying levels of installed solar PV. The findings from these two scenarios are discussed as follows.

8.2.1 Storage without Solar PV

In the first scenario HESSs are installed without solar PV systems. Three different charging strategies were simulated: *co-op*, which focuses on smoothing load, *saver*,

which charges and discharges for optimal cost savings, and *hybrid*, which is a combination of both, as explained in Section 6.2. In the *co-op* and *hybrid* strategy, the HESSs are utilised to smooth load to a moving average (this is known as the *limit*), based on the mean electricity consumption of the previous week. These simulations produced two main findings which are related to the change in grid electricity consumption and the change in annual and daily peak load, explained in further detail below.

Grid Energy – Different charging strategies for HESSs significantly differ in their impact on electricity consumption from the grid. With a strategy which is prioritised to smooth electricity consumption, there is an overall reduction in fluctuation, allowing for a more predictable and steady electricity demand. This is most evident if HESSs follow the *co-op* strategy. In this strategy, the batteries store and shift a large amount of energy, as shown in Table 8.2. This shifting causes a much smoother load, which is shown with a flatter annual load duration curve in Figure 8.3. Furthermore, the results show that there is little to no significant benefit in adding more than 16% of HESSs in a *co-op* or *hybrid* strategy. This is due to a finite number of half hour periods where electricity consumption is below *limit*, and consequently, a finite amount of electricity the HESSs can store, as shown in Figure 8.4.

Table 8.2: Annual energy stored with different levels of installed home energy storage systems.

		Number of home energy storage systems in a community (%)								
		10	12	14	16	18	20	30	50	100
Energy stored (MWh)	<i>co-op</i>	64.3	71.8	77.3	81.2	83.7	85	87	87.4	87.4
	<i>hybrid</i>	49.1	56.7	61.5	63.9	64.8	65	65	65	65

It is also evident from these results that if the HESSs are prioritised to smooth load, they are capable of significantly reducing energy fluctuations, however, it is more likely that the technology will be prioritised to achieve maximum cost savings, as they are consumer driven, discussed in Section 7.2. Prioritising cost savings will cause a massive disruption to how the community consumes electricity from the grid, particularly if there is a large uptake of this technology. This disruption can be seen in the annual load duration curves for the *saver* strategy, particularly in the 50 and 100 % adoption levels, as shown in Figure 8.3. At these adoption levels, approximately 36 and 70 % of the community's annual electricity consumption is shifted, respectively. This large shift is due to the HESSs charging at full charge rate when energy prices are low and discharging at full discharge rate when prices are high. Furthermore, this behaviour causes a large increase in electricity demand for approximately 13% of half hour periods, and a complete displacement of electricity consumption from the grid for 34 and 61 % of half hour periods, in the 50 and 100 % scenarios, respectively. It is evident from these results that the *saver* strategy would likely bring a change in electricity pricing, as supplying electricity to such a load profile would be immensely expensive and inefficient.

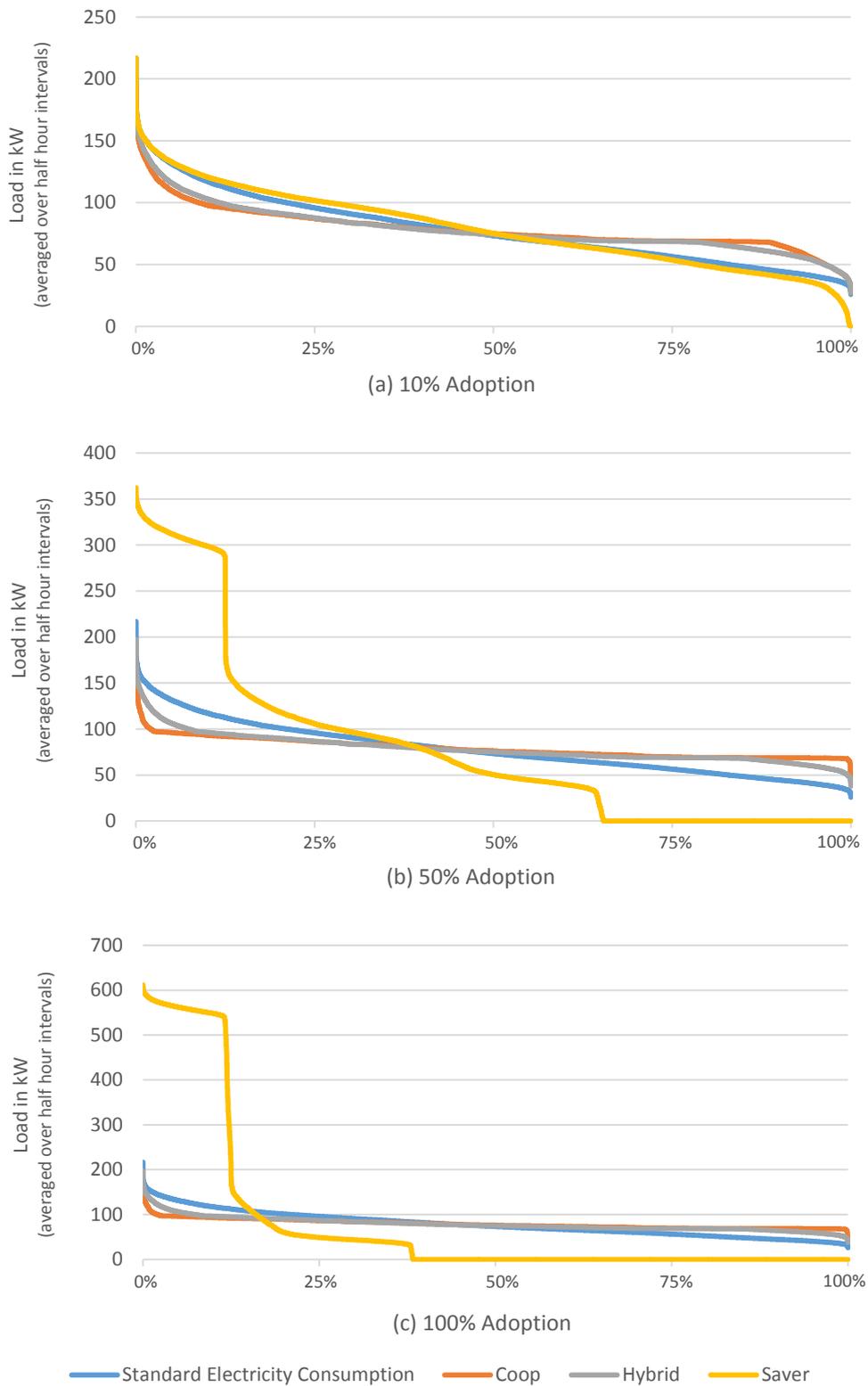


Figure 8.3: Annual load duration curves for a community of households for three different levels of installed home energy storage systems, in each case showing the effect of the three different charging strategies discussed.

Peak load – In a scenario where the HESSs follow a *co-op* or *hybrid* charging strategy there is an overall reduction in the community’s daily and annual peak load, as shown in Table 8.3. The most evident reduction occurs in the 50% adoption level, following the *co-op* strategy. At this level, the annual peak load is reduced by over 22% and there is a mean reduction in daily peak load by approximately 30%. Furthermore, there is no difference between the 50 and 100 % scenarios, due to the limitations in charging the HESSs in the *co-op* and *hybrid* strategy, as discussed previously. If the HESSs follow the *saver* strategy, there is a significant increase in daily peak and annual peak demand. This large increase is a result of the HESSs charging at maximum charge rate when electricity prices are low, as shown in Figure 8.5. This behaviour can add a substantial strain on the electricity infrastructure, and incentivise more power plants that can generate high levels of electricity for a short period of time e.g. fossil fuelled power plants.

Table 8.3: Daily and annual peak demand change with home energy storage systems for different strategies.

		Percentage of households with a home energy storage system		
		10%	50%	100%
Daily peak demand change (%)	<i>co-op</i>	-12.62	-30.3	-30.3
	<i>hybrid</i>	-5.49	-9.86	-9.86
	<i>saver</i>	6.67	158.77	355.28
Annual peak demand change (%)	<i>co-op</i>	-9.02	-22.84	-22.84
	<i>hybrid</i>	-9.02	-9.02	-9.02
	<i>saver</i>	0	67.03	182.33
Standard deviation change (%)	<i>co-op</i>	-39.07	-62.3	-62.3
	<i>hybrid</i>	-31.26	-45.07	-45.07
	<i>saver</i>	12.55	248.91	540.66

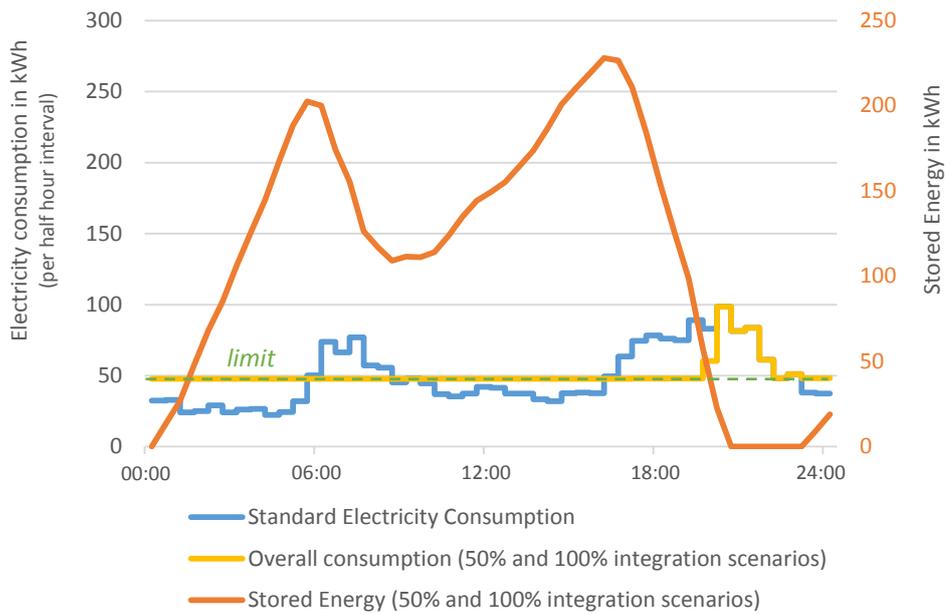


Figure 8.4: Energy stored in the home energy storage systems in a typical day following the *co-op* strategy. The 50 and 100 % adoption levels are identical due to the limitations in charging and discharging to the *limit* (7-day moving average).

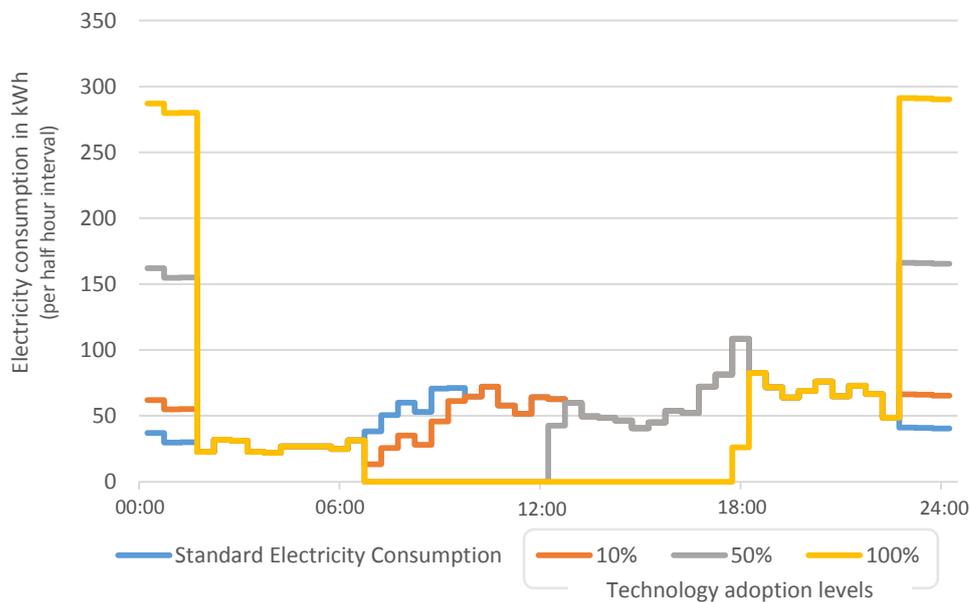


Figure 8.5: Electricity consumption in a typical day with different adoption levels of home energy storage systems following the *saver* strategy.

8.2.2 Storage with Solar PV

In the second scenario HESSs are installed with solar PV systems which were prioritised to achieve maximum cost savings. Furthermore, the HESSs would only charge with solar energy during low electricity prices, and with excess solar energy during high electricity prices. Three different adoption levels were simulated; 10, 50, and 100 %. Three main findings were evident from the simulation results, which are related to the amount of solar energy potentially exported from the community, the utilisation of HESSs, and the change in electricity consumption from the grid. These three findings are explained as follows.

Excess Solar Energy - In the 10 and 50 % adoption levels, all the generated energy is consumed or stored within the community, while in the 100% scenario, on a clear summer day the amount of generated energy would be significantly larger than standard electricity consumption, as shown in Figure 8.6. This would result in the storage of excess solar energy. Furthermore, if the HESSs reach full capacity solar energy can be exported to the grid, as shown in Figure 8.7. However, this only occurred on 12 days in the year, resulting in a less than 1% export of solar energy.

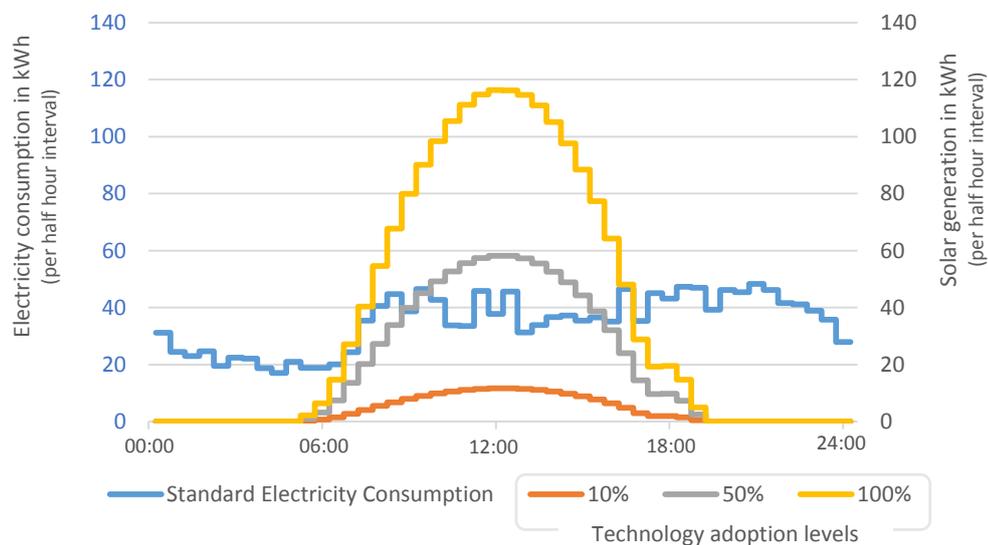


Figure 8.6: Energy generated with varying adoption levels of solar PV systems on a typical clear summer day compared to the standard electricity consumption from the community of households.

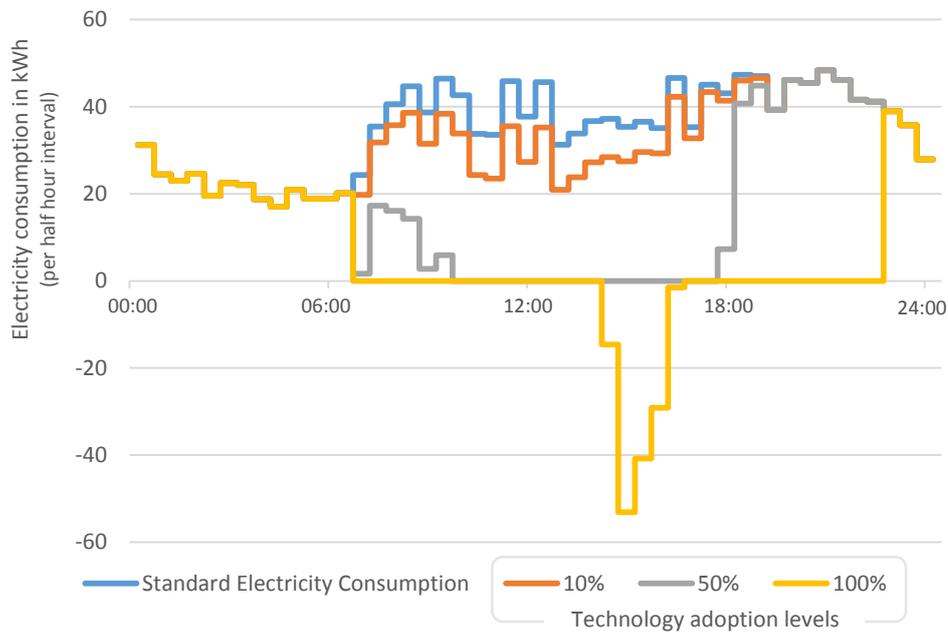


Figure 8.7: Electricity consumption on a typical clear summer day with solar PV systems coupled with home energy storage systems, with varying levels of adoption. Negative consumption corresponds to electricity exported to the grid.

Table 8.4: Annual energy generated from solar PV systems and solar energy stored in the home energy storage systems in a community of households.

	Percentage of households with a solar PV system and a home energy storage system		
	10%	50%	100%
Energy generated (MWh)	40.53	202.66	405.33
Energy stored (MWh)	0.45	18.13	149.99
Energy storage potential (MWh) ⁷⁰	49.28	246.38	492.75
Exported solar energy (MWh)	0	0	2.94
Annual peak demand change (%)	0	0	0
Daily peak demand change (%)	-0.35	-0.64	-13.79
Standard deviation change (%)	3.22	44.07	51.15

⁷⁰ Assuming each HESS does one cycle (13.5 kWh) for each day in a year.

Solar Energy – At a 10% adoption level there are no instances where energy, generated from the solar PV systems, exceeds the community's electricity consumption. Therefore, the HESSs only charge with solar energy in the morning before 7 am when electricity prices are low⁷¹. However, since solar PV systems generate little to no energy before 7am in most seasons, just over 1% of total generated energy is stored, resulting in the HESSs only utilising approximately 1% of its storage potential⁷², as shown in Table 8.4. Similarly, in the 50 and 100 % adoption levels, the HESSs only utilise 7.3 and 30 % of their storage potential, respectively, when only charging with solar energy. These results show that at these adoption levels if the HESSs only charge with solar energy, the same results could be achieved with approximately a third of the capacity.

Grid Load – Across all adoption levels, particularly with the 10 and 50% adoption levels, there is an increase in energy fluctuations, which is evident in the annual load duration curves, as shown in Figure 8.8. Furthermore, since peak demand typically occurs in the afternoon, when there is no sunshine, there is no reduction in annual peak and only a slight reduction in daily peak load, as shown in Table 8.4. However, if the HESSs were fully utilised and charged with grid electricity during low electricity prices, there would be a significantly larger increase in peak load, as shown in the *saver* strategy in Section 8.2.1.

⁷¹ Since it provides more cost savings to store solar energy than diverting electricity consumption when electricity prices are low.

⁷² Compared to a scenario where the HESSs charge to their full capacity each day.

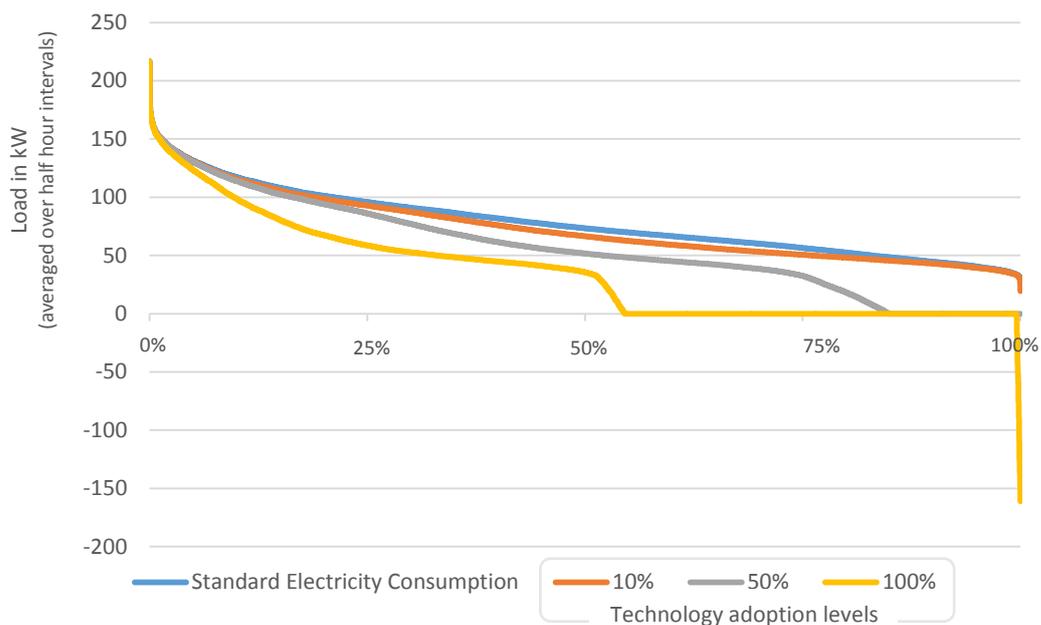


Figure 8.8: Annual load duration curves for a community of households with solar PV and home energy storage systems utilising the *saver* strategy, with varying levels of adoption. Negative value represents rare cases where the home energy storage systems are too full to store solar energy.

