Embargoed until 6am 22 March 2016

Electric cars, solar panels and batteries – how will they affect New Zealand's greenhouse gas emissions?

March 2016

concept

What this report is about

The energy sector stands on the verge of a revolution. Advances in solar panels, electric vehicles and batteries are making these technologies much more affordable and accessible to consumers.

This report looks at the effect on greenhouse gas emissions if there is widespread uptake of these technologies in New Zealand.

It addresses questions such as:

- How will electric vehicles affect New Zealand's emissions?
- What impact will solar panels have on New Zealand's carbon footprint?
- What effect will batteries have on New Zealand's emissions?

Forthcoming reports

This report is the first of three in a broader study looking at the impacts of new technology. Subsequent reports, on economic and social impacts, will address questions such as:

- What are the benefits and costs of the new technologies for consumers, and society as a whole?
- Will the ideal uptake of these technologies occur?
- Will there be social implications, such as differential cost impacts for customers that don't adopt new technologies?
- If changes are necessary to promote the ideal levels of technology uptake, will those changes lead to social issues?

These reports on economic and social issues will be released in the next couple of months.

Project support

Concept acknowledges the following organisations, who have made this study possible by providing financial support, data, or technical assistance.

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This report has been prepared by Simon Coates, and David Rohan at Concept.

The opinions in this report are those of the authors, and do not necessarily reflect the views of organisations in the project support group.

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Summary

What this report is about

Electric vehicles (EVs), solar photovoltaic (PV) panels, and batteries are becoming much more affordable and accessible to consumers. This report examines the effects on greenhouse gas emissions if there is widespread uptake of these technologies in New Zealand. As we discuss later, the effects in New Zealand are different to many other countries, because our electricity system is already based largely on renewable energy sources.

The uptake of new technologies also raises other questions – such as their cost-effectiveness for consumers and society, and whether uptake could have broader social effects. Those types of issues will be examined in two forthcoming reports, which will be released in the next few months.

Types of emission impacts we have considered

In this report, we analyse the expected emission impacts from new technology uptake in the following areas:

- Electricity sector – how new technology uptake will affect emissions by either: displacing conventional power stations (solar panels), increasing power generation needs (EVs), or altering the timing of power generation requirements (batteries).
- Transport sector – how EVs will affect 'tailpipe' emissions by displacing conventional fossil-fuelled vehicles.
- Embodied emissions[1] – taking account of the emissions incurred in the manufacture of the new technologies, relative to their conventional equivalents.

Electric vehicles expected to reduce emissions

EV uptake will reduce 'tailpipe' emissions by displacing conventional internal combustion engine (ICE) vehicles powered by fossil fuels. We expect EV uptake to modestly increase embodied emissions – because the manufacture of an EV is more emissions-intensive than an equivalent ICE vehicle.

However, overall, we expect EVs to result in a significant net reduction of greenhouse emissions.

In respect of electricity sector effects, we have examined two alternative charging regimes for EVs:

1) 'Smart': EVs are predominantly charged at times of the day when there is lower grid demand (e.g. overnight)
2) 'Simple': EVs are predominantly charged at the time when people finish their journeys (particularly just after early-evening rush hour).

Under both regimes, in the near term we expect the electricity for recharging vehicles to mainly come from existing fossil-fuelled power stations, and therefore add to electricity sector emissions but much less than the reduction in tailpipe emissions.

Further, we expect this near term effect to be temporary. As the power system moves to a more balanced position in the medium-

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[1] In many cases, the embodied emissions are likely to occur outside New Zealand's boundaries. Nonetheless, they arise as a direct result of purchasing decisions made by New Zealanders, and are therefore considered in this report.

term, EV demand will increasingly be met by *new* power stations. We expect these to mainly be wind farms and geothermal power stations, due to their cost competitiveness.

These stations have low emissions. For this reason we expect EV uptake to only modestly increase electricity sector emissions in the medium and longer term, relative to a scenario without EV uptake.

In terms of recharging regimes, we expect 'smart' recharging to have lower emissions than 'simple' recharging. This is because smart recharging reduces the growth in electricity demand at times when fossil-fuelled power stations are most likely to operate.

In fact, smart-charged electric cars may slightly reduce *electricity sector* emissions under some conditions. This is because charging cars at off-peak times encourages a greater amount of low emission power stations to be brought forward, than would otherwise be the case.

Figure 1: Lifetime emissions impact of EVs

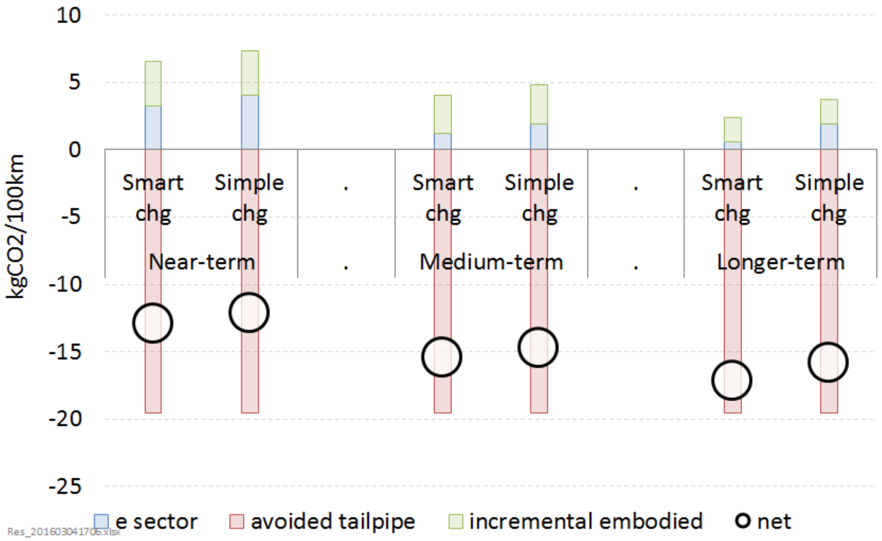

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Figure 1 shows the lifetime emissions impact of EVs purchased at different times in the future. The bars show impacts on the electricity and transport sectors, and embodied emissions respectively. The circle indicates the overall net impact.

EVs are expected to provide net emissions savings based on current conditions, and these are expected to grow over time. We also expect EVs to produce net emission savings under both smart and simple charging regimes, although the savings will be greater for smart charging. These conclusions appear robust against a range of different scenarios relating to future fuel prices, CO_2 prices and electricity demand growth.