8.3 Electric Vehicles

The transition from internal combustion vehicles to EVs has the potential to significantly alter how individual households consume electricity, as shown in Chapter 7. This section describes the impact EVs have on a community level when 10, 50 or 100 % of households use an EV. The analysis is based on simulating various adoption levels of EVs in a community of 100 households using the HEUS simulation tool. The EV is based on a mid-range model, described in Table 7.5, and its behaviour is calculated using the approach described in Section 6.4. The analysis produced three main findings, related to how EVs impact the community's electricity consumption, how EVs perform with solar PV systems, and the benefits of adding all three technologies (solar PV systems, HESSs, and EVs) in a community. These results are explained as follows.

8.3.1 Grid Energy

The adoption of EVs in a community of households will add approximately 4.4, 21.5, and 43 % of additional electricity demand, when 10, 50, and 100 % of households include an EV, respectively⁷³. In a community with no distributed generation it is evident that the charging behaviour of these EVs will have a significant impact on how the community consumes electricity from the grid. To understand the extent of this impact, four different charging strategies were simulated: *greedy*, which charges at maximum charge rate until it has reached its goal capacity, *saver*, which charges at maximum charge rate at a low electricity price (between 11pm and 7am in this simulation) until it has reached its goal capacity, *slow*, which splits the needed energy evenly until the vehicle is unplugged, and *co-op*, which uses the EV's battery to smooth electricity consumption (using vehicle-to-grid technology) while ensuring it reaches its goal capacity before it is unplugged.

In the *greedy* strategy, the EVs charge at their full charge rate as soon as they are plugged in. It is evident from the simulation results that this behaviour causes a substantial variation in electricity consumption during the day, and increases daily and annual peak demand, as shown in Figure 8.9b and Table 8.5. If the EVs follow the *saver* strategy, almost all of the charging occurs in the first hour of the lowest electricity price in each day. This is evident in the annual load duration curve, with a noticeably high load of approximately 700 half hour periods, as shown in Figure 8.9a. This charging strategy causes the largest increase in daily and annual peak load, and an overall larger variation in grid load compared to other strategies, as shown in Table 8.5. In a scenario where the EV's charging is more controlled, there is a potential to distribute the additional electricity demand to reduce the overall impact of charging EVs. This can be seen in the *slow* strategy, where an EV distributes the energy requirements evenly until it is unplugged. This behaviour causes a daily peak increase which is approximately half that of the *greedy* strategy,

⁷³ Assuming each electric vehicle's annual load is 2941 kWh, as discussed in Section 7.3.1, and a community of 100 households has an annual load of 683810 kWh, a generated value using the modelling approach described in Section 5.4.

and an annual peak increase which is significantly lower than that of the *greedy* strategy, as shown in Table 8.5. Furthermore, since the community’s electricity consumption is relatively low during the early and late hours of the day, charging the EVs in the *slow* strategy in the 10 and 50 % adoption level provides an overall smoother load when compared to the standard electricity consumption, as shown in Figure 8.9c and Figure 8.10.

Table 8.5: Daily and annual peak demand change, and standard deviation change, when integrating electric vehicles in a community of households.

		Percentage of households with an electric vehicle		
		10%	50%	100%
<i>greedy</i>	Daily peak demand change (%)	8.98	46.26	94.01
	Annual peak demand change (%)	6.92	44.6	159.89
	Standard deviation change (%)	9.48	56.31	123.82
<i>saver</i>	Daily peak demand change (%)	5.47	147.8	333.67
	Annual peak demand change (%)	0	63.54	172.94
	Standard deviation change (%)	2.87	106.5	286.75
<i>slow</i>	Daily peak demand change (%)	2.8	14.67	31.34
	Annual peak demand change (%)	1.06	3.91	10.84
	Standard deviation change (%)	-1.35	-0.79	12.67

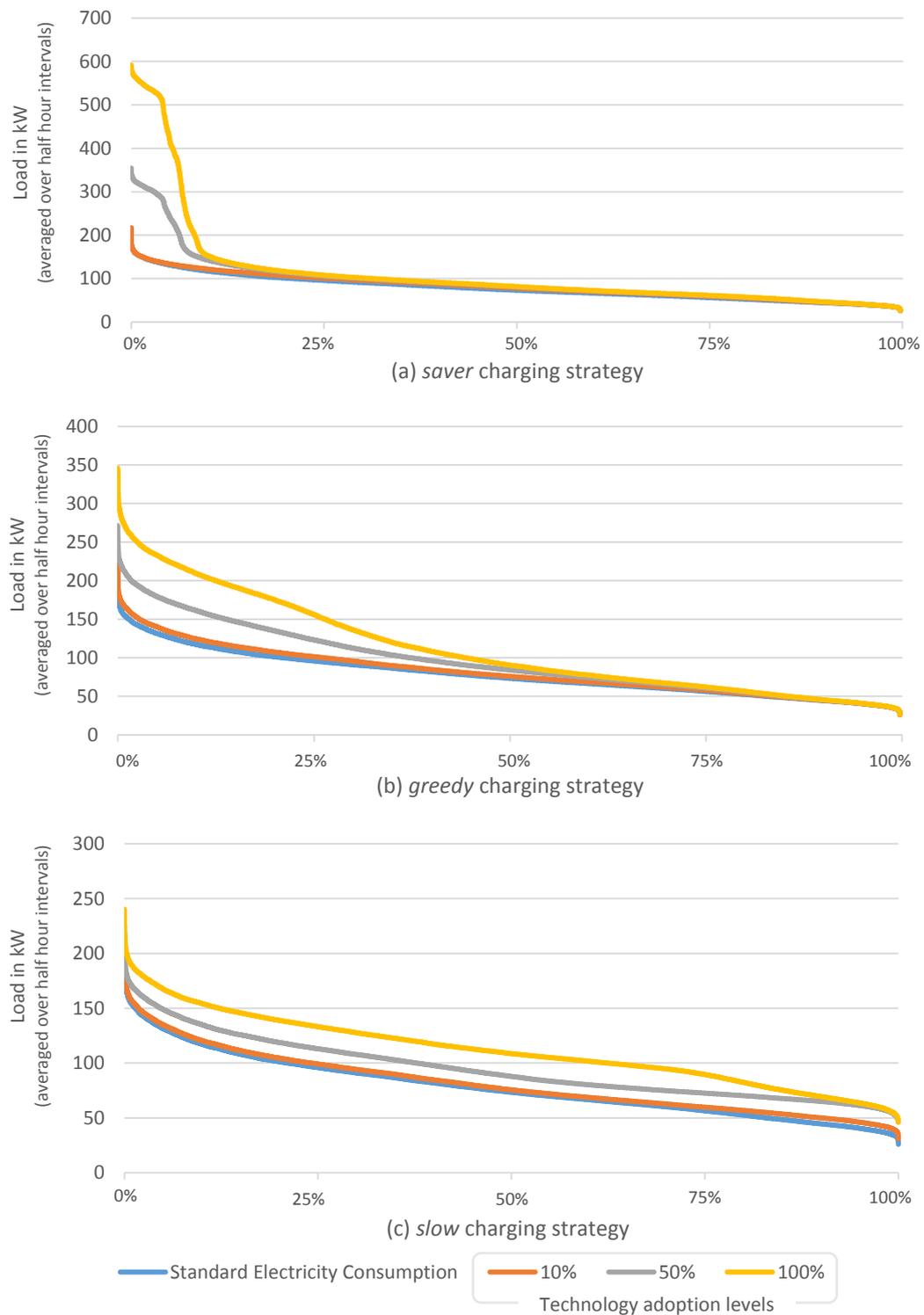


Figure 8.9: Annual load duration curves for a community of households with electric vehicles following the three charging strategies discussed, with different levels of adoption.

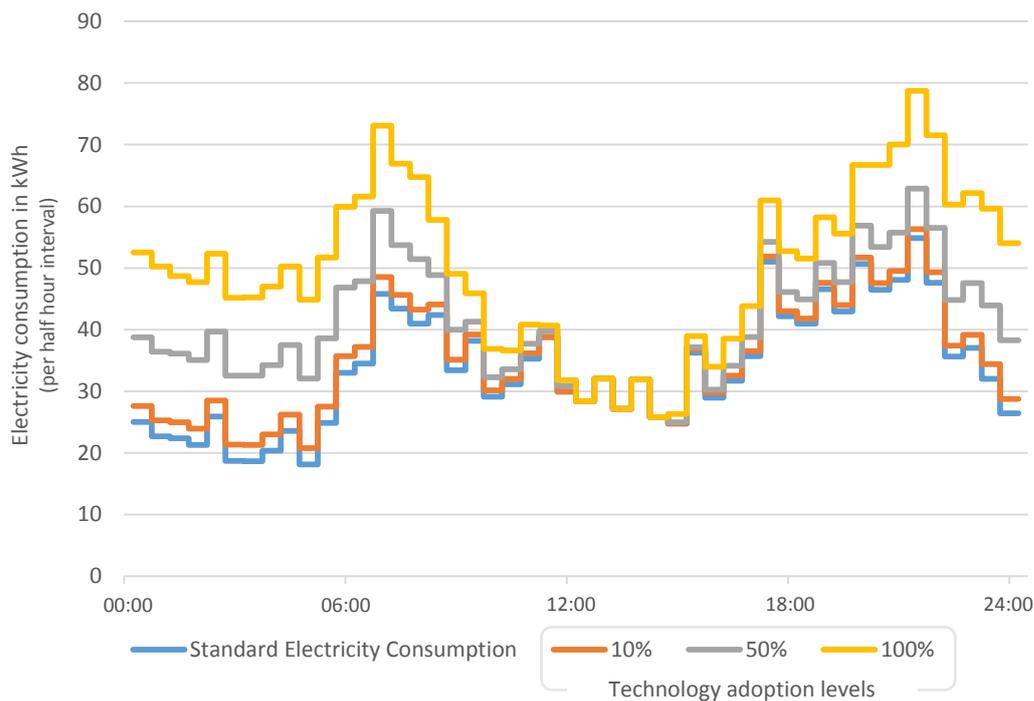


Figure 8.10: Electricity consumption for a community of households with electric vehicles utilising the *slow* strategy, for different adoption levels of EVs.

If EVs incorporate vehicle-to-grid technology, there is the potential to significantly reduce the negative impacts of charging EVs and bring benefits to the community e.g. utilising stored energy in EVs to reduce peak demand. A strategy which simulates vehicle-to-grid technology is the *co-op* strategy. In this strategy, energy is discharged from the EV's battery to smooth the community's electricity consumption to *limit* (7-day moving average). Interestingly, the amount of energy discharged by EVs decreases with higher adoption levels, as shown in Table 8.6. This is because the *limit* increases in higher adoption levels to account for the additional electricity demand from the EVs, as shown in Figure 8.11. This higher *limit* results in less electricity consumption exceeding *limit*, and consequently, less discharging of EVs. This adjustment of *limit* allows the EVs to charge and discharge accordingly, resulting in an overall smoother load, as shown in Table 8.6 and Figure 8.12. Furthermore, this smoothing causes a reduction in daily peak demand

in the 10 and 50 % adoption levels and a slight increase in daily peak demand at the 100% level. Similarly, the annual peak is reduced in all adoption levels.

Table 8.6: Simulation of electric vehicles following the *co-op* strategy in a community of 100 households.

	Percentage of households with an electric vehicle		
	10%	50%	100%
Standard deviation change (%)	-40.4	-39.49	-25.4
Annual peak demand change (%)	-6.92	-7.57	-11.17
Daily peak demand change (%)	-4.93	-2.79	5.03
Discharged amount (MWh)	56.83	33.86	15.38

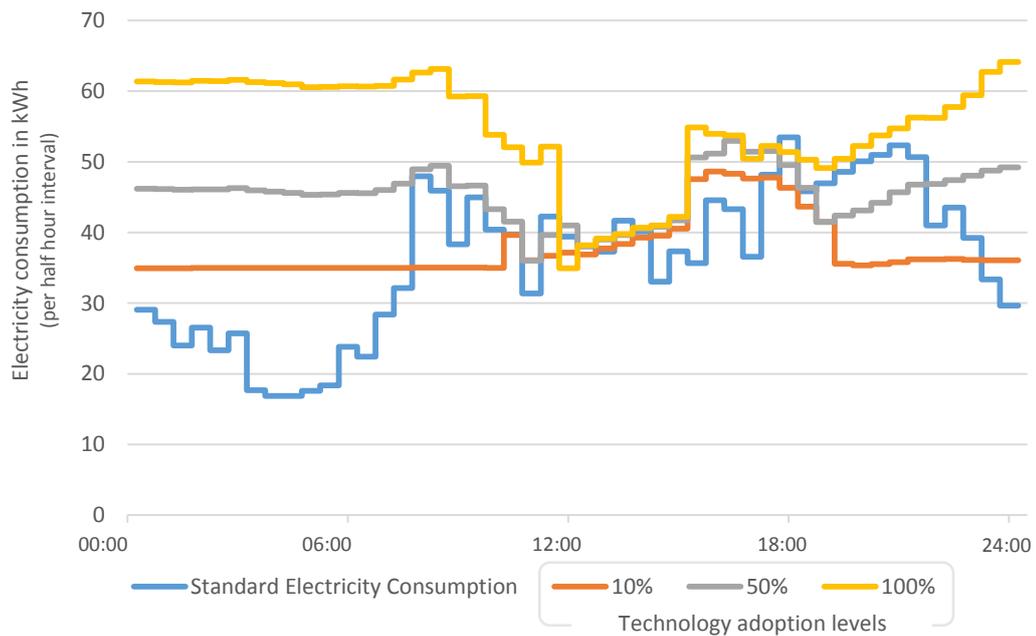


Figure 8.11: Comparison of electricity consumption for different adoption levels of electric vehicles, following the *co-op* strategy on a random day of the year. The decrease in electricity consumption around midday is caused by electric vehicles being unplugged, while the slow increase in consumption is a result of electric vehicles plugging into the households.

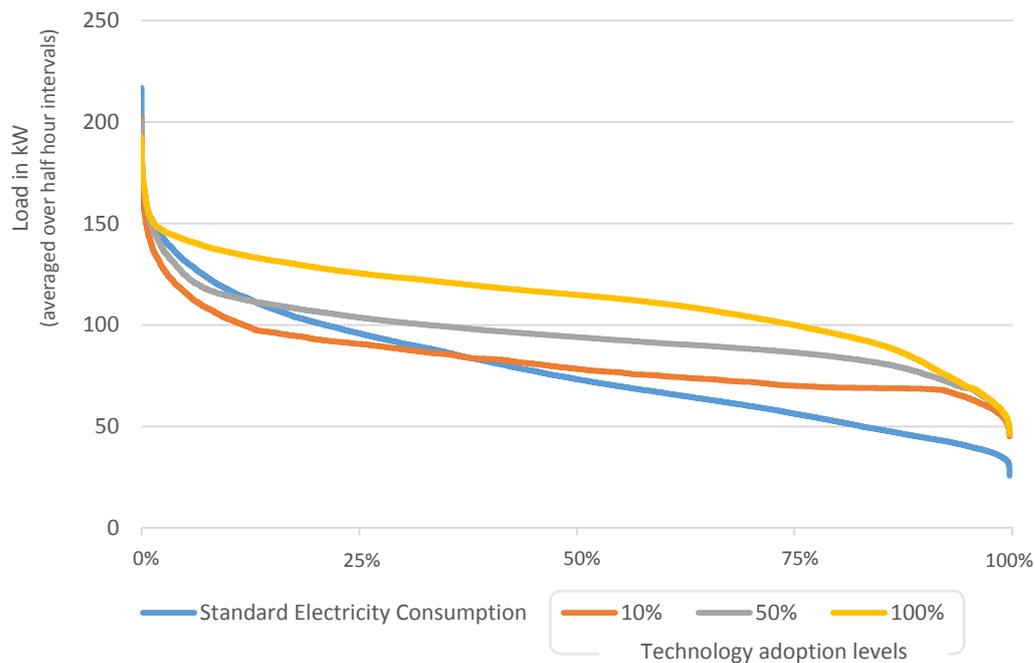


Figure 8.12: Annual load duration curves for a community of households with electric vehicles following the *co-op* charging strategy, with different levels of adoption.

8.3.2 Electric Vehicles with Solar PV

Incorporating EVs in a community with solar PV provides potential storage capabilities to that community, which can be used to smooth grid load and utilise solar energy more efficiently. To analyse the extent of this impact different adoption levels of EVs and solar PV were simulated in a community of households. The EVs are based on mid-range models, described in Table 7.5, while the solar PV systems are based on a 3kW system with characteristics shown in Table 7.2. Two different charging strategies, the EV follows, were simulated. The first scenario (*saver*) assumed EVs would charge during the cheapest period of the day at their full charge rate, while the second scenario (*co-op*) utilised the EV's battery to smooth household load while ensuring there is enough stored energy to meet the energy requirements for the next trips. In the first scenario, solar energy is prioritised to

reduce all grid load before charging an EV, as it yields more savings⁷⁴, while in the second scenario, solar energy is used to smooth grid load before charging the EV. The findings from both scenarios are explained as follows.

Solar Energy – Integrating 10, 50, or 100 EVs in a community of 100 households will add approximately 4.4, 21.5, and 43 %, additional electricity demand, respectively. In a community with solar PV and EVs following the *saver* strategy, the additional demand of EVs is met entirely with grid electricity at a 10% adoption level. This is a result of utilising all solar energy to reduce standard electricity consumption. At the 50 and 100 % adoption level, approximately 7.8 and 28.6 %, respectively, of the EVs’ energy demand is met with solar energy, as shown in Table 8.7. Furthermore, since these EVs utilise solar energy, approximately 50% less solar energy is exported, when compared to a scenario without EVs. Although, theoretically the EVs had enough storage capabilities to store all excess solar energy, solar energy was exported during midday when most or all EVs were unplugged. In the *co-op* scenario, as shown in Table 8.8, approximately 31, 57, and 62 % of the EVs’ energy demand is met by solar energy, at a 10, 50, and 100 % adoption level, respectively. This amount of solar energy, stored in the EVs, is significantly more than in the *saver* scenario. This is because EVs charge with solar energy when standard electricity consumption is below *limit*, whereas, in the *saver* scenario solar energy is used to displace all standard electricity consumption. Furthermore, in this scenario, the amount of solar energy that is potentially exported, is similar to the *saver* scenario, as the EVs follow the same travel behaviour i.e. plug in and out at the same time.

⁷⁴ Replacing one kWh of grid load with solar PV energy will save 28.73 cents, whereas, the savings will be less when charging an electric vehicle, since charging of an electric vehicle is typically done during cheaper price periods (24.72 cents/kWh).

Table 8.7: Simulation of electric vehicles and solar PV in a community of 100 households utilising a *saver* strategy.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Energy demand from electric vehicles (MWh)	29.4	147	294
Solar energy consumed by EVs (MWh)	0	11.4	84
Exported solar energy (MWh)	0	11.6	84
Standard deviation change (%)	8.57	140.81	287.06
Daily peak demand change (%)	5.25	136.35	253.62
Annual peak demand change (%)	0	60.45	169.62

Table 8.8: Simulation of electric vehicles and solar PV in a community of 100 households utilising a *co-op* strategy.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Energy demand from electric vehicles (MWh)	29.4	147	294
Solar energy consumed by electric vehicles (MWh)	9.11	83.85	182.34
Exported energy (MWh)	0	14.61	94.44
Amount of energy discharged by EVs (MWh)	55.2	54.6	50.97
Annual peak demand change (%)	-9.22	11.44	14.95
Daily peak demand change (%)	-12.59	-18.44	-19.96
Standard deviation change (%)	-36.04	20.86	116
Standard deviation change in electricity consumption for the peak 15000 half hour periods (%)	-46.23	-43.143	-28.7269

Grid Load - In the *saver* scenario, the charging behaviour of the EVs, at a 10% adoption level, causes minimal impact on the community's annual grid electricity demand. However, at higher adoption levels the charging of EVs significantly increases electricity consumption for approximately 1000 half hour periods in a year, as shown in Figure 8.13a. This higher electricity consumption, along with the excess solar energy in higher adoption levels, result in a load profile which is significantly more fluctuant than a community without these technologies. This fluctuation is most evident at a 100% adoption level, where the standard deviation of grid electricity consumption across the year is almost three times larger than a scenario without solar PV and EVs, as shown in Table 8.7. In the *co-op* scenario, the EVs are utilised to smooth electricity consumption from the grid. In this scenario, at a 10% adoption level, the EVs discharge approximately 50 MWh over a year. This energy discharge helps to reduce daily and annual peak load, as shown in Table 8.8, and provides an overall smoother grid load, as shown in Figure 8.13b. At the 50 and 100 % adoption levels, less energy is discharged from the EVs, since the *limit* has increased to account for the additional electricity demand from the EVs. However, at these adoption levels the charging and discharging behaviour of the EVs still provide an overall smoother load for approximately 85% of half hour periods in the year, as shown in Figure 8.13b, and a reduction in the daily peak demand. Furthermore, the annual peak demand increases at higher adoption levels, however, the increase is significantly lower than in the *saver* scenario.