Solar PV expected to have little impact on emissions

In the near term, we expect solar PV uptake to displace generation from existing fossil-fuelled stations and therefore reduce emissions. However, as with EV uptake, we expect this effect to be temporary.

As the power system moves to a more balanced position over time, we expect solar PV uptake to increasingly substitute for *new* low emission power stations (such as wind and geothermal) that would otherwise have been built to meet any growth in demand or retirement of old existing stations. For this reason, we expect solar PV uptake to have a limited displacement effect on electricity sector emissions in the medium term.

This is different to what happens in most other countries (see Figure 6 below). It is because most of New Zealand's electricity is generated from renewable sources (hydro, wind and geothermal), and the fact that large-scale renewables also represent the least-cost option for future electricity supply in New Zealand – something that is not the case for most other countries.

Looking out even further, we expect solar PV to modestly *increase* the need for fossil-fuelled generation, and therefore add to electricity sector emissions. This counter-intuitive result is because solar PV generates more power in summer than winter - the opposite of New Zealand's power demand needs.

To fill a widening gap between winter power demand and supply associated with high PV uptake, New Zealand will need more power from controllable sources that operate for only part of the time. We expect this to be met mainly from operation of fossil-fuelled power stations, as existing hydro stations are limited in their ability to further increase the amount of water they store in summer to release in winter.

We have also considered the combined effect of solar PV and batteries. Our analysis shows that batteries combined with solar PV do not fundamentally alter the results for solar PV by itself.

This is because New Zealand's hydro stations already act like a giant battery and provide considerable flexibility to offset the daily swings in PV output.[2] Furthermore, batteries are not well-suited to shifting power across seasons[3] – for which there would be a greater need with high PV uptake.

Figure 2 shows the emissions impact of solar PV uptake from a lifetime perspective for two different scenarios (Central, and High CO_2 prices), and for three different times when the panels are installed: Near-term (in the next couple of years), through to long-term (in 15+ years' time).

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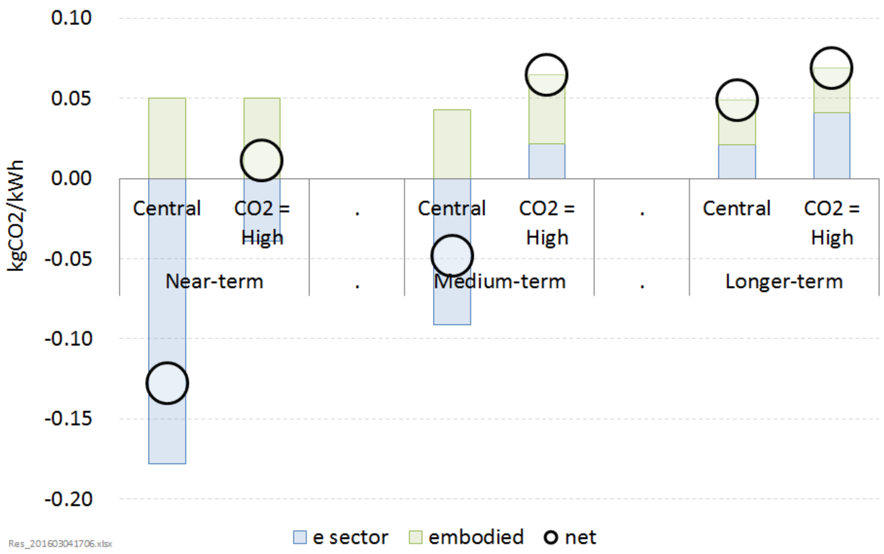
[2] Hydro stations can generally reduce their generation in the middle of the day when solar PV output is highest, and increase production at other times of the day.

[3] That is, filling up a battery once in summer to release once in winter.

Figure 2: Lifetime emissions impact of solar PV



In a world where CO_2 costs are expected to be moderate, then solar PV installed in the near-term is likely to result in a net reduction in CO_2 emissions over its lifetime, whereas solar PV installed in 15 to 20 years' time is likely to result in a net increase in CO_2 emissions.

Ironically, this situation of solar PV resulting in an increase in CO_2 emissions is much more likely if CO_2 prices are high. This occurs because in a high CO_2 price world, PV is likely to displace a greater amount of new wind generation than in a medium CO_2 price world.

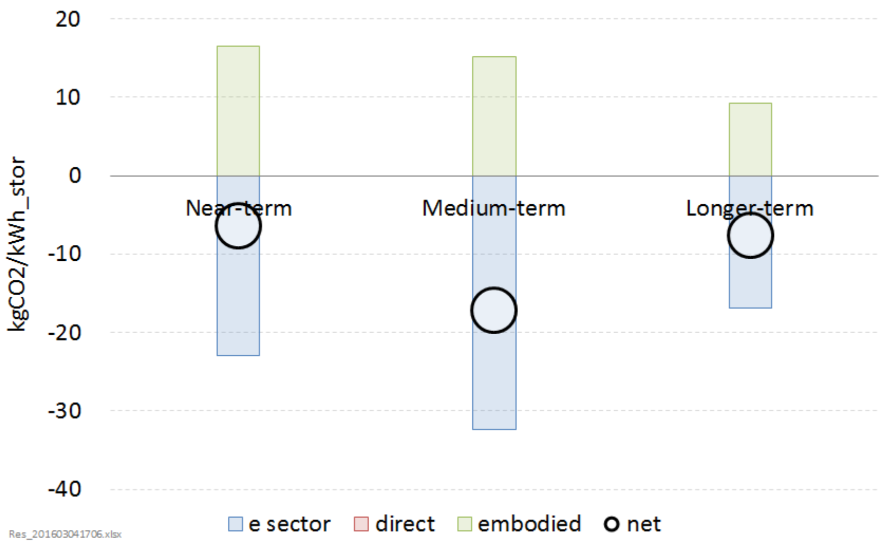
Batteries expected to have little effect on emissions

We expect batteries to be charged at times of low demand (i.e. overnight) and discharged at times of peak demand (i.e. morning and evenings). This will act to 'flatten' the demand for grid-sourced electricity. This tends to favour baseload[4] plant, and means there is reduced need for lower capacity factor 'peaking' plant to operate.