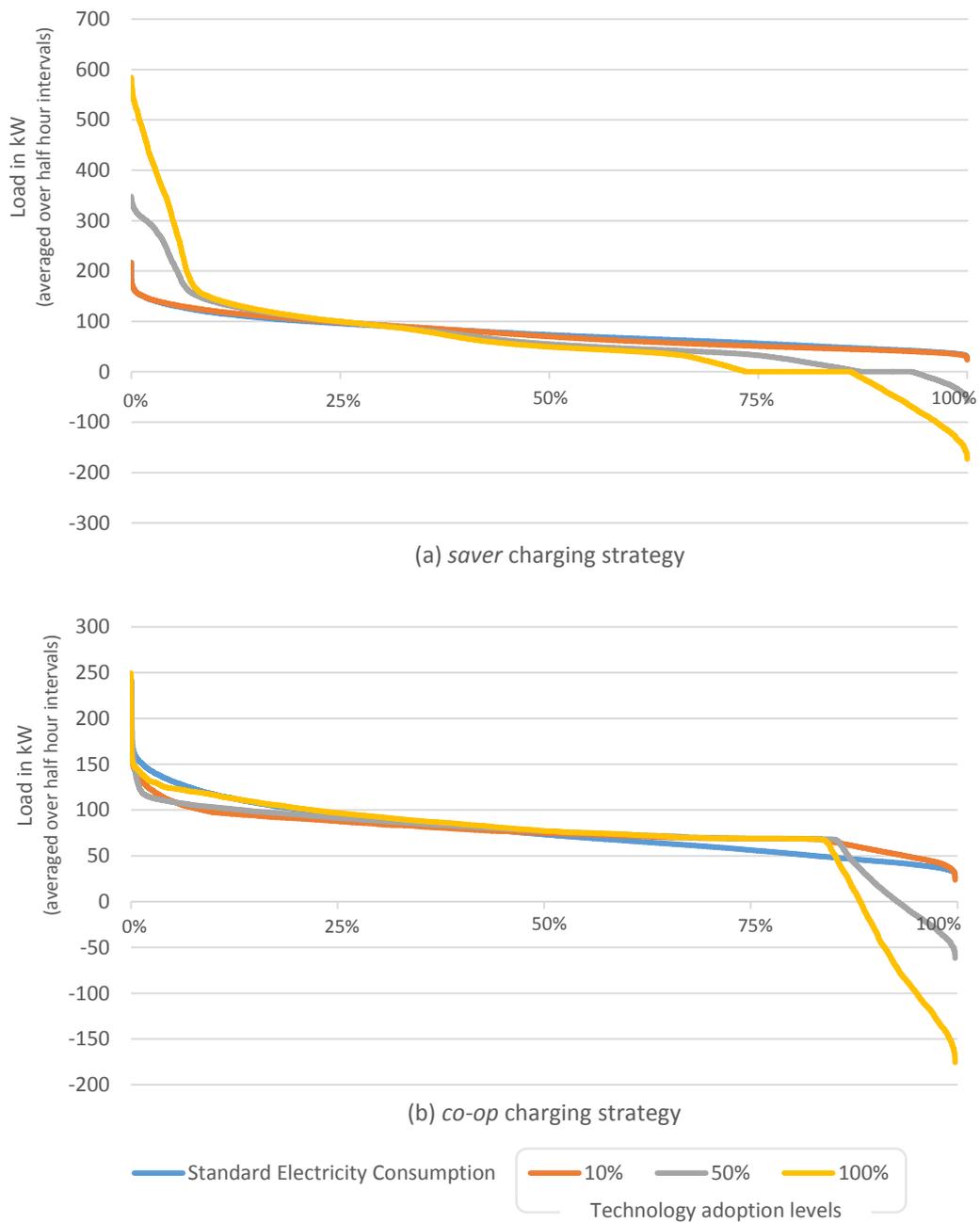


Figure 8.13: Annual load duration curves for a community of households with solar PV and electric vehicles following different charging strategies, with varying levels of adoption.

8.3.3 Electric Vehicles with Distributed Storage and Generation

Incorporating all three technologies in a community provides further possibilities for that community to utilise distributed generation and distributed storage (from the HESS and the EV). To understand the extent of this impact, different adoption levels of EVs, solar PV, and HESSs on a community of households were simulated. The EVs are based on mid-range models, described in Table 7.5, the solar PV systems are based on a 3kW system with characteristics shown in Table 7.2, and the HESSs are based on the Tesla Powerwall 2 AC, as described in Table 7.4. Two different scenarios, explained as follows, were simulated.

The first scenario assumes the technologies are prioritised to smooth household load, rather than achieving cost savings. This is achieved by simulating the EV and HESS to follow the *co-op* strategy. In this scenario, approximately 70 MWh are shifted by EVs and HESSs, as shown in Table 8.9. This energy shifting, results in a reduction of the annual peak demand by approximately 20% and a reduction in the daily peak demand by 28, 38, and 37 %, at a 10, 50 and 100 % adoption level, respectively. Furthermore, this energy shifting provides an overall smoother load for approximately 90% of half hour periods in the year, as shown in Figure 8.14. However, with all three technologies at the 50 and 100 % adoption levels there are still times when solar energy cannot be used or stored within EVs or HESSs. This is largely due to prioritising the technologies to smooth grid load to *limit*. This prioritisation results in charging EVs and HESSs when standard electricity consumption is below *limit*, which can result in these technologies reaching their maximum battery capacity preventing them from storing excess solar energy. A method to utilise more solar energy would be to lower the *limit* so that EVs and HESSs discharge more stored energy, and consequently, utilise more solar energy. This can be seen in a scenario where the *limit* is reduced to 20% of the mean of the previous week's electricity consumption, as shown in Figure 8.15. However, having a low *limit* can cause the electricity consumption from the grid to spike significantly before multiple EVs are unplugged. This is a result of the combination of significantly higher than predicted energy usage and/or significantly lower than

predicted solar energy, and the charging of EVs right before unplugging, to ensure they have enough energy for their next trips. This behaviour causes significantly larger annual and daily peak demands and overall more fluctuations in grid load, as shown in Figure 8.15, compared to a limit set to the 7-day moving average.

Table 8.9: Simulation of electric vehicles, home energy storage systems, and solar PV in a community of 100 households utilising a *co-op* strategy.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Solar energy generated (MWh)	40.53	202.66	405.33
Energy discharged from HESSs and EVs (MWh)	71.7	70.95	67.66
Exported solar energy (MWh)	0	10.99	66.19
Annual peak demand change (%)	-22.84	-18.15	-18.44
Daily peak demand change (%)	-27.62	-37.57	-37.31
Standard deviation change (%)	-48.52	-3.37	78.32
Standard deviation change in electricity consumption for the peak 16000 half hour periods (%)	-53.88	-61.02	-53.64

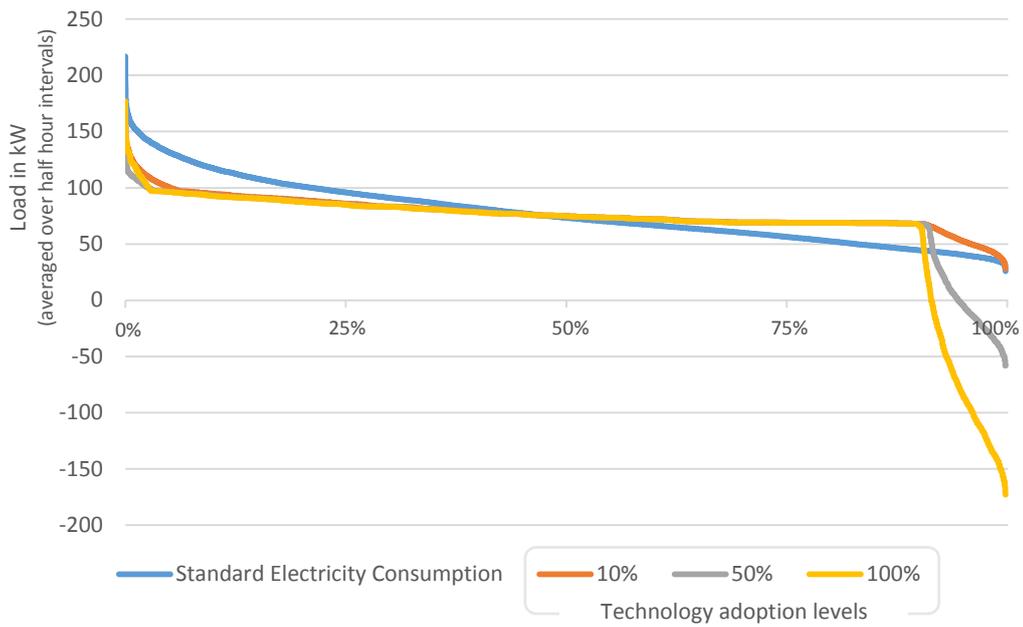


Figure 8.14: Annual load duration curves for a community of households with solar PV, electric vehicles, and home energy storage systems following a *co-op* strategy, with varying levels of adoption.

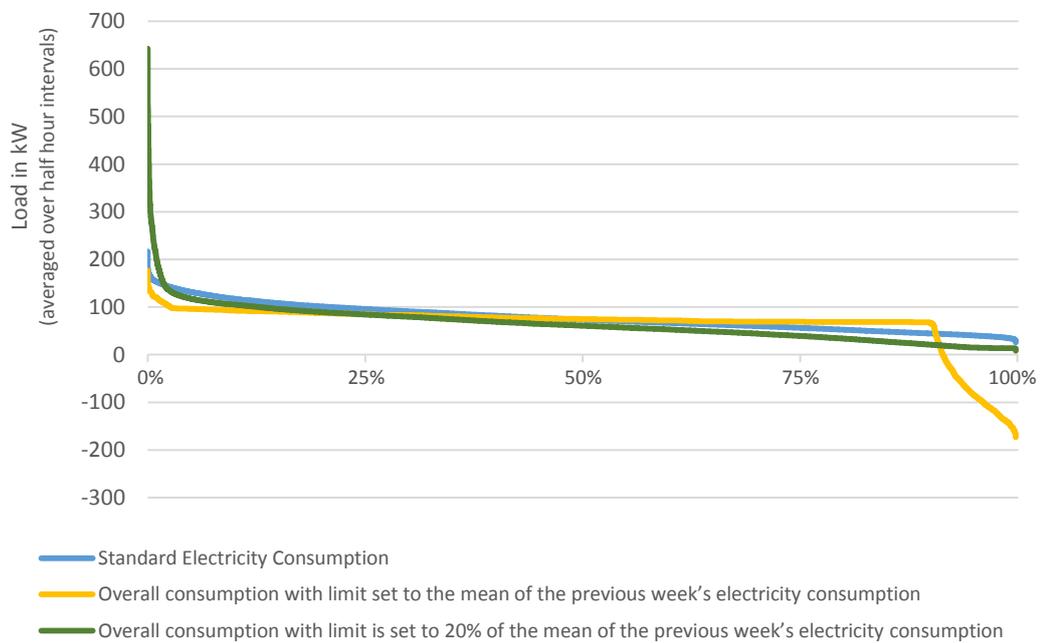


Figure 8.15: Annual load duration curves for a community of 100 households with 100 electric vehicles, home energy storage systems and solar PV systems following a *co-op* scenario with different set *limits*.

The second simulated scenario, assumes that the technologies are used to achieve the greatest cost savings. This is achieved by simulating the EV and HESS to follow the *saver* strategy. In this scenario, solar energy is prioritised to reduce all grid load then charge EVs and any remaining solar energy, stored in the HESSs. Furthermore, the HESSs are only charged with solar energy. At a 10% adoption level, there is no excess solar energy, therefore the HESSs are not utilised and provide no additional benefits to the community. At the 50 and 100 % adoption level, the HESSs are successful in storing excess solar energy, as shown in Figure 8.16. However, the amount of stored solar energy is relatively low when comparing to the HESSs’ storage capabilities, as shown in Table 8.10. Therefore, it is likely these HESSs would also charge with grid electricity to achieve further cost savings, which could significantly alter the community’s load profile, as shown in the *saver* strategy in Section 8.2.1. However, as mentioned in Section 7.2.1, with current electricity tariffs, charging with grid electricity results in minimal cost savings and it is more likely the HESSs’ capacity will be fitted to match the potentially exported solar energy.

Table 8.10: Simulation of electric vehicles, home energy storage systems, and solar PV in a community of 100 households utilising a *saver* scenario.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Solar energy generated (MWh)	40.53	202.66	405.33
Solar energy consumed by electric vehicles (MWh)	0	11.4	84
Energy stored in HESSs (MWh)	0	11.6	84
Exported solar energy (MWh)	0	0	0
Energy storage potential from the HESSs (MWh)	49.28	246.38	492.75
Annual peak demand change (%)	0	60.83	168.54
Daily peak demand change (%)	5.42	137.55	247.11
Standard deviation change (%)	8.61	138.21	243.2

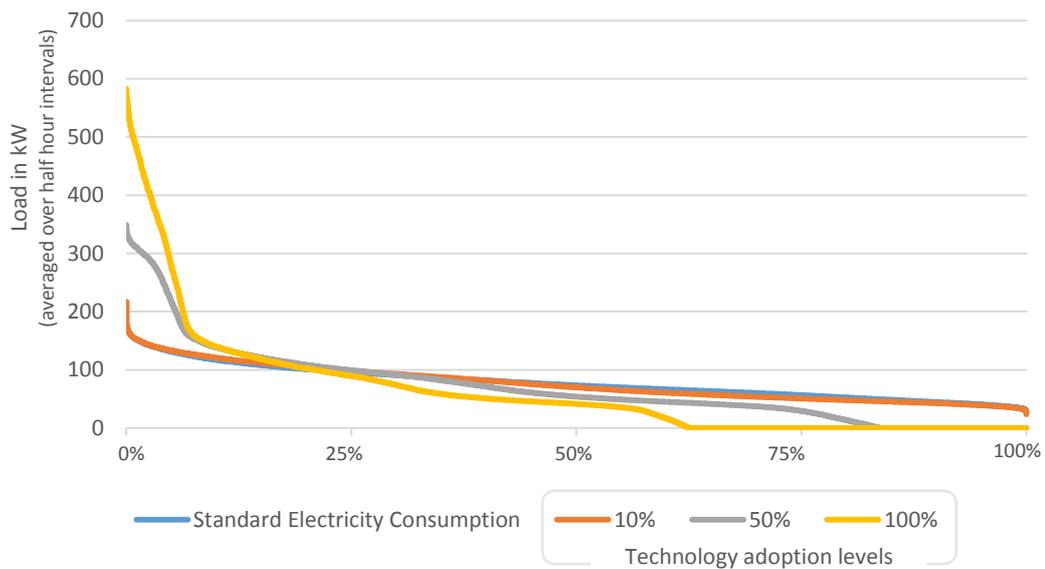


Figure 8.16: Annual load duration curves for a community of households with solar PV, electric vehicles, and home energy storage systems following a *saver* scenario, with varying levels of adoption.

8.4 Summary

In this chapter, HEUS was used to analyse how households that utilise new energy technologies can impact its community. Three different adoption levels (10, 50 and 100 %) were simulated.

The first section described impacts of installing household solar PV systems within a community. The results show that if only a small share of households install solar PV technology, all generated solar energy can be distributed within the community. If there is a large uptake in the community, at the 50 and 100 % adoption level, there are times when there is more generated energy than can be consumed within the community, which means energy is potentially exported to the grid. Furthermore, it was observed that solar PV systems have little impact on reducing peak demand and cause a large dip in electricity consumption during high solar generation times. Thus, the inclusion of solar PV does not reduce the infrastructure needed to supply electricity to the community, and could even require additional infrastructure to support bi-directional flow of electricity.

In the second section, the inclusion of HESSs using a *co-op*, *saver* and *hybrid* strategy was simulated in a scenario with and without solar PV. It became evident that HESSs without solar PV in a *co-op* setting cause a smoother load, however, there is little to no significant benefit in adding HESSs in more than 16% of households, in the *co-op* or *hybrid* strategy, if they are utilised to smooth load to the 7-day moving average. Furthermore, it is more likely a *saver* strategy will be chosen as it is consumer driven, which creates a significantly more fluctuant load profile. Using an HESS with solar PV allows for all or nearly all solar energy to be stored or consumed within the community which leads to a minimal potential export of solar energy, within all adoption levels. The same results could be achieved with only a third of the capacity of the HESS though, because of the relatively low amount of excess solar energy.

The third section of this chapter analysed the adoption of EVs and their effect on the community's electricity demand in different scenarios (with solar PV and with HESSs) and with different charging strategies (*greedy*, *saver*, *co-op* and *slow*). The results show that including EVs in the *greedy* strategy could increase daily and annual peak and lead to fluctuations, while the *saver* strategy causes the largest increase in daily peak load. When EVs are more controlled (*slow* strategy), there is a potential to distribute energy demand and, as a result, reduce overall impact of EV charging. Furthermore, since the community's electricity consumption is relatively low during the early and late hours of the day, charging the EVs in the *slow* strategy, at the 10 and 50 % adoption level, provides an overall smoother load. If EVs incorporate vehicle-to-grid technology, the load can be even further smoothed and the EV fleet can be utilised to reduce peak demand, as shown in the *co-op* strategy. When including EVs with solar PV following the *saver* strategy, at a lower adoption level (10%) there is no excess solar energy and therefore, the EVs will not charge with solar energy. At the 50 and 100 % adoption level, the EVs consume a relatively low amount of excess solar energy (approximately 50%), this is because most or all EVs are typically unplugged during high generation times. In the *co-op* strategy, a higher percentage of EVs' energy demand is met with solar energy, the export though is similar to the *saver* scenario. In the final scenario, EVs were combined with solar PV and HESSs. It was found that if HESSs follow a *co-*

op strategy, there is an overall smoother load and lower daily and annual peak demand. However, when compared to a scenario without HESSs the difference is relatively low. Furthermore, if these technologies follow the *saver* strategy, the HESSs only store excess solar energy which cannot be consumed by EVs. This results in the HESSs only utilising less than a quarter of their battery capacity to store solar energy.

Chapter 9

Countrywide Simulation

“There is more power in unity than division.”

— Emanuel Cleaver

In New Zealand, most of the variability in the national electricity demand is met by hydro generation, as discussed in Section 2.1.1. However, there are limits to the amount of electricity demand that can be met by hydro power plants. These limits include the minimum and maximum generation capacity, and the ramping limit. These values have been estimated to be 974.1MW, 4540.9MW, and 1371.4 MW/h, respectively, on a national level for New Zealand [63]. Therefore, there needs to be careful consideration of new electrical loads that could result in the national electricity demand exceeding these limits

This chapter analyses the impact of integrating new technologies in New Zealand households on the national electricity demand, by using the household electricity usage simulation tool (HEUS). As for the previous chapters, the technologies analysed are solar PV systems, home energy storage systems (HESSs), and electric vehicles (EVs). The national electricity demand is based on the total electricity consumption data from all sectors (e.g. residential, commercial, and industrial) in New Zealand for 2015 (available from the Electricity Authority at www.emi.ea.govt.nz). The electricity tariff used in this simulation is based on a

time-of-use structure with a high electricity price between 7am and 11pm, and a low electricity price between 11pm and 7am. The analysis of the simulation results is split into three main sections which discuss each technology, described as follows.

9.1 Solar PV Systems

For the national simulation, the solar PV output was simulated using NZSPOT, described in Chapter 4, and is based on 3kW system with the characteristics shown in Table 7.2. In this simulation, varying levels of solar PV systems were installed at different locations in New Zealand. The chosen locations were based on the available weather data from NZSPOT and represent different regions in New Zealand, as shown in Table 9.1. Three different adoption levels were simulated, which represent 10%, half, or all households in each region incorporating a 3kW solar PV system. The solar PV systems are assumed to have a tilt that is equal to the location they are installed and have an azimuth angle of 0 degrees (North).

Table 9.1: Number of simulated households in different regions in New Zealand⁷⁵, and the assumed solar PV capacity at different adoption levels.

Location	Represented regions	Estimated households	Collective solar PV capacity at different adoption levels (MW)		
			10	50	100
Dargaville	Northland	53097	15.93	79.65	159.29
Auckland	Auckland	439359	131.81	659.04	1318.08
Hamilton	Waikato, Bay of Plenty, Gisborne, and Hawke's Bay	305697	91.71	458.55	917.09
New Plymouth	Taranaki and Manawatu-Wanganui	123261	36.98	184.89	369.78
Wellington	Wellington	167805	50.34	251.71	503.42
Nelson	Tasman, Nelson, and Marlborough	51747	15.52	77.62	155.24
Greymouth	West Coast	12177	3.65	18.27	36.53
Christchurch	Canterbury	195456	58.64	293.18	586.37
Invercargill	Otago and Southland	111288	33.39	166.93	333.86
Total New Zealand		1459887	437.97	2189.84	4379.66

The results from simulating solar PV systems in households across New Zealand, as shown in Table 9.2, produced two main findings, relating to the generated amount of solar energy, and the impact solar energy has on the national electricity demand. These findings are explained as follows.

⁷⁵ The number of households in a region is based on the total number of separate houses, townhouses, and apartments in that region. Data retrieved from the “2013 Census QuickStats about housing” document from StatsNZ (<http://www.stats.govt.nz>).

Table 9.2: Impact of solar PV systems in households across New Zealand on the national electricity demand.

	Percentage of households with a solar PV system		
	10%	50%	100%
Solar generation (GWh)	591.3	2956.52	5913.03
Exported energy (GWh)	0	0	0
National electricity demand (GWh)	38847.99	36482.77	33526.26
Energy replaced by solar PV (%)	1.5	7.5	14.99
Daily peak demand change (%)	-1.22	-2.15	-2.39
Annual peak demand change (%)	-0.22	-0.22	-0.22
Standard deviation change (%)	-3.67	-4.15	23.86

During a year solar PV systems are expected to generate enough energy to replace approximately 1.5, 7.5, and 15 % of the national electricity demand, at a 10, 50 and 100 % adoption level, respectively. The solar generation varies significantly on a daily and monthly basis, as shown in Figure 9.1. For example, at a 100% adoption level the mean daily generation was 16.2 GWh, which would however, typically vary by approximately 4.6 GWh, with a maximum daily generation of 26GWh on the 9th of November and a minimum daily generation of 3.9GWh on the 7th of June. This daily solar generation, is notably lower than the electricity demand, as shown in Figure 9.1. However, due to the intermittent behaviour of solar generation, it is evident that on a half hourly interval, solar energy has a significant impact on the national electricity demand, as shown in Figure 9.2.

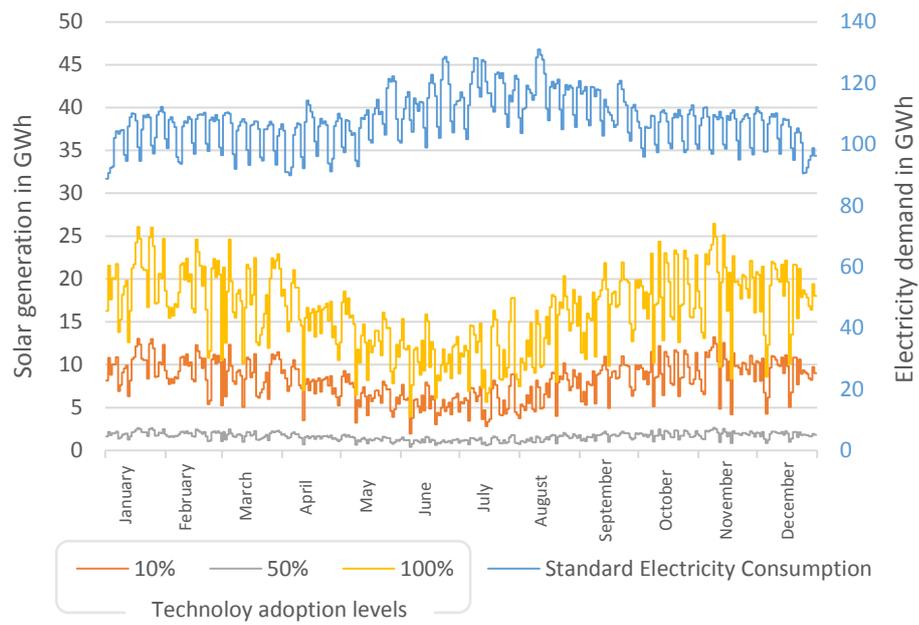


Figure 9.1: Daily solar generation at different solar adoption levels compared to the national electricity demand without solar PV (Standard Electricity Consumption).

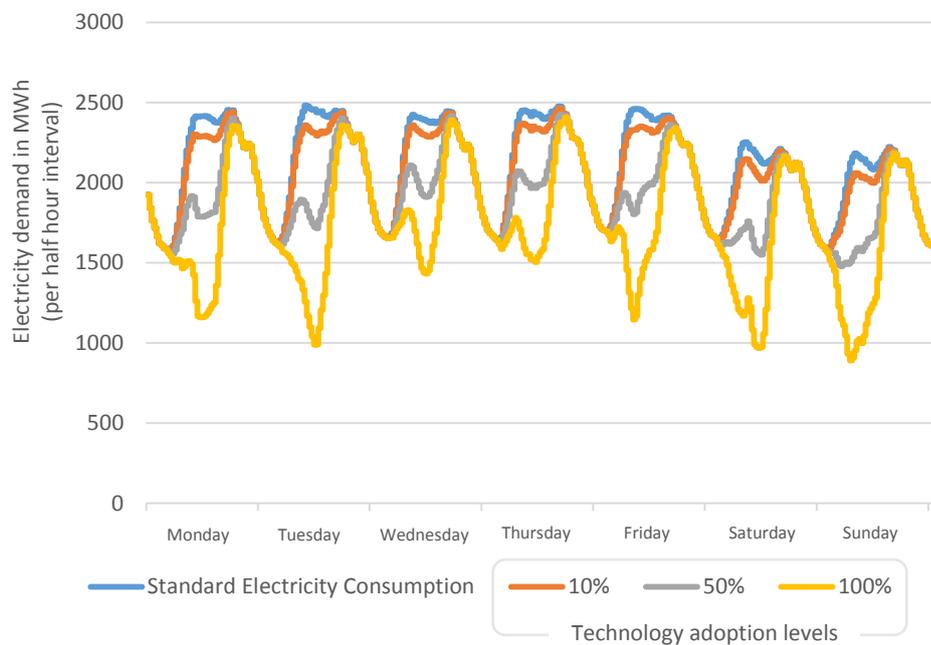


Figure 9.2: Electricity demand at different solar adoption levels in the first full week of the year.

At the 10 and 50 % adoption level, it is evident that the energy produced by the solar PV systems reduces the national load during midday, resulting in a reduction of the morning peak, and an overall smoother load, as shown in Figure 9.2. However, at a 100% adoption level the consumption of solar energy results in a large dip in the national electricity demand. The simulation results also show that solar PV systems have little to no impact on reducing afternoon peak load, resulting in an overall slight reduction of daily and annual peak demand, as shown in Table 9.2. At a 100% adoption level, this minimal reduction of daily peak demand, in combination with the dips caused by solar energy, results in a load profile which is significantly more fluctuant, as shown in Figure 9.2 and Figure 9.3. This load profile will require hydro generation to ramp up and down more frequently, however, since the greatest variation in an hour is 582MWh, it is still within the limits of the national hydro generation capabilities.

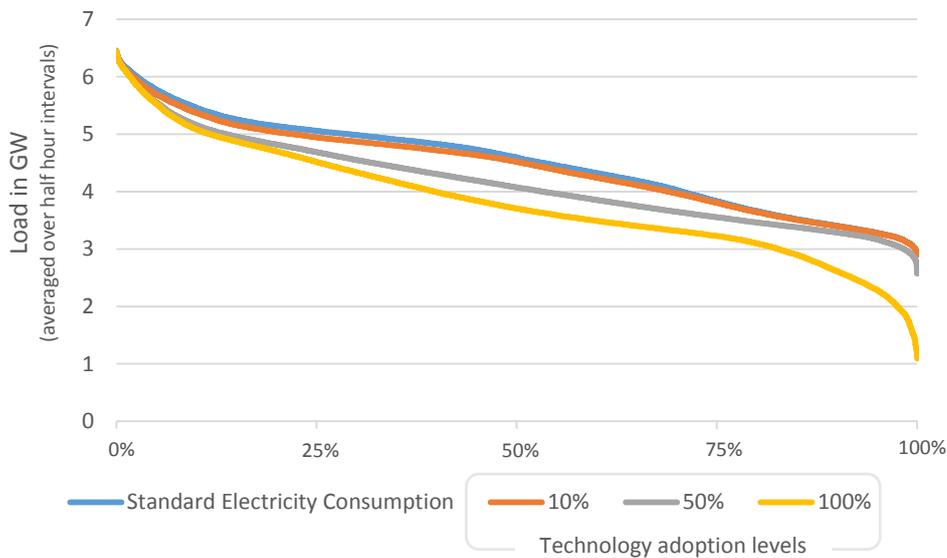


Figure 9.3: Annual load duration curves for the national electricity demand with different adoption levels of solar PV.

9.2 Home Energy Storage Systems

The second technology, simulated in New Zealand households was an HESS. This technology provides the nation with distributed storage capabilities to store distributed energy and grid electricity for future consumption. This storage has the potential to significantly alter the national electricity demand if there is a large uptake of this technology. This section describes the results from simulating HESSs in multiple households in New Zealand using the HEUS simulation tool. The HESSs are based on the Tesla Powerwall 2 AC, as described in Table 7.4, while the number of households that incorporate this technology is based on different adoption levels, as shown in Table 9.3. Two different scenarios with integrated HESSs were simulated; without solar PV, and with varying levels of solar PV. The findings from these two scenarios are discussed as follows.

Table 9.3: Assumed national storage characteristics for different adoption levels of home energy storage.

Adoption level (%)	Simulated households	Storage capacity (MWh)	Maximum charge rate (MW)
10	145,988.7	1,971	730
20	291,977.4	3,942	1,460
30	437,966.1	5,913	2,190
40	583,954.8	7,883	2,920
50	729,943.5	9,854	3,650
60	875,932.2	11,825	4,380
70	1,021,921	13,796	5,110
80	1,167,910	15,767	5,840
90	1,313,898	17,738	6,569
100	1,459,887	19,708	7,299

9.2.1 Storage without Solar PV

In the first scenario, HESSs without solar PV, two different charging strategies were simulated. The first strategy, *co-op*, utilises the HESSs to smooth the national electricity demand to *limit* (7-day moving average). The second strategy, *saver*, charges and discharges for optimal cost savings for the consumer (the HESS's owner). If the HESSs follow a *co-op* strategy, electricity demand becomes significantly more balanced with higher adoption levels as shown in Figure 9.4. Interestingly, most of the charging from HESSs occurs in the weekend, since electricity demand is relatively low then, compared to week days. Consequently, during the last weekdays there is typically not enough stored energy to smooth load, as shown in Figure 9.5.

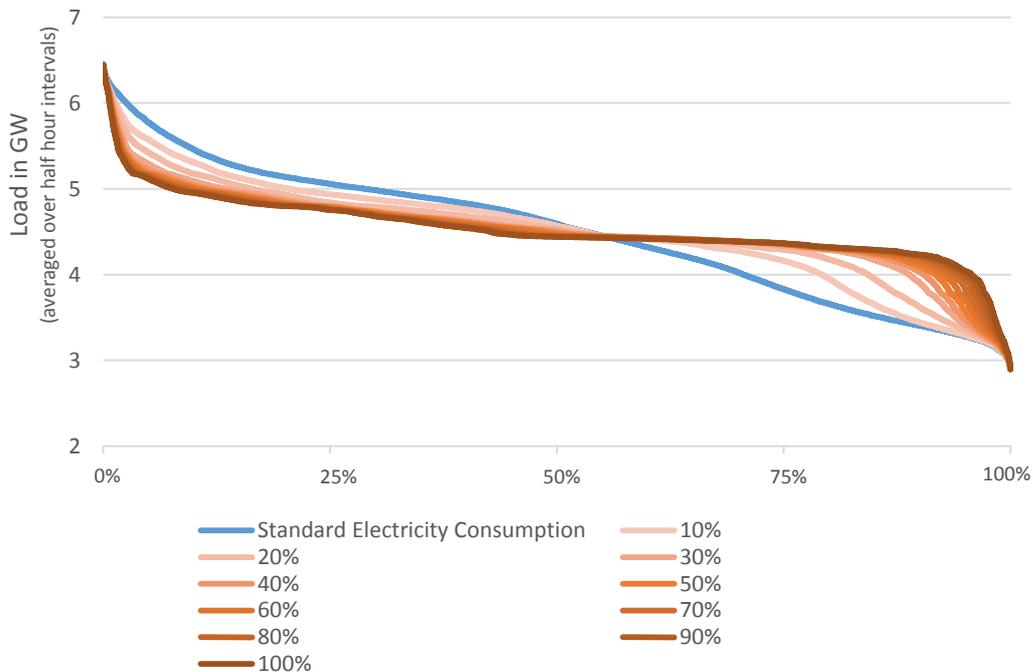


Figure 9.4: Annual load duration curves for the national electricity demand with home energy storage systems following the *co-op* strategy, at different levels of adoption.

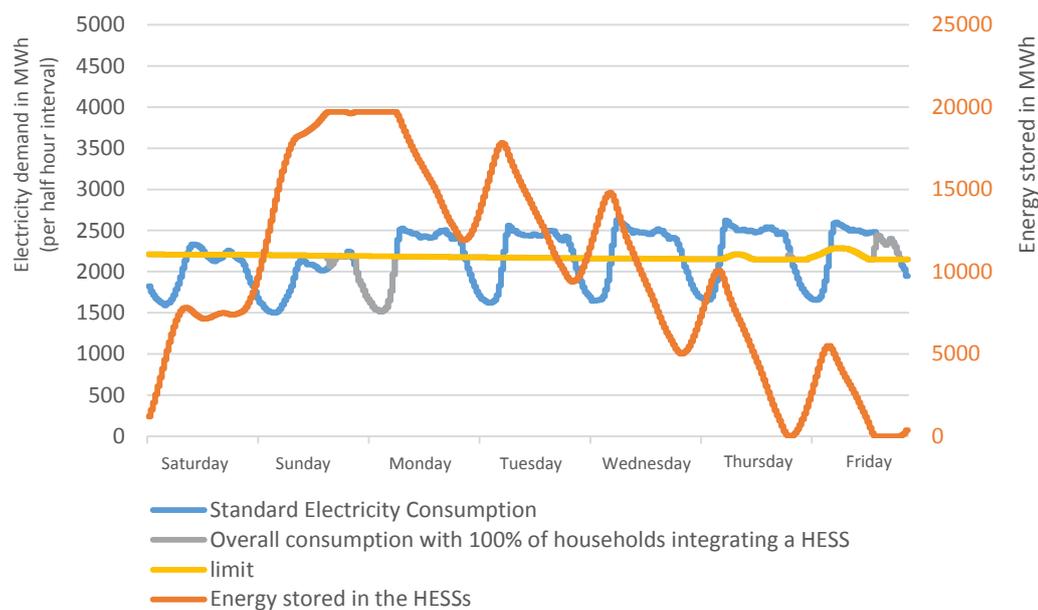


Figure 9.5: Typical energy storage behaviour of home energy storage systems following the *co-op* strategy at a 100% adoption level. Note the HESSs reach full capacity on Sunday and become empty near the end of the week.

It is evident from these results, that HESSs following the *co-op* strategy can benefit the nation by reducing daily and annual peak demand, and reduce variability in the national electricity demand, as shown in Table 9.4. It is also evident from these results that at higher adoption levels, the HESSs only utilise a portion of their storage capabilities. For example, at the 100% adoption level the HESSs only utilise 30% of their shifting potential. This decrease in battery capacity utilisation with increasing adoption levels is a result of the availability of a finite number of half hour periods where electricity consumption is below *limit*, and consequently, a finite amount of electricity the HESSs can store, as discussed in Section 8.2.1.

In the *saver* strategy, the HESSs are prioritised to achieve maximum savings for the consumer by charging at their full charge rate at low electricity prices, and discharging at maximum discharge rate during high electricity prices. In this simulation, the electricity price is low between 11pm and 7am, and conversely, high between 7am and 11pm. This behaviour causes the HESSs to utilise 100% of their capacity, as shown in Table 9.5.

Table 9.4: Impact of home energy storage systems following the *co-op* strategy on the national electricity demand over a year.

	Percentage of households with a home energy storage system (%)									
	10	20	30	40	50	60	70	80	90	100
Energy shifted by HESSs (GWh)	683	1206	1594	1756	1867	1961	2046	2121	2182	2234
Energy shifting potential of HESSs ⁷⁶ (GWh)	719	1439	2158	2877	3597	4316	5036	5755	6474	7193
Shifting potential utilised (%)	95	84	74	61	52	45	41	37	34	31
Annual peak demand change (%)	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22	-0.22
Daily peak demand change (%)	-3.54	-4.95	-6.35	-7.35	-8.3	-9.22	-9.93	-10.7	-11.1	-11.6
Standard deviation change (%)	-13	-25	-34	-38	-41	-43	-46	-48	-50	-51

Table 9.5: Impact of home energy storage systems following the *saver* strategy on the national electricity demand over a year.

	Percentage of households with a home energy storage system		
	10%	50%	100%
Energy shifted by HESSs (GWh)	719.42	3596.71	7193.42
Energy shifting potential of HESSs (GWh)	719.42	3596.71	7193.42
Shifting potential utilised (%)	100%	100%	100%
Annual peak demand change (%)	2.11	47.34	103.86
Daily peak demand change (%)	-0.42	50.39	118.4
Standard deviation change (%)	0.56	127.38	301.48

⁷⁶ Assuming the maximum shifting potential is each home energy storage system charging and discharging their fully capacity daily (13.5 kWh).

The *saver* charging strategy results in all HESSs charging at their full charge rate at 11pm until they reach their full capacity, which is approximately 3 hours, as shown in Figure 9.6. Furthermore, all the stored electricity is typically discharged in the first 4 hours of the high electricity price. This behaviour has the potential to cause a major disruption in the national electricity demand at higher adoption levels. For example, at a 100% adoption level, electricity consumption is increased significantly for over 1000 hours in a year, and is reduced to zero for approximately 1400 hours in a year, as shown in Figure 9.7.

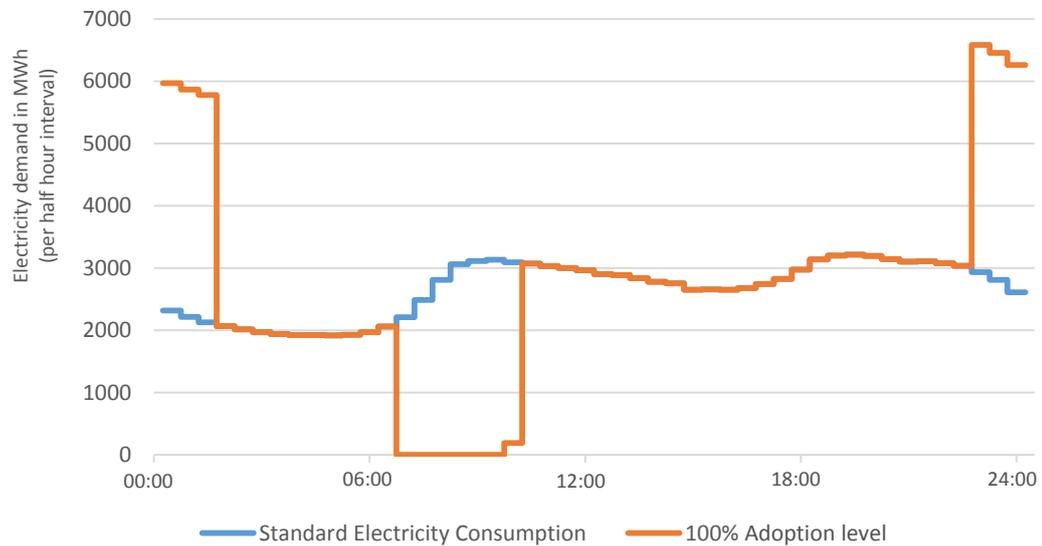


Figure 9.6: Comparison between a typical daily load profile without home energy storage systems, and 100% adoption of home energy storage systems following the *saver* strategy.