In the near term, this flattening of demand is expected to shift some generation from less efficient fossil-fuel plant (e.g. coal-fired) to more efficient fossil fuel plant (e.g. gas-fired). This has a modest beneficial emissions impact.

In the medium term, we expect batteries to further flatten demand, encouraging greater investment in wind and geothermal stations in preference to operation of fossil-fuel plant – creating greater emissions savings.

Figure 3: Lifetime emissions impact of batteries



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[4] That is, plant that has a relatively flat production profile over time, as compared to plant that is designed to run less frequently and only when required – referred to as 'low capacity factor' or 'peaking' plant.

Figure 3 shows the expected lifetime impacts of batteries on emissions. We expect batteries to result in a net reduction in emissions over their lifetime, even though there are embodied emissions associated with their manufacture.

These conclusions appear robust against a range of different scenarios relating to future fuel prices, CO_2 prices and electrciity demand growth.

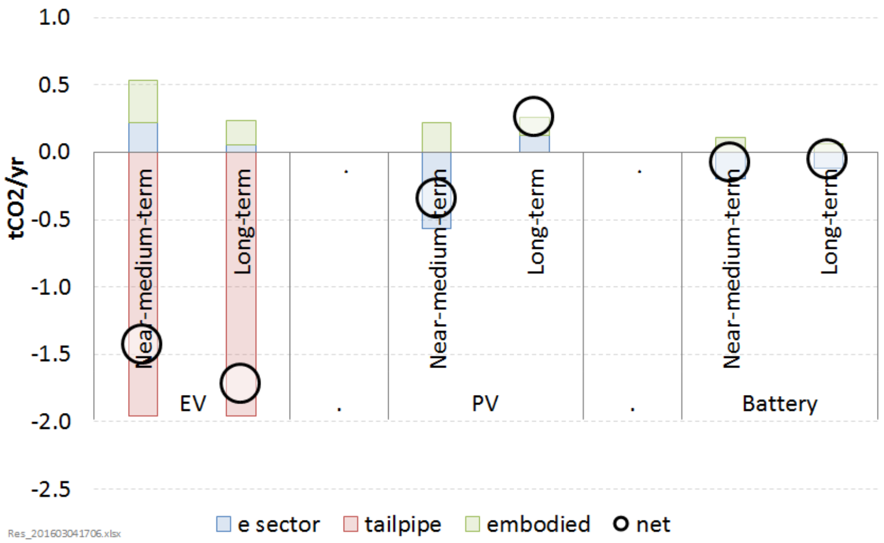
This analysis assumes that battery charging and discharging is undertaken to minimise the peakiness of overall grid demand – i.e. maximise national benefits. However, batteries may be used by some households to minimise the extent of 'export' from their solar panels at times when their PV generation exceeds household demand. This mode of operation could be driven by the relative export versus demand tariffs that households face.

Operating batteries in this fashion will substantially alter their charging pattern: filling up during the middle of the day rather than overnight. This would reduce the electricity sector emissions benefit from batteries – to the point where the embodied emissions could exceed the reduction in electricity sector emissions.

Comparison across EVs, PVs and batteries

We have also examined emission impacts for a typical-sized 'unit' of each technology that might be purchased by a consumer: A 4kW rooftop solar panel, a medium-sized EV, and a 7 kWh storage battery.[5] For a household with discretionary 'green' dollars, investment in these technologies currently involves similar levels of net upfront costs of around $12,000-14,000[6].

Figure 4: Emissions impact of EVs, solar PV and batteries



As shown in Figure 4, we conservatively[7] expect each EV purchased in the near to medium-term to result in an average reduction in

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[5] A 7kWh battery would provide enough power to meet an average home's summer power demand for about a day. Current models are wall or floor-mounted, and are around the size of a large flat screen television, or microwave oven (depending on model).

[6] For EVs, this represents the extent to which an EV is a higher price than a conventional vehicle.

[7] This is considered to be a conservative estimation in that it is based on assumed average annual driving distance of 10,000km – based on consideration of current battery ranges. In the future, the average distance per battery charge is likely to increase – noting also that the average annual distance travelled of a new vehicle purchased in New Zealand is 18,000 km. There is also some international evidence that EVs are being used as the 'main' car in households with multiple

carbon emissions of approximately 1.4 tonnes per year, rising to 1.7 tonnes for EVs purchased further into the future.

By comparison, we expect a 4 kW solar PV panel installed in the near-to-medium term to have a much smaller net effect on emissions – the saved electricity sector emissions largely offset the embodied emissions. We expect the electricity sector emissions saving to decline over time, as solar PV panels increasingly substitute for generation from new wind and geothermal plants. As a result, over the longer term, we expect a 4kW solar PV panel installed in the longer term to increase emissions by about 0.25 tonne per year. As set out previously on page v, this adverse CO_2 effect of solar panels is expected to be worse if CO_2 prices are high.

For a 7kWh household battery by itself, we expect an emissions reduction of around 0.1 tonnes per year, and this does not change much over time. However, this saving could be reduced or eliminated if there is widespread uptake of EVs that are predominantly charged at off peak times.

These results are not surprising given New Zealand's carbon footprint. At present, the average New Zealand household is estimated to directly cause annual emissions of approximately 7 tCO_2. The vast majority of these direct household emissions are from vehicles.

Overall if consumers wish to spend money on new technologies to deliver environmental benefits, by far the biggest emissions saving can be achieved from investing in EVs, whereas batteries and solar PVs have less benefit, and PVs are expected to increase net emissions in the longer term.

New Zealand's results are different to many other countries

In nations such as Australia and the United States, where coal or gas-fired power stations are the predominant source of grid electricity, the emissions impact of new technology is expected to be very different to New Zealand.

Figure 5 shows that in countries reliant on gas-fired generation, EVs produce an emissions saving, but much less than expected in New Zealand. And for countries that are largely dependent on coal-fired generation, EVs are expected to provide no net emissions benefit.[8]

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vehicles, and are being driven comparable distances to conventional ICE equivalents. See: www.gov.uk/government/uploads/system/uploads/attachment_data/file/464763/uptake-of-ulev-uk.pdf

[8] These emission impacts are consistent with those estimated by the United States Department of Energy for EV uptake in that country (after allowing for international differences in average vehicle travel distances and fuel efficiency). See www.afdc.energy.gov/vehicles/electric_emissions.php

Figure 5: Emissions impact of EV - NZ and overseas

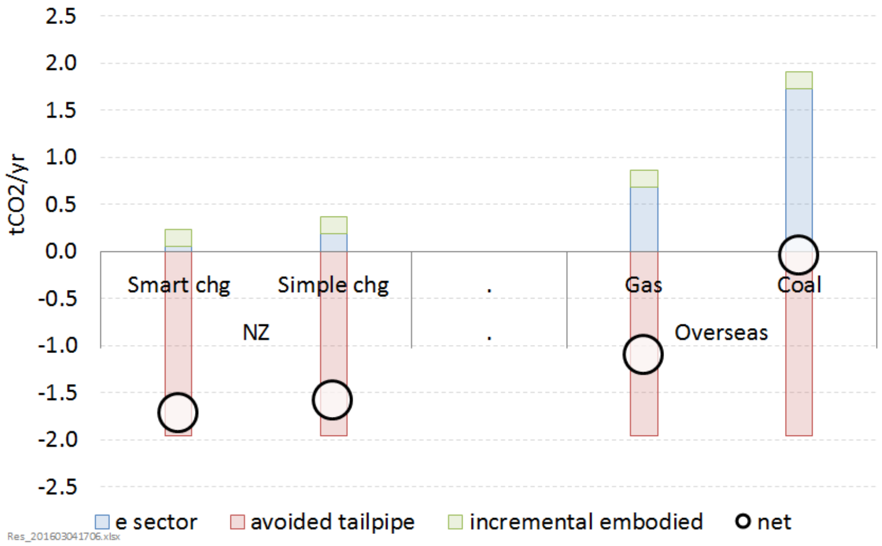
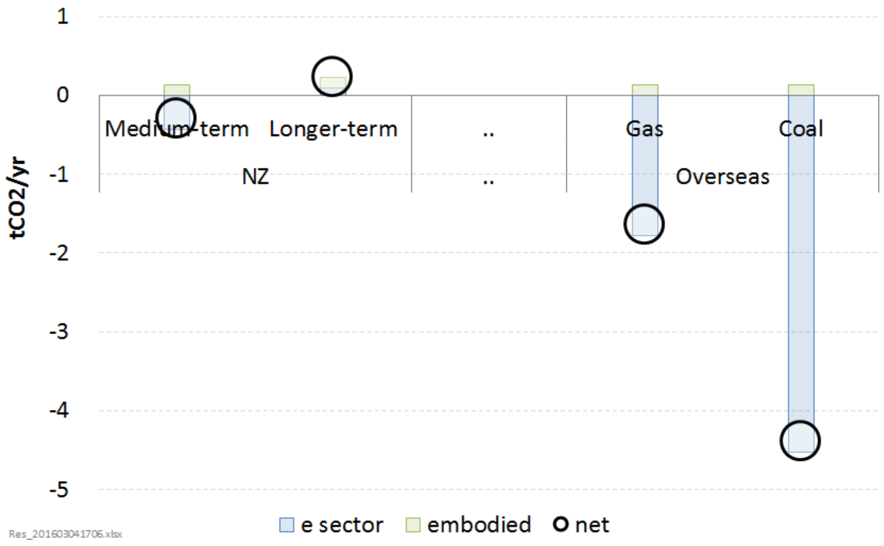


Figure 6 shows the equivalent results for solar PVs. In countries where gas or coal-fired power stations are the main sources for existing and new grid-supplied power, solar PVs will provide substantial emissions benefits.

The key reason for these national differences is that New Zealand derives most of its electricity from low emission sources (such as hydro, wind and geothermal) – and this is expected to continue.

As a result, EVs will mainly be charged from low emission power sources in New Zealand (not from gas or coal-fired generation). Likewise, PVs in New Zealand will mainly substitute for investment in other low emission power generation options – and therefore have little impact on emissions.

Figure 6: Emissions impact of 4 kW solar PV - NZ and overseas



Findings are robust to different assumptions

We have tested whether the relative emissions impacts change with different input assumptions – such as higher or lower CO_2 prices, varying electricity demand, and technology uptake scenarios. This testing indicates that the results do not change markedly for plausible sensitivity cases.[9]

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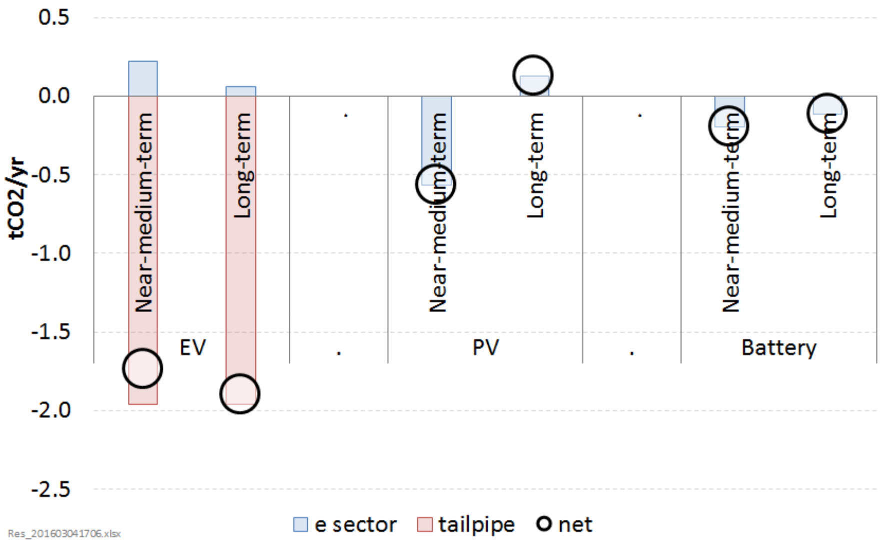
[9] The most significant scenarios which give rise to different results are:

- Scenarios where CO_2 and coal and gas prices are so low that fossil plant become the cheapest new-build options for New Zealand; and
- Scenarios where no new investment is required because electricity demand is permanently static and there is no retirement of existing stations reaching the end of their life.

Both of these scenarios are considered to be very unlikely.

We have also considered a case which excludes embodied emissions (over which there is potentially greater uncertainty, and where the emissions effects are largely felt outside of New Zealand – i.e. in the countries manufacturing the technologies). This is shown in Figure 7, and shows the same relative ranking, with EVs providing the greatest emission benefit, and with more limited effects from PVs and batteries.