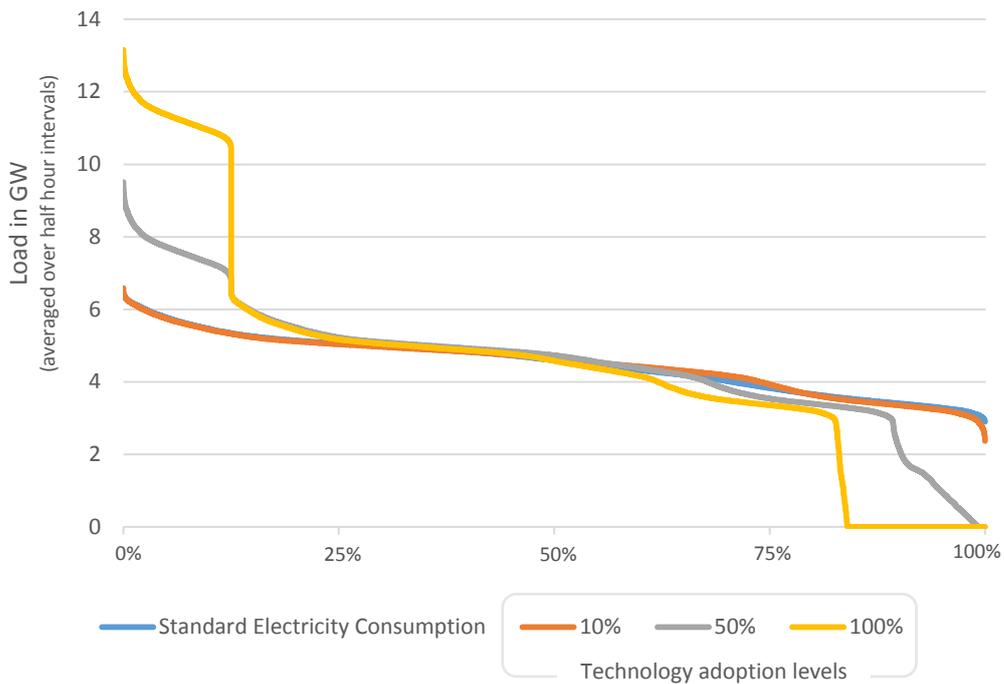


Figure 9.7: Annual load duration curves for the national electricity demand with home energy storage systems following a *saver* strategy, at different levels of adoption.

It is evident from these results that HESSs have the potential to significantly alter the national load profile, which could be disruptive to the electricity infrastructure. Therefore, if there is a large uptake of this technology, a change in electricity pricing is needed, to prevent electricity demand following a similar pattern as the load duration curves as shown in Figure 9.7.

9.2.2 Storage with Solar PV

The second simulated scenario is the inclusion of HESSs with solar PV systems. In this scenario, two charging strategies were simulated: *saver*, and *co-op*. The first strategy (*saver*) assumes the HESSs only charge with solar energy during low electricity prices, and with excess solar energy during high electricity prices. The results from Section 9.1, show that there were no instances where solar energy

exceeded the national electricity demand, therefore the HESSs only charged with solar energy before 7am. This charging behaviour results in a usage of the HESSs' capacity of less than 2%. Furthermore, with the low savings from storing solar energy before 7am⁷⁷, it is more likely the HESSs will store grid electricity during low electricity prices, and store excess solar energy at the household level, as discussed in Section 7.2.2.

The second charging strategy (*co-op*) assumes the HESSs are prioritised to smooth the national electricity demand to *limit* (7-day moving average), as discussed in Section 6.2. In this strategy, the HESSs store solar energy when electricity demand is below *limit*, charge with grid electricity when demand is below *limit*, and discharge when demand is above *limit*. This behaviour causes the HESSs to utilise significantly more solar energy than in the *saver* strategy, as shown in Table 9.6.

Table 9.6: Impact of solar PV and home energy storage systems following the *co-op* strategy on the national electricity demand over a year.

	Percentage of households with solar PV and an HESS		
	10%	50%	100%
Electricity demand (GWh)	38930.27	36766.14	33910.6
Share of energy stored in HESSs is solar energy (%)	3.49	32.08	67.35
Energy shifted by HESSs (GWh)	733.88	2500.74	3331.44
Energy shifting potential of HESSs (GWh)	719.42	3596.71	7193.42
Shifting potential utilised (%)	102.01	69.53	46.31
Annual peak demand change (%)	-0.22	-0.22	-0.46
Daily peak demand change (%)	-4.24	-12.62	-20.16
Standard deviation change (%)	-22.93	-38.29	-31.53

⁷⁷ Storing solar energy at 24.72 cents/kWh to replace electricity consumption at 28.73 cents/kWh, will save approximately 1.2633 cents for each kWh that is discharged, assuming a 90% battery efficiency.

The results from this simulation show that the inclusion of HESSs following a *co-op* strategy, provide a reduction in the national daily and annual peak demand, and reduce the variability in the national electricity demand, as shown in Table 9.6 and Figure 9.8. Therefore, it is evident that HESSs have the potential to significantly benefit the nation if there is enough incentive to smooth electricity demand. However, with current electricity prices it is more likely the HESSs will follow the *saver* strategy, negating these benefits.

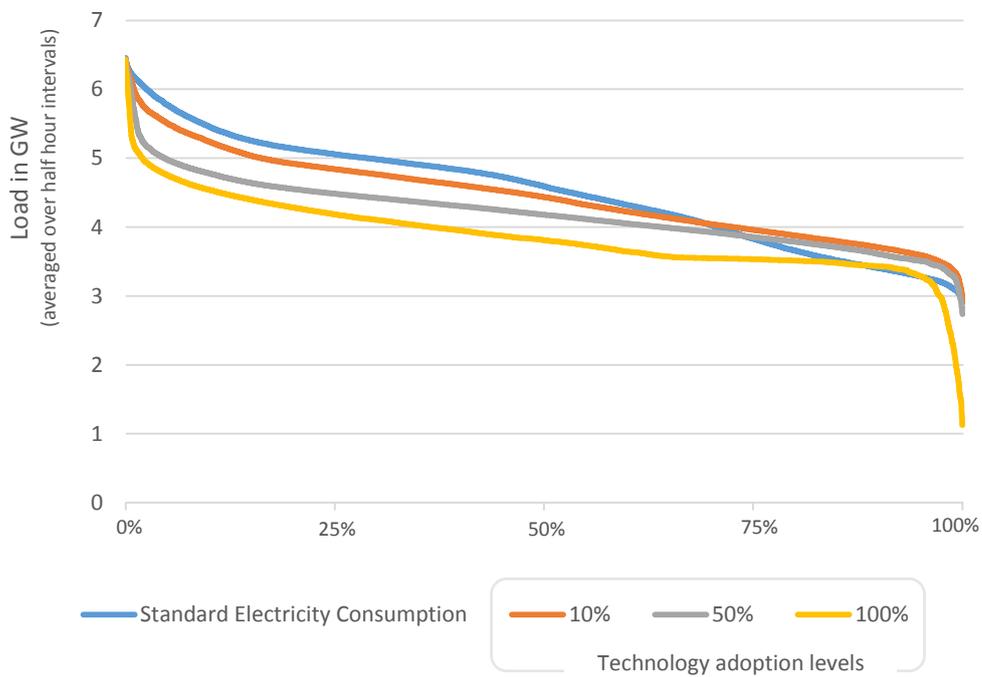


Figure 9.8: Annual load duration curves for the national electricity demand with solar PV and home energy storage systems following a *co-op* strategy, at different levels of adoption.

9.3 Electric vehicles

The last technology simulated in New Zealand households was an EV. It is evident from Chapters 8 and 9 that this technology has the potential to either alleviate or exacerbate variability in electricity consumption on a household and a community level. This section analyses how the inclusion of varying levels of EVs can impact the national electricity demand. The simulated EVs are based on a mid-range model, described in Table 7.5, while the different adoption levels were chosen as 10, 50, and 100 %. These adoption levels represent scenarios where 10%, half, or all households in New Zealand incorporate an EV, as shown in Table 9.7.

Table 9.7: Assumed number of electric vehicles and their collective capacity and charge rate at different national adoption levels.

	Percentage of households with an electric vehicle		
	10%	50%	100%
Number of electric vehicles	145989	729944	1459887
Collective capacity (MWh)	7299	36497	72994
Charge rate (MWh)	730	3650	7299

The analysis of simulating EVs in New Zealand households produced three main findings. These findings are related to how different charging strategies of EVs impact the national electricity demand, how EVs perform with solar PV, and lastly, how the combination of EVs, solar PV systems, and HESSs will impact the national electricity demand. These findings are explained as follows.

9.3.1 Grid Energy

In 2015 New Zealand’s annual electricity demand was approximately 39439 GWh. If 10, 50, or 100 % of households in New Zealand had an EV, this demand would have risen by approximately 1.1, 5.4, and 10.8 %, respectively. Although, this demand is relatively low on an annual basis, on a smaller scale the charging behaviour of an EV can have a significant impact on the national electricity demand. To understand the extent of this impact, four different charging strategies were simulated in households across New Zealand: *greedy*, *saver*, *slow*, and *co-op*. The first three strategies represent behaviours with no vehicle-to-grid capabilities and simply charge at different times and rates, as shown in Figure 9.9.

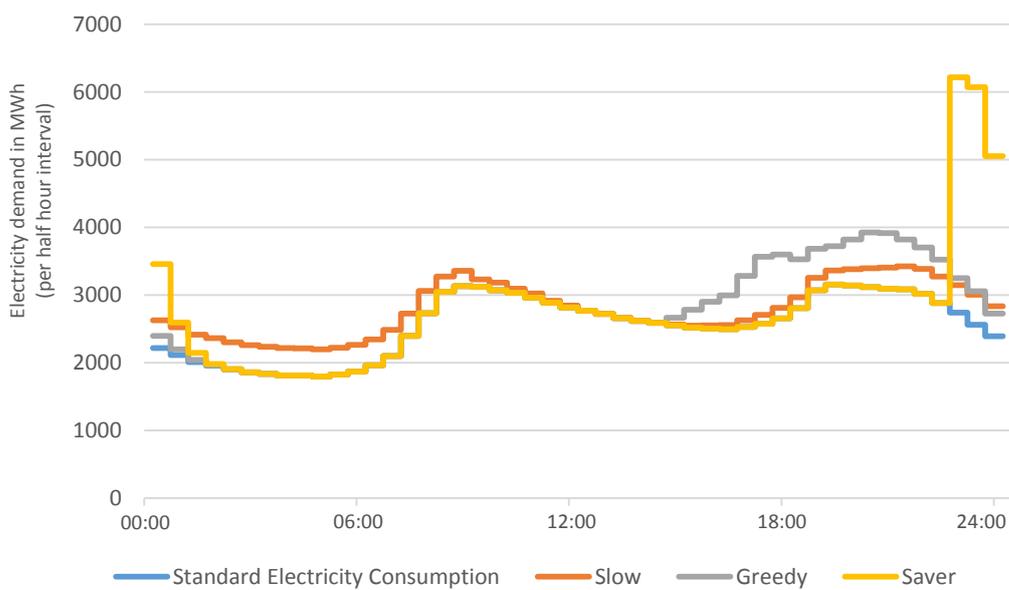


Figure 9.9: National electricity consumption on a typical day with a 100% adoption level of electric vehicles following different charging strategies.

The results from simulating these three charging strategies, as shown in Table 9.8 and Figure 9.10, make evident that the most disruptive strategy is *saver*, then *greedy* and lastly, *slow*. In the *slow* strategy, the EV’s electricity demand is distributed evenly from when they are plugged into the household, until they get

unplugged. This behaviour results in a small reduction of daily and annual peak, and interestingly, an overall smoother load profile, as most of the charging occurs when the national electricity demand is low. In the *greedy* strategy, most of the charging occurs between midday and midnight which results in a larger afternoon peak load, as shown in Figure 9.9. However, since EVs plug in and charge at different times, the added electricity demand is semi-distributed. In the *saver* charging strategy, nearly all of the EV's charging occurs within two hours after 11pm (when electricity prices are low). This behaviour results in a significant rise in daily and annual peak demand for the nation (approximately 100%), and would require significantly more infrastructure, to deal with such an increase of demand for a short period of time.

Table 9.8: Impact of electric vehicles following different charging strategies on the national electricity demand over a year.

		Percentage of households with an electric vehicle		
		10%	50%	100%
<i>greedy</i>	Daily peak demand change (%)	1.74	12.8	28.1
	Annual peak demand change (%)	1.66	11.31	25.1
	Standard deviation change (%)	3.08	19.79	47.54
<i>saver</i>	Daily peak demand change (%)	0.32	46.05	110.64
	Annual peak demand change (%)	1.41	43.65	96.11
	Standard deviation change (%)	-0.38	33.86	115.77
<i>slow</i>	Daily peak demand change (%)	0.81	4.52	9.58
	Annual peak demand change (%)	0.62	3.57	7.38
	Standard deviation change (%)	-2.43	-50.88	-18.02
Added energy demand from EVs (GWh)		429.35	2146.76	4293.53

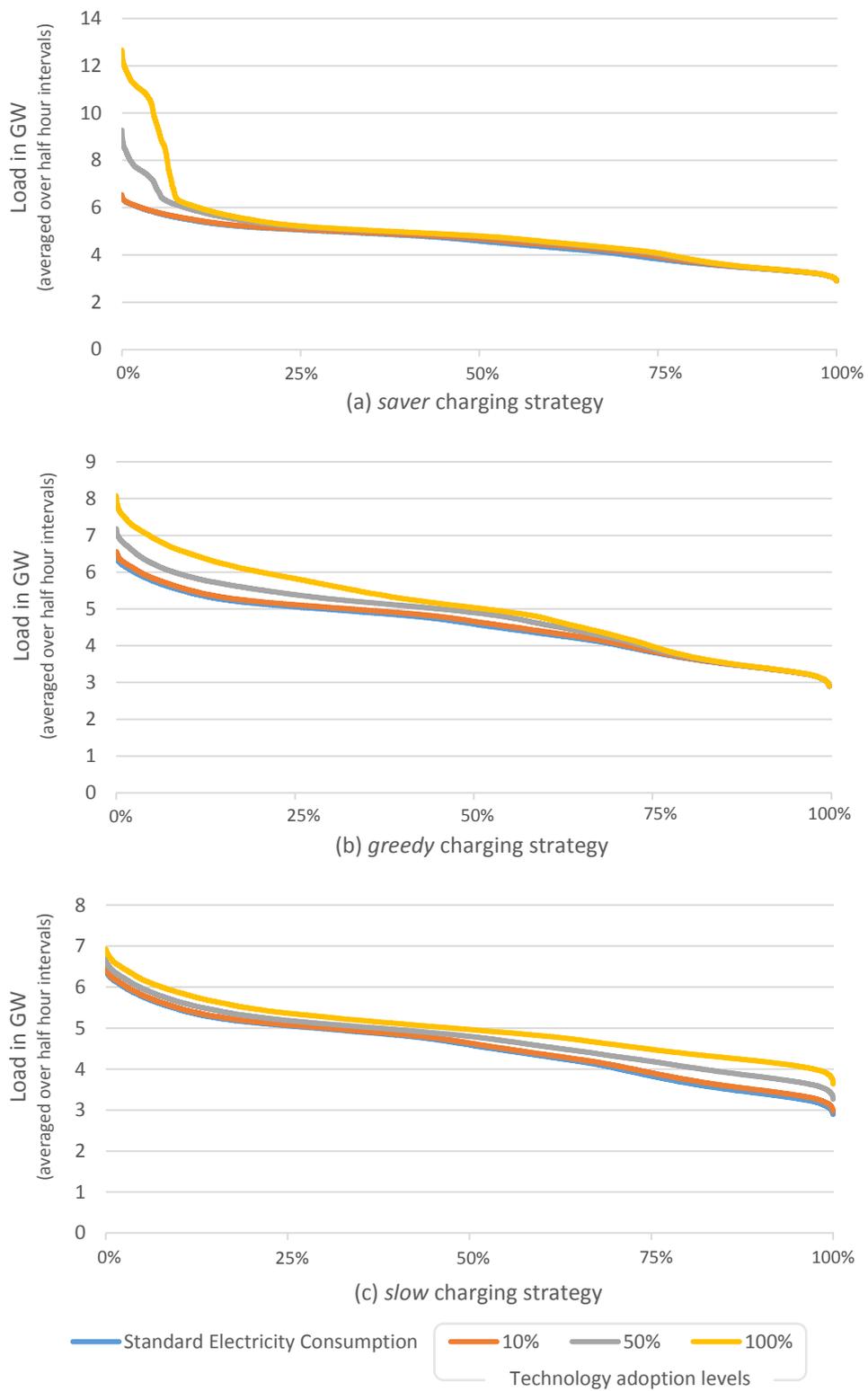


Figure 9.10: Annual load duration curves for the national electricity demand with electric vehicles following different charging strategies, at different levels of adoption.

In the *co-op* strategy, the EV's battery is utilised to smooth the national electricity demand to *limit* (7-day moving average). The simulation results, as shown in Table 9.9, are similar to the results produced at a community level. The utilisation of the EV fleet as grid storage, provides a reduction in daily and annual peak demand at the 10 and 50 % adoption level, and an overall more balanced load profile at all adoption levels, as shown in Figure 9.11. A balanced load profile is beneficial for the nation, as it incentives more cost-efficient baseload generation, and reduces the infrastructure strain to supply peak demand.

Table 9.9: Simulation of electric vehicles following a *co-op* strategy at a national level.

	Percentage of households with an electric vehicle		
	10%	50%	100%
Standard deviation change (%)	-29.72	-48.38	-48.36
Annual peak demand change (%)	-2.73	-1.08	-0.05
Daily peak demand change (%)	-4.98	-0.72	5.35
Discharged amount (MWh)	1050.89	1034.69	737.84

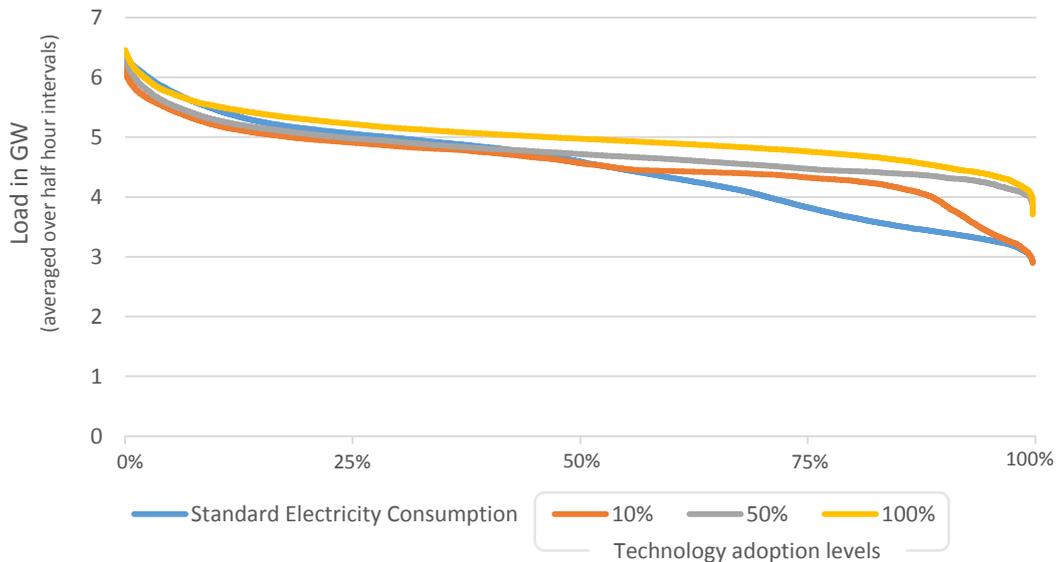


Figure 9.11: Annual load duration curves for the national electricity demand with electric vehicles following a *co-op* strategy, with different levels of adoption.

9.3.2 Electric Vehicles with Solar PV

The inclusion of an EV in a household with solar PV, allows the EV to minimise its impact on the grid by utilising solar energy. However, as shown in Section 7.3.3, if the EV follows a *saver* strategy, it is more economical for the consumer to replace standard electricity consumption, than to charge the EV with solar energy. Therefore, only excess solar energy is used to charge the EV. If we apply the same principal on the national electricity demand, it becomes evident that no solar energy would be stored within the EVs, assuming a 10, 50, and 100 % adoption level, as shown in Table 9.10. This behaviour results in a load profile which includes the negative impacts from charging EVs (i.e. large spikes in load), and the negative impacts from solar generation (i.e. large dips in load), as shown in Figure 9.12.

Table 9.10: Simulation of electric vehicles following a *saver* strategy with solar PV at a national level.