Figure 7: EVs, PV and batteries (exc. embodied emissions)



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Accordingly, we consider that the analysis in this report provides a robust picture of the likely relative impacts of EVs, solar PV and batteries on emissions in New Zealand.

Contents

1 Purpose

1.1 What the broader study is about

Advances in electric vehicles (EVs), solar photovoltaic (PV) panels, and batteries are making these technologies much more affordable and accessible to consumers.

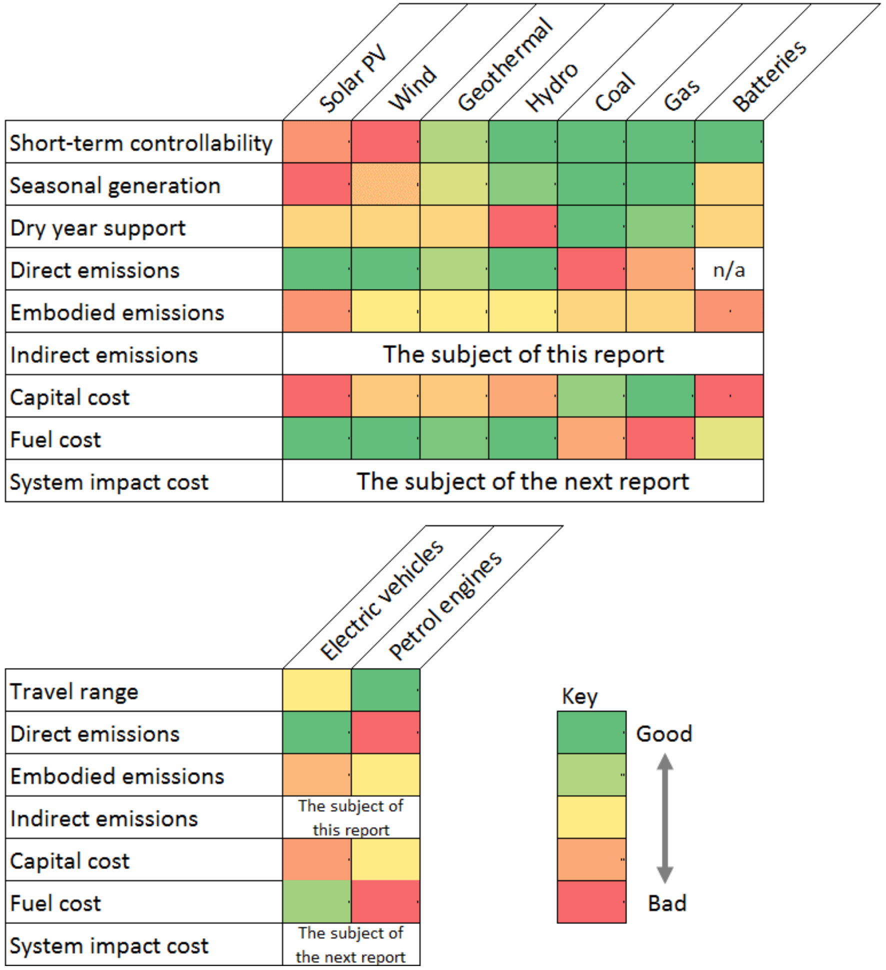
Widespread availability of these technologies has the potential to bring substantial benefits. It may also pose challenges in some areas, especially as existing policy and industry arrangements have been largely designed around ‘old’ technologies. These arrangements may frustrate technology uptake, and/or encourage poor outcomes in some cases.

Each of the new technologies has advantages and disadvantages, relative to its conventional alternatives. Example of the pros and cons are outlined in Table 1.

This aim of this study is to explore the likely benefits and challenges associated with widespread uptake of these new technologies in detail. We will build on previous qualitative studies to analyse the size of likely effects, and will be undertaking specific new analysis to examine the likely whole-of-electricity-system effects of such technologies on emissions and costs.

We hope this analysis will contribute to a better informed dialogue among consumers, industry and policy-makers about the effects and implications of new technology uptake. Ultimately, this should contribute to policies and arrangements that ensure New Zealand reaps the greatest possible benefit from new technologies.

Table 1: Examples of relative pros and cons



	Solar PV	Wind	Geothermal	Hydro	Coal	Gas	Batteries
Short-term controllability	🟧	🟥	🟩	🟩	🟩	🟩	🟩
Seasonal generation	🟥	🟧	🟨	🟩	🟩	🟩	🟨
Dry year support	🟨	🟨	🟨	🟥	🟩	🟩	🟨
Direct emissions	🟩	🟩	🟩	🟩	🟥	🟧	n/a
Embodied emissions	🟧	🟨	🟨	🟨	🟨	🟨	🟧
Indirect emissions	The subject of this report						
Capital cost	🟥	🟧	🟧	🟧	🟩	🟩	🟥
Fuel cost	🟩	🟩	🟩	🟩	🟧	🟥	🟨
System impact cost	The subject of the next report						

	Electric vehicles	Petrol engines
Travel range	🟨	🟩
Direct emissions	🟩	🟥
Embodied emissions	🟧	🟨
Indirect emissions	The subject of this report	
Capital cost	🟧	🟨
Fuel cost	🟩	🟥
System impact cost	The subject of the next report	

Key
🟩 Good
🟩
🟨
🟧
🟥 Bad

The study explores the effect of new technologies in three broad areas:

- Environmental – especially the impact of each new technology on New Zealand's greenhouse gas emissions[10]
- Economic – the benefits and costs of these new technologies for consumers and New Zealand as a whole
- Social – effects that might arise from differential technology uptake across different groups in society.

1.2 What this specific report is about

This is the first report in the three-part study, and focuses on the effect of EV, PV and battery uptake on greenhouse gas emissions.[11]

Further reports to be released in coming months will look at the economic and social implications of the uptake of these new technologies.

1.3 Why carry out this study now?

Although there has only been modest uptake of new energy technologies in New Zealand so far, change is occurring rapidly in some countries. For example, over 40% of homes have a solar panel in some parts of Australia. In Norway, EVs have reached over 20% of all new car sales.

Some effects from new technology uptake in other countries have been unexpected. We think it is beneficial to learn from those experiences now, to see if there are any lessons for New Zealand.

We also know that New Zealand is unusual in some respects. For example, our electricity system has among the highest proportions of renewable generation in the world. This means that new technology impacts may well be different in New Zealand, compared to other countries.