	Percentage of households with solar PV and an electric vehicle		
	10%	50%	100%
Energy demand from electric vehicles (MWh)	29.4	147	294
Solar energy consumed by electric vehicles (MWh)	0	0	0
Exported solar energy (MWh)	0	0	0
Standard deviation change (%)	-3.48	40.87	150.71
Daily peak demand change (%)	-0.72	46.08	110.6
Annual peak demand change (%)	1.25	43.57	96.21

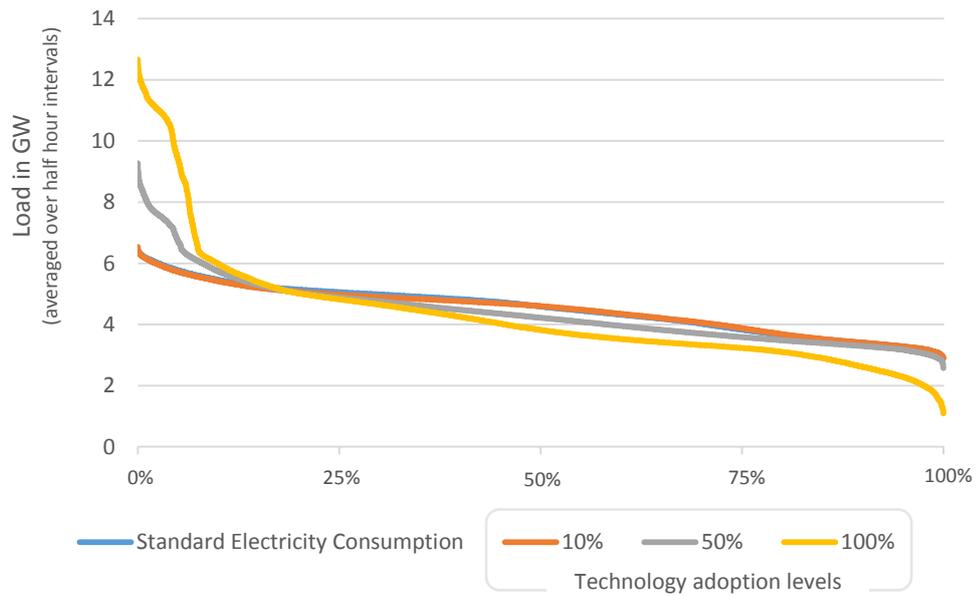


Figure 9.12: Annual load duration curves for the national electricity demand with solar PV and electric vehicles following a *saver* strategy, with different adoption levels.

Another charging strategy which is less invasive, is the *co-op* strategy. The results from this strategy, are also similar to the community and household level. In this strategy, the EVs charge with solar energy to prevent large dips in the national electricity demand, and charge and discharge with grid electricity accordingly to smooth demand to *limit*. This behaviour results in a reduction in daily and annual peak demand, and an overall smoother load for all adoption levels, as shown in Table 9.11 and Figure 9.13. It is evident from these results that the inclusion of EVs with solar PV can in fact benefit the nation if their charging is controlled. Furthermore, if the EVs incorporate vehicle-to-grid technology, they can also reduce the national peak load.

Table 9.11: Simulation of electric vehicles following a *co-op* strategy with solar PV at a national level.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Energy demand from electric vehicles (GWh)	29.4	147	294
Solar energy consumed by electric vehicles (MWh)	6.75	607.15	2156.26
Exported energy (GWh)	0	0	0
Amount of energy discharged by electric vehicles (GWh)	974.82	1108.2	975.79
Annual peak demand change (%)	-5.64	-0.72	-1.21
Daily peak demand change (%)	-6.45	-10.64	-10.34
Standard deviation change (%)	-30.63	-40.44	-1.58
Standard deviation change in electricity consumption for the peak 15000 half hour periods (%)	-42.33	-48.39	-41.08

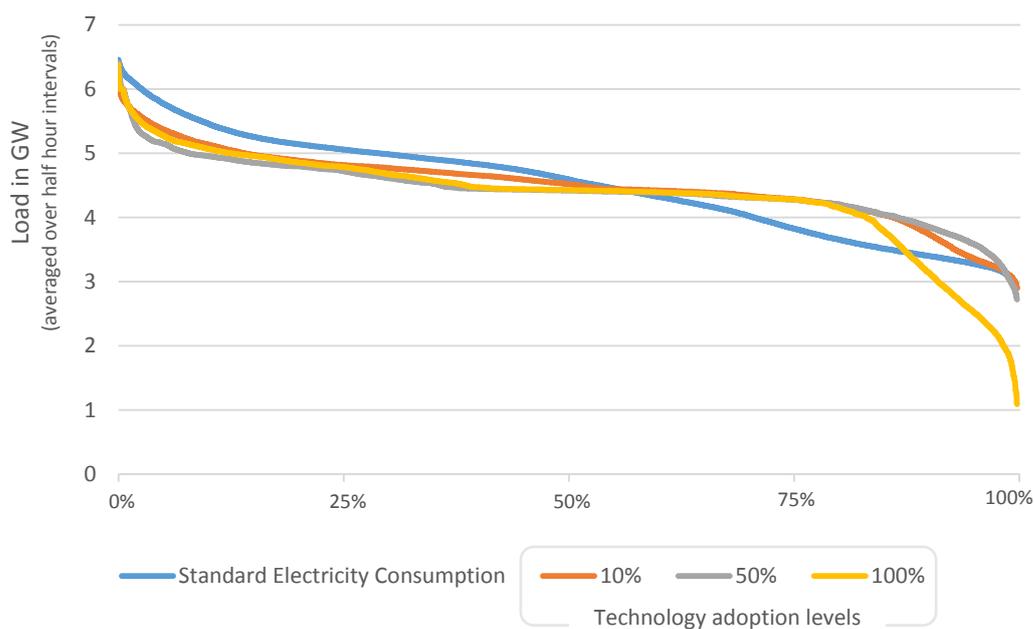


Figure 9.13: Annual load duration curves for the national electricity demand with solar PV and electric vehicles following a *co-op* strategy, with varying levels of adoption.

However, if the EVs follow the *co-op* charging strategy, there are still occasions when there is a sudden drop in electricity demand, as shown in Figure 9.14. This is a result of a high level of solar generation and most EVs being unplugged. At a 100% adoption level, these sudden drops are substantial (e.g. there was a sudden drop of 1671MWh in a half hour period on the 7th of November) which could be problematic for the nation, as it would require a sudden shut down of multiple power plants and spillage of electricity.

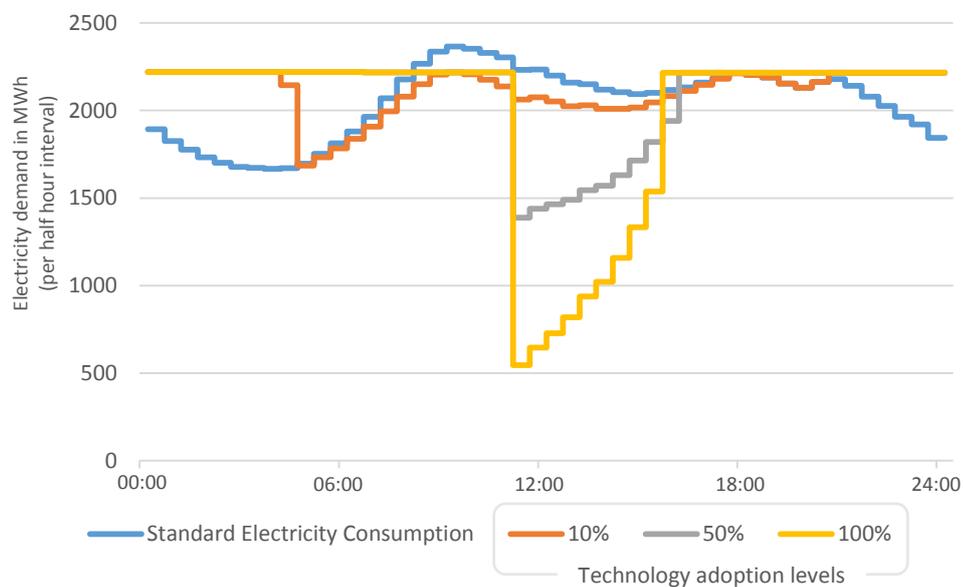


Figure 9.14: Example day where electricity consumption is low and solar generation is high, resulting in a sudden drop in electricity demand at the 50 and 100 % adoption level.

9.3.3 Electric Vehicles with Distributed Storage and Generation

A nation with all three technologies (HESSs with EVs and solar PV systems) has the opportunity to utilise solar energy and distributed storage (from the HESSs and EVs) to reduce the variability in the national electricity demand. If these technologies follow a *co-op* strategy, there is a greater reduction in daily and annual

peak demand, and overall less fluctuations in the grid, as shown in Table 9.12, when compared to a scenario without HESSs, as shown in Table 9.11. However, it is also evident that the amount of additional energy that is shifted from the inclusion of HESSs decreases significantly with higher adoption levels. This is a result of the limited amount of electricity that can be consumed by EVs and HESSs (as discussed in Section 8.2).

Table 9.12: Simulation of solar PV, electric vehicles, and home energy storage systems following a *co-op* strategy at a national level.

	Percentage of households with an electric vehicle and a solar PV system		
	10%	50%	100%
Solar energy generated (GWh)	591.3	2956.52	5913.03
Energy discharged from HESSs and EVs (GWh)	1525.08	1224.31	1149.64
Shifting potential of HESSs (GWh)	719.42	3596.71	7193.42
Exported solar energy (MWh)	0	0	0
Annual peak demand change (%)	-0.22	-0.43	-7.06
Daily peak demand change (%)	-7.94	-13.6	-14.6
Standard deviation change (%)	-40.69	-43.41	-10.85
Standard deviation change in electricity consumption for the peak 15000 half hour periods (%)	-49.34	-52.34	-52.71

Another simulated charging strategy is the *saver* strategy. This strategy is very disruptive to the national electricity demand, as all of the HESSs and EVs begin charging at their full charge rate at the same time (i.e. at 11pm). This charging lasts until the HESSs reach their full capacity, and the EVs reach their energy requirements, which is typically within 3 hours. Furthermore, since the HESSs are at their full capacity before the solar PV systems begin generating electricity, no solar energy is stored within the HESSs, as shown in Table 9.13. Therefore, the combination of these technologies in the *saver* strategy, provide no additional benefits to one another e.g. storing solar energy in HESSs or EVs. This results in the charging of EVs and HESSs causing a significant increase in electricity demand for approximately 1100 hours of the year, and furthermore, solar generation and the

discharging of the HESSs reducing the national electricity demand to zero for approximately 2300 hours of a year, as shown in Figure 9.15.

Table 9.13: Simulation of solar PV, electric vehicles, and home energy storage systems following a *saver* strategy at a national level.

	Percentage of households with an electric vehicle, home energy storage system and a solar PV system		
	10%	50%	100%
Solar energy generated (GWh)	591.3	2956.52	5913.03
Solar energy stored in HESSs (GWh)	0	0	0
Energy discharged from HESSs (GWh)	719.42	3596.71	7193.42
Energy storage potential from the HESSs (GWh)	719.42	3596.71	7193.42
Annual peak demand change (%)	12.48	99.69	210.15
Daily peak demand change (%)	8.55	114.02	246.34
Standard deviation change (%)	4.54	212.09	490.43

It is evident from these results that if there is a large uptake of these three technologies, electricity tariffs have to be changed and incentives should to be made available. This is because creating an electricity system to supply a load profile which has rapid increases in peak demand for short periods of time, and no electricity demand for approximately a quarter of the year, would be immensely inefficient and impracticable.

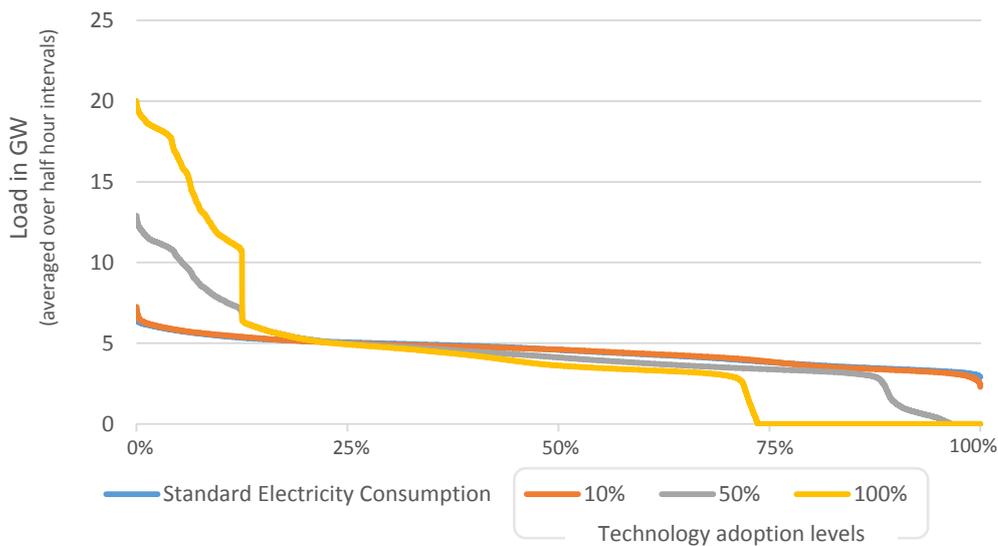


Figure 9.15: Annual load duration curves for the national electricity demand with solar PV, home energy storage systems, and electric vehicles following a *saver* strategy, with different levels of adoption.

9.4 Summary

This chapter analysed the impacts of integrating new technologies in New Zealand households on the national electricity demand.

The first section described the impact of installing solar PV at a household level on the national electricity demand. It became evident that during a year, solar PV systems generated enough energy to reduce approximately 1.5, 7.5, and 15 % of the national electricity demand, at a 10, 50 and 100 % adoption level, respectively. The reduction at the 10 and 50 % adoption level results in an overall smoother load during the day, however at a higher adoption level, large dips in the national electricity demand become evident. Furthermore, it was shown that solar PV has little impact on the national afternoon peak demand.

The second section discussed the impacts of installing HESSs in New Zealand households on the national electricity demand. In this section, the impacts of different charging strategies were compared, as well as the impacts HESSs have in combination with household solar PV systems. It was found that HESSs in the *co-*

op strategy can benefit the nation by reducing daily and annual peak demand as well as variability in national electricity demand. However, at a 100% adoption level, HESSs only utilise approximately 30% of their storage capacity. In the *saver* strategy, HESSs utilise all of their storage capacity, causing a major disruption to the national electricity demand, at higher adoption levels. In a scenario with solar PV, there were no occasions when solar generation exceeded the national electricity demand, therefore, if these HESSs only stored excess national solar energy, they would not be utilised. However, if these HESSs utilised solar energy to smooth the national electricity demand, as shown in the *co-op* strategy, a significant portion of solar energy would be stored and discharged in the HESSs appropriately, resulting in a reduction in fluctuations in electricity demand.

The third section discussed the impact of integrating EVs in New Zealand households on the national electricity demand. Different charging strategies of the EV (*slow*, *greedy*, *saver*, *co-op*) were compared, and it was analysed how EVs in combination with solar PV and HESSs at a household level impact national electricity demand. It became evident that if the EVs follow the *slow* strategy, there is only a slight increase in daily and annual peak demand, and interestingly, there is an overall smoother load at the 10 and 50 % adoption level, as most charging occurs when national electricity demand is low. If the EVs follow the *saver* strategy, however, there is a significant increase in daily and annual national peak demand, which would be disruptive to the current electricity sector, if there is a large uptake. If the EVs follow a *co-op* strategy, it is evident that the EV fleet can be utilised as grid energy storage, and reduce daily and annual peak demand at the 10 and 50 % adoption level, as well as provide a more balanced load at all adoption levels. If EVs are utilised to store excess solar energy, it is evident from these simulated scenarios, that there are no occasions when solar generation exceeds national electricity demand, and therefore, no solar energy is stored in the EVs. In the *co-op* strategy, it is evident that the EVs can charge with solar energy to maintain a smooth national electricity demand. However, in this strategy sudden drops can occur during midday, when the majority of EVs are unplugged, which can be problematic as it would require a sudden shut down of multiple power plants and spillage of electricity. The inclusion of HESSs have the potential to reduce the severity of these

sudden drops, however, it is also evident that the amount of additional energy that is shifted from the inclusion of HESSs decreases significantly with higher adoption levels. This is due to the limitations in smoothing the national electricity demand to the 7-day moving average (*limit*).

Chapter 10

Summary and Conclusions

This thesis has evaluated the potential impact the inclusion of new technologies in a household has on electricity demand at a household, community, and national level.

Chapter 2 made evident that New Zealand's electricity sector uses a large amount of renewable generation (approximately 80%), which the New Zealand government has set out to increase even further (to 90% by 2025), along with a decrease of fossil fuel dependence and a reduction of greenhouse gas emissions. Hydro generation is a predominant part of New Zealand's renewable generation mix, and plays a significant role in dealing with peaks and variability in electricity demand, which sets it apart from many other countries. However, with a high reliance on hydro generation, the electricity sector is vulnerable to the natural environment, in this case the variability of rainfall, which affects security of supply. The residential sector accounts for a large share of the national electricity demand and has the most significant influence on the national peak demand. Thus, managing electricity demand at the residential sector by using new energy technologies is crucial to manage peak load and increase renewable generation. This research provided insights into this issue through investigating the main research question:

How can new energy technologies within a household potentially impact New Zealand's residential electricity demand profiles?

Findings regarding three sub-questions, which were established to provide insight into this research question, are discussed as follows.

10.1 Which new technologies are available at the household level?

The first sub-question: *which new technologies are available at the household level?* lead to a literature review, presented in Chapter 2, which showed that among the new technologies, the greatest disruption comes from solar PV systems, electric vehicles (EVs), and home energy storage systems (HESSs). This disruption is a result of the electrification of the transport sector and the decentralization of electricity supply through distributed generation and distributed storage. These technologies, therefore, were further investigated in the remaining sub-questions.

10.2 What are the characteristics and use of these technologies?

The second research question: *what are the characteristics and use of these technologies?* lead to the investigation and development of various charging strategies to simulate possible behaviours an EV and HESS can follow. Three charging strategies were developed for the HESS which: brings maximum savings to the consumer (*saver*), smoothes electricity consumption (*co-op*), or a combination of both (*hybrid*). The charging strategies for the EV include: a behaviour where the vehicle has vehicle-to-grid capabilities and is utilised to smooth electricity consumption (*co-op*), or where there are no vehicle-to-grid capabilities and the EV charges at a specific charge rate and time to reach its desired

energy capacity (these strategies include the *slow*, *greedy*, and *saver* charging strategy). Furthermore, due to a gap in literature, a simulation tool (NZSPOT) was developed to calculate fine-grained (hourly) power output for solar panels, at different configurations, at any location in New Zealand. Four main findings were produced from simulating a solar PV system at 10 locations in New Zealand using this tool:

- Changing the tilt angle on solar panels has a large impact on the seasonal energy output, however, little impact on annual output.
- The annual output from a static solar PV system varies greatly at different locations, with a simulated average of approximately 2012kWh, a minimum of 1656kWh (Christchurch), and a maximum of 2357kWh (Nelson).
- Tilt tracking results in an increase of annual energy output of approximately 5%, while azimuth tracking provides an increase of approximately 20%.
- Dual axis tracking provides approximately 30% more energy during the year, however, costs approximately 17% more than adding 30% additional solar panels, which would result in a similar energy output.

The developed charging strategies for an HESS and EV, along with solar PV data from NZSPOT were used in the following sub-question to understand their impacts on electricity demand.

10.3 How do the characteristics and use of these technologies impact the household, the community, and the nation?

The third research question: *how do the characteristics and use of these technologies impact the household, the community, and the nation?* serves as the core component of this research, and was addressed through two steps, starting with gathering accurate household, community, and national electricity usage data. The national electricity usage data was taken from a governmental webpage, for each

half hour period in 2015. However, due to the limited availability of fine-grained electricity usage data at a household level, a small scale quantitative survey with household dwellers in collaboration with the local distribution company (WEL Networks) was carried out. The collected data from this survey was also used to develop a modelling approach to generate household electricity consumption data, which was used to simulate electricity consumption for a community of households. Another outcome of this survey was a publicly available web interface of the collected data, allowing the survey participants and fellow researchers to compare different household energy usage. Furthermore, an analysis of the collected data from this survey produced five main findings:

- There is no significant correlation between electricity usage and the collected household variables.
- There are no days during the week that have a significantly different daily energy usage.
- The morning peak in the weekend is typically two hours later than on weekdays.
- Most households used 10% more electricity in the weekend.
- On average, daily electricity consumption was 19 kWh, with a summer day typically using 16.6 kWh, and a winter day using approximately 42% more with 23.6 kWh.

The second step in answering the third sub-question was to create a web-based tool (HEUS), capable of utilising the solar PV data from NZSPOT, and simulating EVs and HESSs with different charging strategies on electricity consumption, findings of which are discussed as follows.

10.3.1 Household

The core findings from simulating a solar PV system, HESS, and a EV in 16 households (households taken from the *in-depth* survey), are based on the mean of all households, and outlined as follows:

-
- Only approximately half of the generated energy of a 3kW solar PV system was directly consumed (i.e. without an HESS and EV). Furthermore, with a larger solar PV capacity, the household would typically only utilise the additional generated energy during the start and end of generation times.
 - Solar PV has little to no reduction in daily and annual peak demand.
 - An HESS has the potential to significantly reduce daily and annual peak demand (by 54 and 11 %) or significantly increase daily and annual peak demand (by 200 and 55 %), depending on its charging strategy.
 - A household with an HESS, prioritised to achieve maximum savings, will not use electricity from the grid for approximately 30% of the year.
 - Incorporating an HESS to store only excess solar energy in a household with a solar PV system, will result in the HESS utilising less than half of its battery capacity.
 - An EV increases a household's energy demand by approximately 40%.
 - If the charging of the EV is left uncontrolled, the daily peak demand can almost double, and the annual peak demand increase by approximately 50%.
 - An EV only utilises a small portion of excess solar energy, since the EV is typically unplugged during high generation times.
 - The current upfront cost of the HESS results in a significant net loss, and therefore, the maximum cost savings is achieved without this technology as shown in Figure 10.1.