1.4 How this report is structured

The balance of this report is set out as follows:

- Section 2 describes the overall analytical framework and tools that have been used to estimate emissions impacts
- Section 3 describes the results of the analysis in terms of the expected effects on emissions from uptake of EVs, PVs and batteries
- Appendix A provides more detailed information on how embodied and direct emissions have been analysed
- Appendix B provides more detailed information on how transport sector emissions have been analysed
- Appendix C describes the detailed model that has been used to assess electricity sector impacts of the uptake of new technology
- Appendix D provides background information on EVs, PVs and batteries for readers who are less familiar with these new technology options.

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[10] Throughout this report, "emissions" refers to greenhouse gas emissions, expressed in terms of CO_2 equivalents.

[11] We note that new technologies might have other environmental effects. For example, EVs are expected to reduce harmful particulate emissions. On the other hand, the disposal of batteries from EVs and household storage units may raise environmental issues. We have not considered such issues in this report.

2 How emission impacts have been analysed?

This section explains how the impact of technology uptake on New Zealand's emissions has been analysed.

2.1 Examine system wide effects

The uptake of new technology can both increase and displace emissions. For example, the use of EVs will lead to higher emissions if the power for charging them comes from stations that emit greenhouse gases.

At the same time, EVs will reduce emissions by displacing internal combustion engine (ICE) vehicles. We examine both *additional* and *displaced* emissions when assessing net emission impacts.

In some cases, the displacement effects are fairly obvious (such as reduced 'tailpipe' emissions from petrol-powered cars). However, the displacement effects in the electricity sector are more complex, and require detailed modelling, as discussed from section 2.6.1.

It is particularly this area of displacement effects in the electricity sector where this report goes beyond the analysis in other published studies. This is important because these electricity sector effects are material, and because New Zealand's renewables-dominated generation sector is unusual, internationally.

2.2 Timeframes for assessing emission impacts

EVs, solar panels and batteries will last many years. The impact of these technologies on day-one may be different to the impact over time, because significant uptake will have system-wide effects.

For this reason, we have looked at three different 'snapshots':

- Near-term – the impact in the next couple of years, based on current system conditions
- Medium term – the impact from about 4-5 years' time to capture a mix of shorter and longer term effects, such as impact of new technology uptake on investment and retirement decisions for power stations
- Longer-term – the impact from about 15 years' time, which captures the full effect of new technology uptake on investment decisions.

We have also looked at the cumulative impact of each technology over its expected lifetime.

2.3 Types of emission impacts that have been considered

We have looked at the emission impacts in the following areas:

- Embodied emissions – how uptake of each technology type affects emissions associated with their manufacture
- Transport sector – how EVs affect emissions by displacing petrol and diesel as road transport fuels
- Electricity sector – how uptake of each technology will affect the electricity system as a whole.

It is possible that technology uptake could have other effects on emissions, such as via lifting consumer awareness of their energy usage. At present, there is limited information available on these issues and we have not sought to account for them in this study.

2.4 Embodied emissions

The manufacturing of EVs, solar panels and batteries may release more or less emissions, relative to their conventional equivalents. These embodied emission differences have been taken into account when considering the ‘lifetime’ emission impacts for each technology.

We recognise that in practice, many of the embodied emissions will occur outside of New Zealand’s geographic boundaries, because the technology components are mainly manufactured overseas. Nonetheless, we attribute such emissions to ‘New Zealand’ in this report, because the emissions are *caused* by New Zealand’s demand for the relevant items.

Further information on how embodied emissions have been calculated is set out in Appendix A.

2.5 Transport sector emissions

Transport sector impacts arise from the displacement effect of EVs on tailpipe emissions from ICE vehicles. The emissions impacts have been estimated based on New Zealand and overseas data. Further information is set out in Appendix B.

2.6 Electricity sector emissions

Electricity sector effects are heavily influenced by New Zealand’s unique characteristics. Displacement and addition effects are also relatively complex in this sector. While individual EVs or solar panels will not materially alter power station operation and investment requirements, if new technology uptake occurs on a large scale, there will be system-level impacts.

For this reason, we have used a detailed model of New Zealand’s electricity system to carry out the analysis. This model looks at how each technology will affect operations at existing power stations, and future investment and retirement decisions.

The use of EVs, solar PV panels or batteries will change the power generation needed from grid-scale power stations. We call this the effect on residual grid demand.

- Charging of EVs *increase* the amount of electricity needed from grid-scale power stations
- Solar PV panels *reduce* the amount of electricity needed from grid-scale power stations
- Batteries alter the *pattern* of grid-scale generation: Increasing the requirement at times when batteries are being filled-up, and decreasing the requirement when they are discharged again. Overall, there will be a small net increase in grid demand due to battery charging losses.

By considering the station types affected by the changes in residual grid demand, we can assess the system-wide impacts of different technology uptake scenarios on emissions.

2.6.1 Explore initial and dynamic impacts

Adding a PV panel, EV, or battery to the system today will affect the generation from existing power stations. However, the mix of power stations on the system is not static. Over time, some power stations retire because they become uneconomic. New generation is needed to replace these stations, and to satisfy increases in electricity demand.

The type of new grid-scale generation that is built depends on many factors, and among the most important are the level and 'shape' of residual grid demand. For this reason, the uptake of new technology will affect both existing stations and investment in new grid-scale stations over time.

For example, if off-peak electricity demand increased strongly due to large-scale overnight charging of EVs, this would affect new power station investment in a different way than if the same amount of annual demand growth were to occur during day-time periods.

This is because the different demand 'shapes' will affect how much demand can be met by power stations which run with a flat production profile (known as baseload[12]), and how much needs to be met by power stations running for only part of the time (e.g. only during winter, or only during morning or evening peaks) – known as lower capacity factor generation.

Because EVs, solar panels and batteries are all expected to last for 15 to 20 years or more, it is important to consider the longer-term *dynamic* effects of these technologies on emissions, as well as their initial *static* impacts.

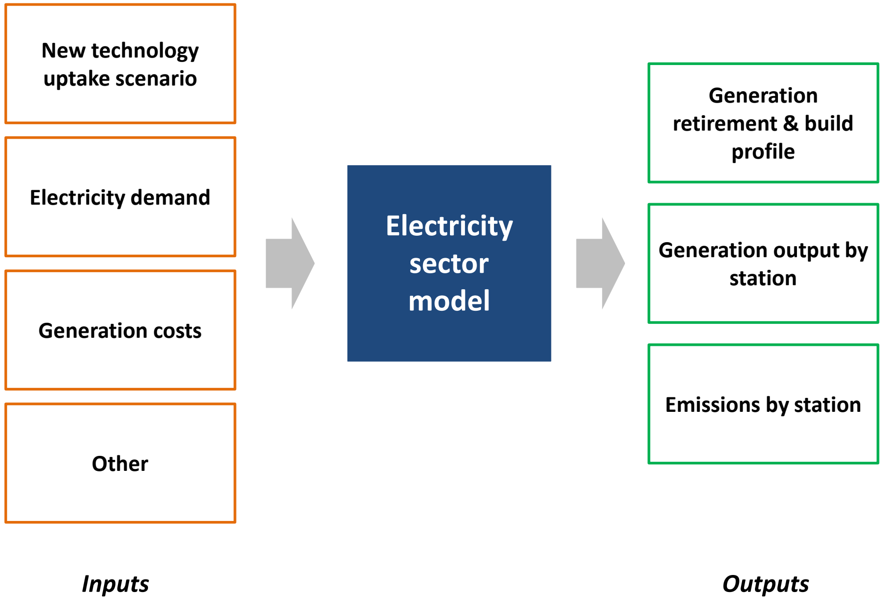
This study looks at both effects. The rest of this section provides a summary of how the electricity sector model works. For readers who want more technical information, this is set out in Appendix B.

2.7 How the electricity sector model works

In essence, the electricity sector model identifies the cheapest way to satisfy future electricity demand each year from 2016 through to 2040.

Figure 7 summarises the key inputs and outputs of the model.

Figure 8: Overview of electricity sector model



An important aspect of the modelling approach is that the uptake of each of the new technologies under consideration is externally specified by the user, rather than being calculated by the model

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[12] 'Baseload' in industry terminology generally refers to stations that produce energy most of the time, such as geothermal power stations. Individual wind turbines are not strictly baseload generators, because output varies with wind speed. However, wind generation in aggregate has fairly predictable energy production, and remaining short term variations (such as within day effects) can be 'balanced' using the flexibility of hydro generation. For this reason, it is categorised as baseload in the context of issues covered by this report.

based on an assessment of the economics of the technology. The model's results are therefore not sensitive to the cost of the new technologies, over which there is greater uncertainty than for existing power stations and new build options.

This contrasts with the investment, retirement, and operation of grid-scale generation (i.e. hydro, wind, geothermal, and fossil plant) which are all calculated by the model as part of its optimisation in order to arrive at a least-cost outcome.

In performing the optimisation, the model takes into account:

- The 'shape' of residual grid demand for different technologies. For example, whether EVs are charged at off-peak times or during peak demand periods. This is important because if new technology results in a 'peakier' grid demand – either on a seasonal or within-day basis – this will tend to result in more fossil-fuelled generation than if the new technology results in 'flatter' grid demand. This is because the relatively low capital cost of fossil-fuelled generation means it is more cost-effective at meeting lower capacity factor duties than high capital intensity renewables such as wind and geothermal which are better suited to baseload duties.
- Seasonal and within-day effects, and capabilities of the hydro stations. Whether altered grid demand is peakier on a within-day or seasonal basis is important in terms of the ability of the existing hydro stations to alter their pattern of generation in response. Put simply, existing hydro stations can alter their generation patterns to a significant (but not unfettered[13]) extent to meet changes in the *within-day* pattern of demand, but are much less able alter their *seasonal* generation patterns – i.e. storing more water in summer to release in winter.
- Whether the system is in broad balance, or relative surplus:
  - When the system is in relative surplus (as has been the case in recent years), increased grid demand tends to be met mostly from using slack capacity at existing fossil power stations because this doesn't require major investment. Similarly, existing thermals tend to be displaced by short-term reductions in grid demand.[14]
  - If the supply/demand situation is more balanced, the effects of altered grid demand will be predominantly felt through altered grid-generation investment and retirement decisions. Depending on the nature of the altered grid demand (e.g. 'peaky' or 'flat'), the altered grid demand may affect the investment outcomes for new baseload generation (which in NZ tends to be low emission) more than the altered investment/retirement and operational outcomes for low-capacity factor generation (which tends to be fossil).

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[13] There are some absolute limits to the ability of hydro schemes to alter their within-day pattern of generation in response to altered patterns of within-day demand – i.e. physical capacity limits to generate more at peaks, plus minimum river flow constraints which can limit their ability to further reduce generation at periods of low demand.

[14] Hydro stations do alter their pattern of production in response to a change in demand (level and/or shape of demand). Thus, at times water is 'displaced' by new technology, but this is compensated for by the displaced water being released at other times during the year – which in turn will displace fossil generation. Accordingly, over a year as a whole, altered demand in a system in relative surplus is fundamentally met by altered fossil generation. Only if the level of relative surplus is such that there would be significant amounts of hydro spill will altered demand be met by altered hydro generation.

- Key external drivers determining the relative economics of different generation options. This is particularly relevant for determining which new-build generation options are likely to be least cost to meet growth in demand – whether baseload, or low capacity factor operation. Key drivers include:
  - Fuel and CO_2 prices
  - The fuel efficiency of fossil options
  - The capital costs of new generation options
  - The fixed operating & maintenance (FOM) costs of keeping a plant operational
  - Non-fuel variable operating & maintenance (VOM) costs
- Fundamental limitations of New Zealand's physical system.
  - In particular, managing dry-year/wet year variability from hydro-generation stations requires some form of 'back-up' generation that will have low average utilisation. It is generally not economic to build low emission plants for this purpose, and the cheapest option tends to be fossil-fuelled stations with low capital cost.

2.7.1 Sources for input assumptions

Input assumptions are based largely on independent external sources. For example:

- The CO_2 price assumptions are drawn from the 'Kayak' and 'Waka' scenarios published by the Business Energy Council in 2015
- The oil and coal price assumptions are based on international forward price curves for such commodities
- The demand growth projections are based on projections of GDP and population growth produced by the NZ Treasury and Statistics New Zealand – the exception being assumptions about demand from the Tiwai aluminium smelter which have been developed by Concept
- Generation cost and performance data is based on a variety of public sources – in particular information published by the Electricity Authority and its predecessor.

The main Concept derived set of assumptions relate to wholesale gas prices and the cost of providing 'flexible' gas and coal to meet lower-capacity factor duties. These assumptions are largely based on Concept modelling using public data sources.