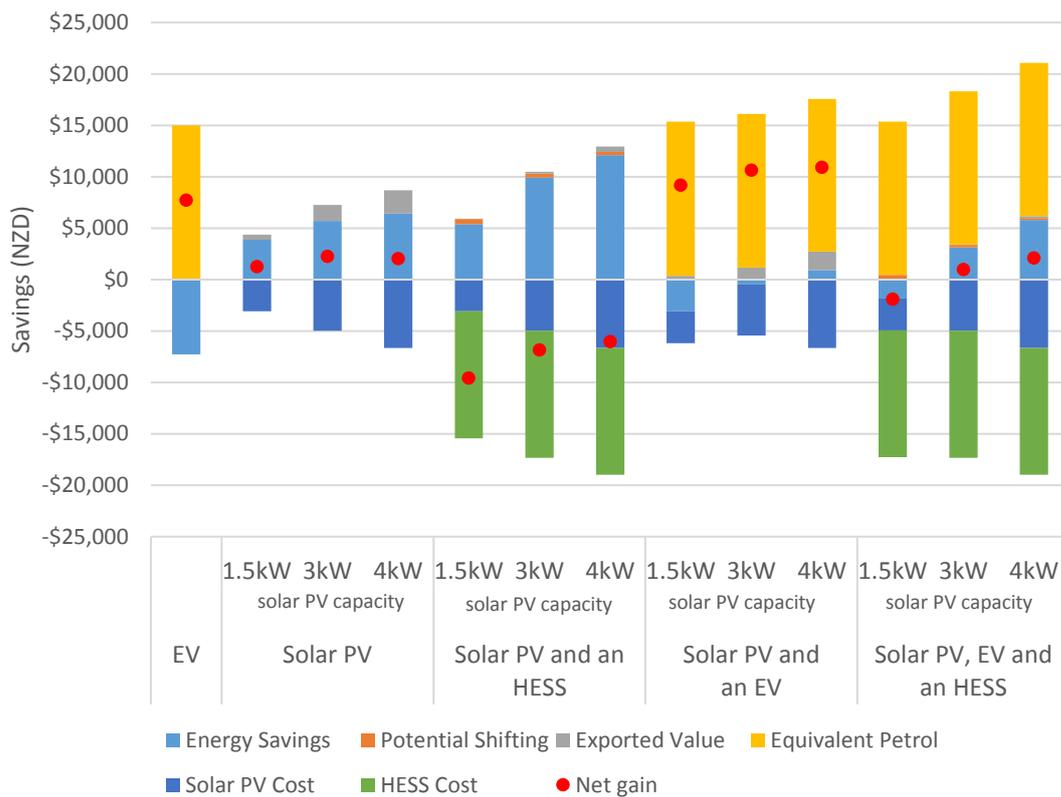


Figure 10.1: A comparison of the mean cost savings of the inclusion of different technologies, over a 10-year period, following the *saver* strategy within 16 households from the *in-depth* survey.

10.3.2 Community

The core findings from simulating various adoption levels of solar PV systems, HESSs, and EVs on a simulated community of 100 households are:

- At a 10% adoption level, all solar energy can be distributed within the community.
- There is little to no significant benefit in having more than 16% of households with an HESS smoothing the community’s electricity demand (to the 7-day moving average).
- In a community with 100% uptake of HESSs and solar PV, less than 1% of solar energy is potentially exported.

-
- At the 50 and 100 % adoption level of EVs and solar PV systems, the inclusion of EVs results in approximately 50% less potentially exported solar energy.

10.3.3 Nation

The core findings from simulating various adoption levels of solar PV systems, HESSs, and EVs in households across New Zealand are:

- During a year, solar PV systems are expected to generate enough energy to replace approximately 1.5, 7.5, and 15 % of the national electricity demand, at a 10, 50 and 100 % adoption level, respectively.
- Solar PV has little impact on the national afternoon peak demand.
- If HESSs are prioritised to smooth the national electricity demand to a 7-day moving average, only 30% of their storage capacity is utilised, at a 100% adoption level.
- If HESSs are prioritised to achieve maximum cost savings for the consumer, there is a significant increase in the national demand for over 1000 hours in a year, and these HESSs have the potential to completely reduce the national electricity demand for approximately 1400 hours in a year.
- At a 100% adoption level, if all EVs charge at the same time, the daily and annual peak demand is almost doubled.

10.4 Discussion and Future Work

Three web tools were developed, in order to answer the main research question of this thesis. These web tools and model were a valuable resource for this research. To ensure the continuity and usefulness of these resources, the following improvements are suggested.

- Database of Household Consumption: This tool could be expanded to allow fellow researchers and possibly household owners to upload their consumption data.
- NZSPOT: The addition of various weather stations from different countries, or possibly the ability to retrieve weather data from a data centre that provides irradiance information from any location on the globe.
- HEUS: The simplification of the interface of this tool, to allow the average household owner/dweller to understand the possible monetary value new technologies have.
- Household model: Tackling the time correlation issue in the household model and the ability to forecast consumption depending on parameters e.g. weather conditions, household size, and number of occupants.

The results presented from the use of these web tools and household model provide valuable insights into the potential impacts the selected technologies have on New Zealand's residential electricity demand profiles. It has to be noted, however, that in the simulations, it was assumed all households have the same electricity tariff, and technologies follow the same behaviour. In reality though, households across the nation have varying electricity tariffs, and utilise technologies differently. As a result, less severe impacts across the nation are to be expected, especially in the *saver* strategy, as the EVs and HESSs will charge at different times according to their electricity tariff. This is a possible area for future work e.g. simulating the impact of different electricity tariffs and technology characteristics.

If there is a large uptake of solar PV at a household level, it is also likely this uptake would be extended to the commercial and industrial sectors. Similarly, other renewable generation, such as wind, geothermal, and tidal generation, is also expected to become more commonly used in the future. Therefore, possible future work could analyse the balancing potential of these technologies with varying adoption levels of different renewable generation. This information could provide insights into how these technologies in combination with different renewable generation can help New Zealand reach its energy strategy goals, and how this

impacts security of supply. This would require accurate modelling of New Zealand's existing electricity industry, and modelling of possible future power plants in a New Zealand setting e.g. tidal generation.

It was evident from this research that the EV and HESS have a significant potential in balancing the national electricity demand, benefiting the electricity sector. However, the current electricity tariff incentivises a more disruptive impact on the national electricity sector. Given these results, and the imperatives of the New Zealand energy strategy, it would make sense to carry out future work to develop an electricity tariff which captures the benefits presented in the *co-op* strategy, while preserving consumer choice.

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Appendices

Appendix A

Solar Panel Simulation Results

This appendix contains material from NZSPOT, a simulation created as part of this research to estimate the hourly power output from a solar PV system in New Zealand, as described in Chapter 4.

Table A.1 provides results from NZSPOT for a solar PV system at Kaitaia, Dargaville, Auckland, Hamilton, and New Plymouth.

Table A.2 provides similar results as Table A.1, however focuses on results for Wellington, Nelson, Greymouth, Christchurch, and Invercargill.

Table A.1: NZSPOT output for a 1.5kW solar PV system in Kaitaia, Dargaville, Auckland, Hamilton, and New Plymouth.⁷⁸									
		Solar Panel Setup							
		Static system			Tilt Tracking		Azimuth Tracking		Dual Tracking
		Latitude tilt	Winter tilt	Summer tilt	every season	every month	2 Hour ⁷⁹	Continuous	
Kaitaia	Annual generation (kWh)	1986	1968	1950	2068	2081	2359	2387	2584
	Generation difference (%)	Benchmark	-0.91	-1.81	4.13	4.78	18.78	20.19	30.11
Dargaville	Annual generation (kWh)	2092	2073	2054	2181	2194	2489	2522	2723
	Generation difference (%)	Benchmark	-0.91	-1.82	4.25	4.88	18.98	20.55	30.16
Auckland	Annual generation (kWh)	2118	2100	2078	2206	2219	2508	2541	2733
	Generation difference (%)	Benchmark	-0.85	-1.89	4.15	4.77	18.41	19.97	29.04
Hamilton	Annual generation (kWh)	2080	2064	2041	2162	2175	2466	2502	2684
	Generation difference (%)	Benchmark	-0.77	-1.88	3.94	4.57	18.56	20.29	29.04
New Plymouth	Annual generation (kWh)	2015	1992	1983	2090	2102	2399	2438	2601
	Generation difference (%)	Benchmark	-1.14	-1.59	3.72	4.32	19.06	20.99	29.08

⁷⁸ Assuming an inverter efficiency of approximately 95% and a system loss of 14%.

⁷⁹ Tracking the sun's azimuth angle from 11 am to 1 pm

Table A.2: NZSPOT output for a 1.5kW solar PV system in Wellington, Nelson, Greymouth, Christchurch, and Invercargill.⁷⁸									
		Solar Panel Setup							
		Static system			Tilt Tracking		Azimuth Tracking		Dual Tracking
		Latitude tilt	Winter tilt	Summer tilt	every season	every month	2 Hour ⁷⁹	Continuous	
Wellington	Annual generation (kWh)	2050	2014	2027	2120	2134	2466	2515	2657
	Generation difference (%)	Benchmark	-1.76	-1.12	3.41	4.1	20.29	22.68	29.61
Nelson	Annual generation (kWh)	2357	2335	2317	2445	2461	2846	2903	3086
	Generation difference (%)	Benchmark	-0.93	-1.7	3.73	4.41	20.75	23.17	30.93
Greymouth	Annual generation (kWh)	1933	1910	1903	1998	2008	2265	2305	2428
	Generation difference (%)	Benchmark	-1.19	-1.55	3.36	3.88	17.18	19.24	25.61
Christchurch	Annual generation (kWh)	1656	1631	1634	1706	1717	1950	1987	2083
	Generation difference (%)	Benchmark	-1.51	-1.33	3.02	3.68	17.75	19.99	25.79
Invercargill	Annual generation (kWh)	1834	1804	1814	1886	1896	2158	2209	2296
	Generation difference (%)	Benchmark	-1.64	-1.09	2.84	3.38	17.67	20.45	25.19

Appendix B

Material for Preliminary Survey

This appendix contains material from the *preliminary* survey, which was conducted to investigate which and when appliances were used within households, as described in Chapter 5.

B.1 The approval letter received from the Human Research Ethics Committee of the Computing and Mathematical Sciences.

B.2 The agreement letter received from WEL Networks, agreeing they will send the researcher electricity usage data.

B.3 The email sent to participants which outlines the researcher and invites them to partake in the survey.

B.4 The Participation Information Sheet, which describes the purpose of this study.

B.5 The Research Consent Form, which is signed by each participant before the interview.

B.6 The Research Questions, which was asked during the participants interview.

B.1 Approval Letter

Computing and Mathematical Sciences
Rorohiko me ngā Pātaitao Pāngarau
The University of Waikato
Private Bag 3105
Hamilton
New Zealand

Phone +64 7 838 4021
www.fcms.waikato.ac.nz



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

7 November 2013

Joris Suppers
C/- Department of Computer Science
THE UNIVERSITY OF WAIKATO

Dear Joris

Request for approval to conduct a research study with human participants

I have considered your request to conduct a study for your PhD research project *Retrieving and understanding household electricity consumption*.

The purpose of the study is gather household electricity consumption information for the purpose of gaining an understanding on possible peak reduction load smoothing and energy costs.

I note that WEL Networks have provided a letter stating they will release the information to you on receipt of the participating household providing permission for them to do so.

An Identity Number will be allocated to each household so that no personal details of will be used in any publications or reports.

The procedure described in your request is acceptable.

The research participants' information sheet, consent form and questionnaire meet the requirements of the University's human research ethics policies and procedures.

Yours sincerely,

A handwritten signature in black ink that reads "Lyn Hunt".

Lyn Hunt
Human Research Ethics Committee
School of Computing and Mathematical Sciences

B.2 Agreement Letter

6th November 2013



WEL Networks Limited
114 Maul Street, Te Rapa

PO Box 925
Hamilton 3240
New Zealand

Telephone +64 7 850 3100
Fax +64 7 850 3210

Email connect@wel.co.nz
www.wel.co.nz

RE: Provision of Smart Meter Data

To whom it may concern,

WEL Networks Ltd agrees to provide power consumption information obtained from WEL's Smart Boxes to Joris Suppers for the purpose of use in his research project, where he can provide WEL with proof of customer consent for this information to be released. The information provided, is not to be used for any other purpose or passed to any other organisation.

Yours faithfully,

A handwritten signature in blue ink, appearing to read 'John Versluys', is written over a light blue horizontal line.

John Versluys

Distribution Automation Manager

WEL Networks Ltd

B.3 Invitation Email

Greetings All,

I'm Joris a computer science PhD student, I am conducting a study to try to establish a freely available database on electricity consumption within households and would like to ask help from anyone who lives in the Waikato region and has a Smart Meter / Smart Box installed.

This survey is only 10 questions, and is easily answered when the smart meter ID (see below) is known)

They are typically next to your electricity meter and look like this:



To Survey: www.something.com

These Smart Meters monitor your electricity usage in 30 min intervals, and sends these readings to the distribution company (WEL).

With your permission, I would like to retrieve these readings from the distribution company, so that I can develop a website which holds a database of electricity consumption within households. If you give me permission to use your household's data, WEL have agreed to provide me with your historical readings from when the meter was installed or from when you have moved into this household. This data will give a better understanding of when and how much electricity is being used, how different variables effect power consumption and will also provide a free database of household power usage which is a crucial part for future research projects.

You will also be able to see how much electricity your household consumes.

This study has been approved by the FCMS Ethics Committee, and if you would like to participate please complete the survey at the link below.

If you would like to help, or have any further question please don't hesitate in emailing me.

Best Regards

Joris Suppers

Email

Sj78@students.waikato.ac.nz

B.4 Participation Information Sheet

Participant Information Sheet



Ethics Committee, Faculty of Computing and Mathematical Sciences

Project Title

Building a publically available household electricity consumption database

Purpose

This research is conducted as partial requirement for Computer Science PhD Thesis. This project requires the researcher to choose up to one hundred households within the Waikato region that have smart meters installed, and retrieve their electricity consumption data from the distribution company (WEL Networks) which own these meters. This data will give an understanding in where and how much electricity is being used within the household. The data collected will be previous usage in 30-minute intervals from when the smart meter was installed or from when the occupant moved into the household. The data collected will be anonymous and be stored in a database, which will be made publically available for individuals to see how different variables effect power consumption within the household.

What is this research project about?

Establish a website database which holds household energy usage for up to 100 households, this database allows users to sort households by energy sources used, occupants, total income and if the house's location is rural or suburban. The purpose of this database is to provide fellow researchers with a dataset to help with their research, and additionally raise energy awareness to the public audience. This energy awareness is achieved by providing an interactive platform where the user can see how different variables effect power consumption within a household.

What will you have to do and how long will it take?

The researcher will need your permission to retrieve your electricity consumption from the distribution company (WEL Networks); this means a copy of the consent form will be made for WEL Networks, and an 8 digit number from the smart meter is needed (If permission is granted the researcher could do this). While analyzing the data collected the researcher may ask for relevant information such as which and when appliances are used within the household.

What will happen to the information collected?

The household energy consumption data collected from WEL, will be used by the researcher to build a publically available database. The researcher and supervisor will be privy to your personal details and email responses. The researcher will keep personal details such as names and addresses in a separate document then the electricity consumption data and will treat this document with the strictest confidentiality. No participants will be named in the database and every effort will be made to disguise their identity. An ID will be assigned for each household so that no personal information will be in any publications and/or reports.

Declaration to participants

If you take part in the study, you have the right to:

- Refuse to answer any particular question, and to withdraw from the study before analysis has commenced on the data.
- Ask any further questions about the study that occurs to you during your participation.
- Be given access to a summary of findings from the study when it is concluded.

Who's responsible?

If you have any questions or concerns about the project, either now or in the future, please feel free to contact either:

Researcher:

Name: *Joris Suppers*

Email: *sj78@students.waikato.ac.nz*

Supervisor:

Name: *Mark Apperley*

Email: *m.apperley@cs.waikato.ac.nz*

B.5 Consent Form

Research Consent Form



Ethics Committee, Faculty of Computing and Mathematical Sciences

Building a publically available household electricity consumption database

Consent Form for Participants

I have read the **Participant Information Sheet** for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that I am free to withdraw from the study before analysis has commenced on the data, or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the researcher has commenced analysis on my data. I agree to provide information to the researchers under the conditions of confidentiality set out on the **Participant Information Sheet**.

I agree to participate in this study under the conditions set out in the **Participant Information Sheet**, and declare **the researcher is allowed to retrieve electricity consumption from this smart meter** with this ID stated below.

ID that will be used: _____

8 Digit Number: _____

If you moved in after the smart meter was installed what date did you move in?

Day: _____ Month: _____ Year: _____

Name: _____

Signed: _____

Date: _____

Researcher:

Name: *Joris Suppers*
Email: *sj78@students.waikato.ac.nz*

Supervisor:

Name: *Mark Apperley*
Email: *m.apperley@cs.waikato.ac.nz*

B.6 Research Questions

Hello,

Thank you for all for choosing to help me in my research, I would like to ask you a few questions to help me better understand your electricity household data. This survey is best done when you are within your household as you will need to read the smart meter's number.

1. What Energy sources are used to heat your household?

Electricity mains gas bottled gas fossil fuels (coal, gas) no heating is done

2. Do you use a heat pump?

3. What Energy sources are used for cooking inside your household?

Electricity mains gas bottled gas fossil fuels (coal, gas) no cooking is done

4. What Energy sources are used for water-heating inside your household?

Electricity mains gas bottled gas fossil fuels (coal, gas) no water heating

5. How many occupants in the households?

Adults: 1 2 3 4 5+ Children: 1 2 3 4 5+

6. What is the approximate total income of the household?

20k or less 30k – 50k 50 – 70k 70k or more

7. Are solar panels installed?

No yes approximate size : 1 kW or less 1-2kW 2kW – 4 kW 4kW or more

8. What best describes the household location?

Urban Rural

I will also need the 8 digit number on your Smart Meter / Smart Box this is used to give to the distribution company (WEL) which will provide me with the previous Energy readings from when the meter was installed. This meter is typically next to your electricity meter, if you are not comfortable in getting this number please don't hesitate in asking me, I will gladly come get this number at a suitable time for you.



1. What is your 8 digit number?
2. If you moved in after the smart meter was installed what date did you move in?

Day: Month: Year:

(attach participation and consent form)

If any further questions arise during my study I may email you, or if you have any further questions please email me.

I would like to thank you again for your participation.

Regards
Joris Suppers

Email
sj78@students.waikato.ac.nz

Appendix C

Material for In-depth Survey

This appendix contains material from the *in-depth* survey, which was conducted to collect household electricity consumption data, as described in Chapter 5. Participants for this survey were either gathered through email or through door knocking at different districts in Hamilton, New Zealand.

C.1 The approval letter received from the Human Research Ethics Committee of the Computing and Mathematical Sciences.

C.2 The agreement letter received from WEL Networks, agreeing they will send the researcher electricity usage data.

C.3 The email sent to participants which outlines the researcher and invites them to partake in the survey.

C.4 The Participation Information Sheet, which describes the purpose of this study.

C.5 The Research Consent Form, which was read and signed by participants.

C.6 The Research Questions, given to participants in the web-based survey, and asked in person.

C.1 Approval Letter



C.2 Agreement Letter



Energy Information Research Group
University of Waikato
Hamilton

Hamilton 9/7/2015

WEL Networks Ltd agrees to provide power consumption information obtained from WEL's Smart Boxes to Joris Suppers for the purpose of use in his PhD project "Smart Grids, the Internet of Energy, and Energy Use Efficiency", where he can provide WEL with proof of customer consent for this information to be released. The information provided is not to be used for any other purpose or passed to any other organisation.

Regards

A handwritten signature in black ink, appearing to read 'Anna Doerr', written in a cursive style.

Anna Doerr

METERING SERVICES BUSINESS MANAGER

C.3 Invitation Email

Greetings,

I'm Joris a Computer Science PhD student. I am conducting a study to establish a publicly available database on electricity consumption within households; this database will also be free of charge. I would like to ask help from anyone who lives in the Waikato region, has a Smart Meter / Smart Box installed (Shown in the picture below) and is the energy account holder.

If you agree to participate, your commitment will be to complete a short survey, and to give me permission to access your historical smart meter data. This survey should only take a few minutes, and is easily answered once your smart meter ID is known; this is an 8-digit number shown below, and you have proof (e.g. billing statement) of your energy usage.



These Smart Meters monitor your electricity usage in 30 minute intervals, and send the readings to the distribution company (WEL), who then send this to your electricity retailer.

With your permission I would retrieve these readings from the distribution company WEL, so that I can develop a website which holds a database of electricity consumption within households. This data will give a better understanding of when and how much electricity is being used, how different variables affect power consumption and will also provide a free database of household energy usage which is a crucial part for future research projects.

If you participate, your household data will be anonymised and you will be given an ID number so you can see how your consumption compares with others.

So please if you have a Smart Meter installed, help build this database by participating in this survey. I would also appreciate it, if you could ask anyone who you think might be interested in participating.

Link To Survey: <http://www.joris.co.nz/survey>

If the above link is not working try: <http://www.123contactform.com/form-1487969/Household-Energy-Survey>

As a result of collecting this data, I will create a report on how these different variables affect power consumption. If you would like a copy of this report, please email me.

If you would like to participate by filling in a word document and send it via email, meet in person, or if you have any further question please don't hesitate to email me.

Best regards, Joris Suppers Email: Sj78@students.waikato.ac.nz

C.4 Participation Information Sheet

Participant Information Sheet



Ethics Committee, Faculty of Computing and Mathematical Sciences

Project Title

Building a household electricity consumption database

Purpose

This research is conducted as partial requirement for Computer Science PhD Thesis. This project requires the researcher to choose up to one hundred households within the Waikato region that have smart meters installed, and retrieve their electricity consumption data from the distribution company (WEL Networks) which own these meters. This data will give an understanding in where and how much electricity is being used within the household. The data collected will be previous usage in 30-minute intervals from when the smart meter was installed or from when the occupant moved into the household. The data collected will be anonymous and be stored in a database, which will be made publically available for individuals to see how different variables effect power consumption within the household.

What is this research project about?

Establish a website database which holds household energy usage for up to 100 households, this database allows users to sort households by energy sources used, occupants, total income and if the house's location is rural or suburban. The purpose of this database is to provide fellow researchers with a dataset to help with their research, and additionally raise energy awareness to the public audience. This energy awareness is achieved by providing an interactive platform where the user can see how different variables effect power consumption within a household.

What will you have to do and how long will it take?

The researcher will need your permission to retrieve your electricity consumption from the distribution company (WEL Networks); this means a copy of the consent form will be made for WEL Networks, and an 8 digit number from the smart meter is needed (If permission is granted the researcher could do this). While analyzing the data collected the researcher may ask for relevant information such as which and when appliances are used within the household.

What will happen to the information collected?

The household energy consumption data collected from WEL, will be used by the researcher to build a publically available database. The researcher and supervisor will be privy to your personal details and email responses. The researcher will keep personal details such as names and addresses in a separate document than the electricity consumption data and will treat this document with the strictest confidentiality. No participants will be named in the database and every effort will be made to disguise their identity. An ID will be assigned for each household so that no personal information will be in any publications and/or reports.

Declaration to participants

If you take part in the study, you have the right to:

- Refuse to answer any particular question, and to withdraw from the study before analysis has commenced on the data.
- Ask any further questions about the study that occurs to you during your participation.
- Be given access to a summary of findings from the study when it is concluded.

Who's responsible?

If you have any questions or concerns about the project, either now or in the future, please feel free to contact either:

Researcher: Name: *Joris Suppers* Email: sj78@students.waikato.ac.nz

Supervisor: Name: *Mark Apperley* Email: m.apperley@cs.waikato.ac.nz

DATABASE WEBSITE: <http://ci.cms.waikato.ac.nz/data>

YOUR HOUSE ID: _____

C.5 Consent Form

Research Consent Form



Ethics Committee, Faculty of Computing and Mathematical Sciences

Building a household electricity consumption database

Consent Form for Participants

I have read the **Participant Information Sheet** for this study and understand the details of this study. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that I am free to withdraw from the study before analysis has commenced on the data, or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the researcher has commenced analysis on my data. I agree to provide information to the researchers under the conditions of confidentiality set out on the **Participant Information Sheet**.

I agree to participate in this study under the conditions set out in the **Participant Information Sheet**, and declare that I am the main account holder of my electricity account and **the researcher is allowed to retrieve electricity consumption from this smart meter** with this ID stated below.

Smart Meter ID: _____

If you moved in less than a year ago what date did you move in?

Day: _____ Month: _____ Year: _____

Name: _____

Signed: _____

Date: _____

PLEASE ATTACH PROOF OF BEING THE MAIN ACCOUNT HOLDER

Researcher:

Name: *Joris Suppers*
Email: *sj78@students.waikato.ac.nz*

Supervisor:

Name: *Mark Apperley*
Email: *m.apperley@cs.waikato.ac.nz*

C.6 Research Questions

University of Waikato: Household Energy Survey



Random ID: _____

8 Digit Smart Meter Number: _____

Have you been living here more than a year? _____ If not what date you moved in: _____

1. Heat your household?
Electricity mains gas bottled gas fossil fuels (coal, gas) wood no heating is done
2. Do you use a heat pump?
Yes No
3. Cooking inside your household?
Electricity mains gas bottled gas fossil fuels (coal, gas) wood no cooking is done
4. Water-heating inside your household?
Electricity mains gas bottled gas fossil fuels (coal, gas) wood no heating is done
5. How many occupants in the households?
Adults: 1 2 3 4 5 6 7+ Children: 0 1 2 3 5 6 7+ Regular Visitors?(Children):
6. What is the approximate total income of the household?
20k or less 20k – 50k 50 – 70k 70k or more
7. Are solar panels installed?
No Yes approximate size : 1 kW or less 1-2kW 2kW – 4 kW 4kW or more Not sure
8. What best describes the household location?
City Country
9. Other large energy users or generators? (e.g. pools, wind turbine)

Email (for updates or questions):

Appendix D

Material for Follow up Interviews

This appendix contains material from the follow up interviews from four of the participants from the *in-depth* survey, as described in Chapter 5. These interviews were conducted in an informal matter, with the purpose to present results from the household electricity usage simulation tool (HEUS) created, explained in Chapter 6, using the participant's electricity data.

D.1 The approval letter received from the Human Research Ethics Committee of the Computing and Mathematical Sciences.

D.1 Approval Letter

Computing and Mathematical Sciences
Korohiko me ngā Pūtaiao Pāngarau
The University of Waikato
Private Bag 3105
Hamilton
New Zealand

Phone +64 7 838 4021
www.fcms.waikato.ac.nz



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

29 July 2016

Joris Suppers,
C/- Department of Computer Science
THE UNIVERSITY OF WAIKATO

Dear Joris

Request for approval to conduct a user study with human participants

On the basis of the information you have provided on the FCMS Preliminary Ethics Application Form relating to your research "Presenting simulation results", the Committee has given you approval to proceed with your proposed study.

We wish you well with your research.

A handwritten signature in black ink, appearing to read 'Masood Masoodian'.

Masood Masoodian
Human Research Ethics Committee
School of Computing and Mathematical Sciences

Appendix E

Household Simulation Calculations

This appendix contains material used by the household simulation tool (HEUS), described in Chapter 6, to simulate the impact solar PV systems, home energy storage systems, and electric vehicles have on a household's electricity consumption.

E.1 Cumulative probability of vehicle travel times for each hour of the day for all days of the week.

E.2 The 15 algorithms used by HEUS to simulate the technologies in a household.

E.1 Cumulative probability of vehicle travel times

	Hour of Day	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Morning cumulative probability	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1	0.027	0.003	0.002	0.004	0.003	0.005	0.017
	2	0.037	0.006	0.004	0.006	0.006	0.008	0.024
	3	0.047	0.008	0.007	0.007	0.008	0.011	0.027
	4	0.053	0.010	0.008	0.009	0.010	0.013	0.031
	5	0.061	0.020	0.015	0.015	0.017	0.022	0.040
	6	0.078	0.043	0.037	0.036	0.039	0.046	0.061
	7	0.115	0.109	0.106	0.106	0.105	0.113	0.103
	8	0.190	0.292	0.281	0.302	0.292	0.294	0.188
	9	0.336	0.610	0.610	0.624	0.610	0.604	0.365
	10	0.629	0.816	0.814	0.822	0.817	0.812	0.636
11	1.000	1.000	1.000	1.000	1.000	1.000	1.000	
Afternoon cumulative probability	12	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	13	0.149	0.120	0.113	0.106	0.107	0.113	0.149
	14	0.291	0.220	0.217	0.209	0.207	0.216	0.280
	15	0.424	0.337	0.335	0.331	0.319	0.326	0.403
	16	0.551	0.489	0.488	0.464	0.465	0.477	0.526
	17	0.681	0.638	0.628	0.608	0.614	0.624	0.651
	18	0.788	0.791	0.778	0.764	0.771	0.771	0.768
	19	0.866	0.877	0.873	0.862	0.863	0.864	0.857
	20	0.922	0.928	0.924	0.919	0.920	0.922	0.912
	21	0.960	0.961	0.961	0.956	0.959	0.956	0.947
	22	0.987	0.988	0.987	0.985	0.985	0.981	0.976
	23	1.000	1.000	1.000	1.000	1.000	1.000	1.000

E.2 Calculations

The different algorithms used in the webpage tool created to simulate electricity consumption when using an energy management system (EMS). This tool is accessible at <http://ei.cms.waikato.ac.nz/>.

Algorithm 1: Procedure to simulate electricity consumption.

```
1  procedure simulation()
2    for each time do
3       $e = \mathbf{e}_{time}$ 
4       $l = \text{user defined limit}^{80}$ 
5       $g = \mathbf{g}_{time}$ 
6       $p = \text{charge price}$ 
7       $a = \text{lookahead}$ 
8      useGeneration( $e, l, g$ )
9      if  $evStrategy == cooperative$  then
10         addEVCapacityToHSS( $time, home, a, p, \mathbf{ev}, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
11      else
12         chargeEV( $e, maxlimit, \mathbf{ev}$ )
13      end if
14      storeGeneration( $home, g$ )
15      useOrExportGeneration( $e, g$ )
16      adjustLimit( $home_{capacity}, time, a, l, maxlimit, p, maxchargeprice, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
17      chargeOrDischargeHSS( $time, e, l, home, p, dischargeprice, \mathbf{p}$ )
18    end for
19  end procedure
```

⁸⁰ The *limit* can be set by the user to one of seven different values, these include: (1) The moving average of all previous values, (2) the average of the previous week, (3) the average of the previous month, (4) a user defined value, (5) 20% below the previous week's average, (6) 80% below the previous week's average, and lastly (7) double the previous week's average.

Where

g	is a vector holding generation data for each time-period
e	is a vector holding energy usage data for each time-period
p	is a vector holding energy price data for each time-period
<i>car</i>	is an object describing an electric vehicle. This object contains the electric vehicles plug-in time, plug-out time, energy requirement, current capacity, maximum battery capacity, and maximum charge/discharge rate. The objects plug-in time, plug-out time, and energy requirement is recalculated when the electric vehicle is plugged out, this is to represent new trip times.
ev	is a vector holding all <i>car</i> objects (electric vehicles) in this simulation
<i>evStrategy</i>	is an object describing what strategy to charge the connected electric vehicles i.e. slow, greedy, or co-op.
<i>home</i>	is an object describing the home energy storage system. This object contains the HSS's current capacity, maximum battery capacity, and maximum charge/discharge rate.
<i>homeStrategy</i>	is an object describing what strategy the home energy storage system is in i.e. co-op, saver, or hybrid.

Algorithm 2: Use generation to reduce load to limit.

```
1  procedure useGeneration(e, l, g)
2      n = 0
3      if e > l then
4          n = e - l
5          if g > n then
6              e = l
7              g -= n
8          else
9              e -= g
10             g = 0
11         end if
12     end if
13 end procedure
```

Algorithm 3: Set storage capacities.

```
1  procedure addEVCapacityToHSS( $t, h, a, p, \mathbf{ev}, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
2       $m = 0$ 
3       $c = h_{capacity}$ 
4      for each  $car$  in  $\mathbf{ev}$  do
5          if  $car_{plug-in+1} == t$  then
6               $c += car_{capacity}$ 
7               $h_{maxcapacity} += car_{maxcapacity}$ 
8          end if
9          if  $car_{plug-out+1} == t$  then
10              $o = nowEVGoals(t, m)$ 
11              $n = energyNeeded(t, a, c, l, p, \mathbf{ev}, \mathbf{e}, \mathbf{g}, \mathbf{p})$ 
12              $u = 0$ 
13             if  $c - o > n$  then
14                  $u = n$ 
15             else if  $c > o$  then
16                  $u = c - o$ 
17             end if
18              $car_{capacity} = c - u - o + car_{goal}$ 
19             if  $car_{capacity} > car_{max-capacity}$  then
20                  $u += car_{max-capacity} - car_{capacity}$ 
21                  $car_{capacity} = car_{max-capacity}$ 
22             end if
23             if  $car_{capacity} < car_{goal}$  then
24                  $n = car_{goal} - car_{capacity}$ 
25                 if  $u < n$  then
26                      $car_{capacity} += u$ 
27                 else
28                      $car_{capacity} += n$ 
29                 end if
30             end if
31              $c -= car_{capacity}$ 
32              $m -= car_{goal}$ 
33              $h_{maxcapacity} -= car_{maxcapacity}$ 
34         end if
35     end for
36      $h_{capacity} = c$ 
37 end procedure
```

Algorithm 4: Charge electric vehicles.

```
1  procedure chargeEV( $e, m, g, \mathbf{ev}$ )
2      for each plugged in  $car$  in  $\mathbf{ev}$  do
3          if  $car_{capacity} + g < car_{maxcapacity}$  then
4               $car_{capacity} += g$ 
5               $g = 0$ 
6          else if  $car_{capacity} < car_{max-capacity}$  then
7               $s = car_{maxcapacity} - car_{capacity}$ 
8               $car_{capacity} += s$ 
9               $g -= s$ 
10         end if
11         if  $car_{capacity} < car_{goal}$  then
12              $n = car_{goal} - car_{capacity}$ 
13             if  $evStrategy == slow$  then
14                 
$$n = \frac{n}{car_{plugout} - t}$$

15             else if  $evStrategy == greedy$  and  $n$ 
16                  $> car_{chargerate}$  then
17                  $n = car_{chargerate}$ 
18             end if
19             if  $n + e > m$  and  $e < m$  then
20                  $n = m - e$ 
21             else if  $e > m$ 
22                  $n = 0$ 
23             end if
24              $e += n$ 
25              $car_{capacity} += n$ 
26         end if
27     end for
28 end procedure
```

Algorithm 5: Store generation in the home energy storage system.

```
1  procedure storeGeneration( $h, g$ )
2      if  $h_{capacity} < h_{maxcapacity}$  then
3           $u = g$ 
4          if  $h_{capacity} + u > h_{maxcapacity}$  then
5               $u = h_{maxcapacity} - h_{capacity}$ 
6          end if
7           $h_{capacity} += u$ 
8           $g -= u$ 
9      end if
10 end procedure
```

Algorithm 6: Use or export the remaining generation.

```
1  procedure useOrExportGeneration( $e, g$ )
2       $e -= g$ 
3  end procedure
```

Algorithm 7: Adjust the limit to account for future peaks.

```
1  procedure adjustLimit( $c, t, a, l, m, p, q, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
2      repeat
3           $o, u = lookaheadUsage(t, a, l, p, \mathbf{e}, \mathbf{g}, \mathbf{p})$ 
4           $l = l \times 0.05$ 
5           $p = p \times 0.05$ 
6          if  $l \geq m$  then
7               $l = m$ 
8          end if
9          if  $p \geq q$  then
10              $p = q$ 
11         end if
12     until  $u + c \geq o$  or  $l == m$  and  $p == q$ 
13     emergencyCharge( $t, l, c, p, \mathbf{ev}$ )
14 end procedure
```

Algorithm 8: Charge or discharge the home energy storage system.

```
1  procedure chargeOrDischargeHSS( $t, e, l, h, p, d, \mathbf{p}$ )
2       $charge = false$ 
3       $discharge = false$ 
4      if  $h_{strategy} == saver$  then
5          if  $h_{capacity} < h_{maxcapacity}$  and  $\mathbf{p}_t \leq p$  then
6               $charge = true$ 
7          else if  $h_{capacity} > 0$  and  $\mathbf{p}_{time} > d$ 
8               $discharge = true$ 
9          end if
10     end if
11     if  $h_{strategy} == average$  then
12         if  $e < l$  and  $h_{capacity} < h_{maxcapacity}$  then
13              $charge = true$ 
14         else if  $e > l$  and  $h_{capacity} > 0$ 
15              $discharge = true$ 
16         end if
17     end if
18     if  $home_{strategy} == hybrid$  then
19         if  $e < l$  and  $h_{capacity} < h_{maxcapacity}$  and  $\mathbf{p}_t \leq p$  then
20              $charge = true$ 
21         else if  $e > l$  and  $h_{capacity} > 0$ 
22              $discharge = true$ 
23         end if
24     end if
25      $u = perform(discharge, charge)$ 
26      $h_{capacity} += u$ 
27      $e += u$ 
28 end procedure
```

Algorithm 9: Calculate the amount to discharge or charge from the home energy storage system.

```
1  function perform(discharge, charge, h, e, l)
2      if charge == true then
3           $u = h_{maxcapacity} - h_{capacity}$ 
4          if  $u > h_{home\_chargerate}$  then
5               $u = h_{chargerate}$ 
6          end if
7          if  $u + e > l$  and  $h_{strategy} \neq saver$  then
8               $u = l - e$ 
9          end if
10     else if discharge == true
11          $u = h_{capacity}$ 
12         if  $u > h_{dischargerate}$  then
13              $u = h_{dischargerate}$ 
14         end if
15         if  $e - u < l$  and  $h_{strategy} \neq saver$  then
16              $u = e - l$ 
17         end if
18          $u = u \times -1$ 
19     end if
20     return u
21 end function
```

Algorithm 10: Change *limit* and charge price if an electric vehicle's capacity is below a threshold where it cannot charge to its required capacity.

```

1  function emergencyCharge( $t, l, c, p, \mathbf{ev}$ )
2       $y = c$ 
3      for each plugged in  $car$  in  $\mathbf{ev}$  do
4           $m = car_{goal} / car_{chargerate}$ 
5           $s = (car_{plugout} - m + 1)$ 
6          if  $t > car_{plugout} - m$  and  $t \leq car_{plugout}$  then
7               $p = t - s + 1$ 
8               $e = car_{chargerate} \times p$ 
9              if  $y < e$  then
10                  $n = e - y$ 
11                  $l += n$ 
12                  $p = A$  high price to ensure charging happens
13                  $y += n$ 
14             end if
15              $y -= e$ 
16         end if
17     end for
18 end function

```

Algorithm 11: Predict the needed energy to reduce future usage to *limit*.

```

1  function energyNeeded( $t, a, c, l, p, \mathbf{ev}, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
2       $o, u = lookaheadUsage(t, a, l, p, \mathbf{e}, \mathbf{g}, \mathbf{p})$ 
3       $n = 0$ 
4       $f = 0$ 
5      if  $evStrategy$  is cooperative then
6           $f = futureEVGoals(t, a, \mathbf{ev})$ 
7      end if
8      if  $u + c < o + f$  then
9           $n = o + f - u - c$ 
10     return  $n$ 
11 end function

```

Algorithm 12: Calculate the needed energy for electric vehicles that will plug out within the lookahead period.

```
1  function futureEVGoals( $t, a, \mathbf{ev}$ )
2       $u = 0$ 
3      for each  $car$  in  $\mathbf{ev}$  do
4          if  $car_{plugout} \leq t + a$  and  $car_{plugout} \geq t$  then
5               $u += car_{goal}$ 
6          end if
7      end for
8  end function
```

Algorithm 13: Calculate the needed energy for electric vehicles that has just plugged out.

```
1  function nowEVGoals( $t, m, \mathbf{ev}$ )
2       $e = m$ 
3      for each  $car$  in  $\mathbf{ev}$  do
4          if  $car_{plug-out} + 1 = t$  then
5               $e += car_{goal}$ 
6          end if
7      end for
8      return  $e$ 
9  end function
```

Algorithm 14: Return a prediction of the amount of energy below and above $limit$ and the number of periods under $limit$.

```
1  function lookaheadUsage( $t, a, l, p, \mathbf{e}, \mathbf{g}, \mathbf{p}$ )
2       $b, c, d = \text{previousUsage}(t - \text{one week}, t, a, l, p, \mathbf{e}, \mathbf{g}, \mathbf{p})$ 
3       $f, h, i = \text{previousUsage}(t - \text{two weeks}, t, a, l, p, \mathbf{e}, \mathbf{g}, \mathbf{p})$ 
4      return  $\frac{b + f}{2}, \frac{c + h}{2}, \frac{d + i}{2}$ 
5  end function
```

Algorithm 15: Calculate and return the amount of energy below and above limit and the number of periods under limit from a time period in the past.

```
1  function previousUsage(s, t, a, l, p, e, g, p)
2      o, u, x = 0
3      for i ← 0 to a do
4          d = es+i - gt-one day+i
5          if homeStrategy is average then
6              if d < l then
7                  u += l - d
8              else
9                  o += d - l
10             end if
11         end if
12         if homeStrategy is hybrid then
13             c = ps+i
14             if d > l then
15                 o += d - l
16             else if d < l and c ≤ p
17                 u += l - d
18                 x ++
19             end if
20         end if
21     end for
22     return o, u, x
23 end function
```