2.7.2 Model computes the cheapest sources of power

Based on a given set of inputs (including the technology uptake scenario), the model identifies the lowest cost mix of stations to meet residual grid demand. It does this for each year by comparing power costs from existing plants with those from potential new power stations.[15]

Where an existing power station has higher costs than new plant, the older station is retired by the model.[16]

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[15] The capital cost of new power stations is included in this evaluation, whereas capital costs for existing power stations are not considered due to such costs being sunk.

[16] This only occurs for existing fossil stations if the variable plus annual fixed costs exceed the cost of building a new plant. Existing low emission plants are

New stations are also built to satisfy demand growth over time. Whether such stations are new baseload stations (e.g. a geothermal or wind plant) or new peaking stations (i.e. typically a gas-fired open cycle gas turbine or OCGT) will depend on, amongst other things, the extent to which demand growth is peaky or flat, and the ability of the existing hydro fleet to alter its pattern of generation to balance out any increased peakiness.

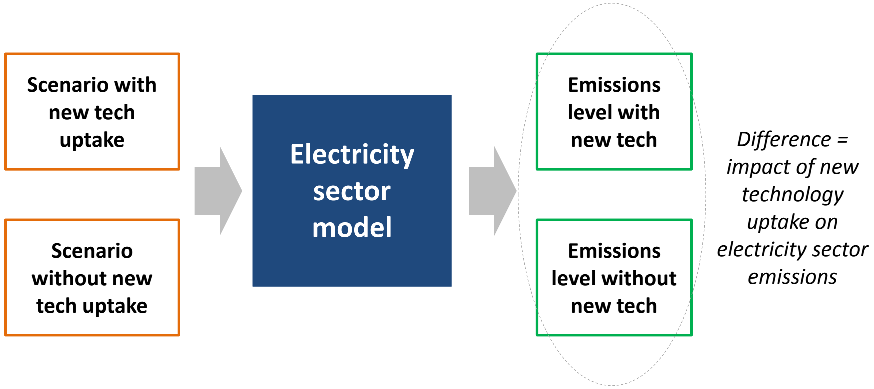
The model calculates the level of output for each station for each year. This information is combined with data on emission factors to compute the total electricity sector emissions for the given set of input data.

2.7.3 Calculating the emissions impacts

The impact of a new technology uptake scenario is calculated by running the model twice – first a basecase without new technology uptake, and then with the chosen uptake scenario (such as significant growth in solar PV installations).

For a given year, the change in total emissions between the two scenarios represents the impact of the new technology uptake on emissions over the electricity system, as shown in Figure 9. To facilitate comparisons across different technology types and time, we express these impacts in terms of $kgCO_2$ per kWh of the new technology.[17]

Figure 9: Calculating electricity sector emissions



This is illustrated in the following figures which show the projected generation for one of the many different scenarios that were run: First in a future where there is no solar PV uptake, and second where there is a high level of solar PV uptake.

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not retired in this fashion as they have very low variable costs and their capital costs are considered to be sunk.

[17] Being kWh generated in the case of PV, kWh demand from charging batteries in the case of EVs, and kWh of storage capacity in the case of stand-alone batteries.

Figure 10: Projected generation for illustrative scenario: A) Without solar PV, B) With solar PV

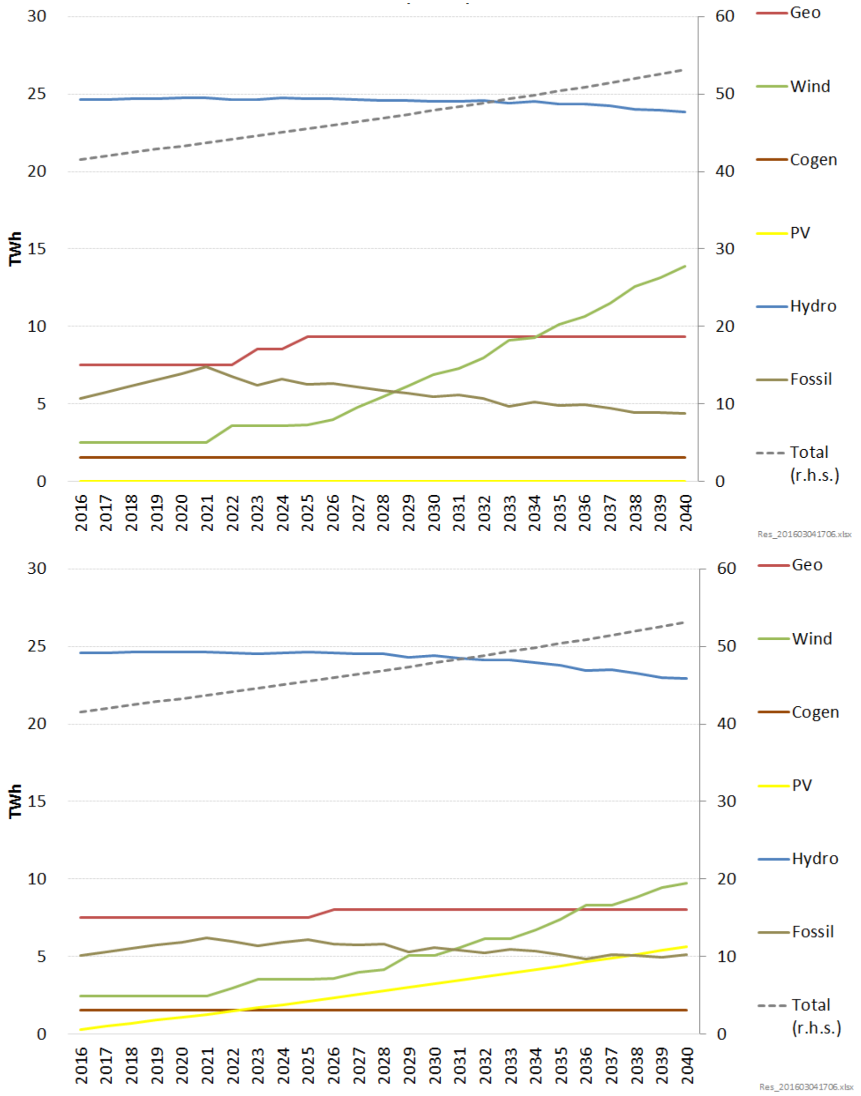
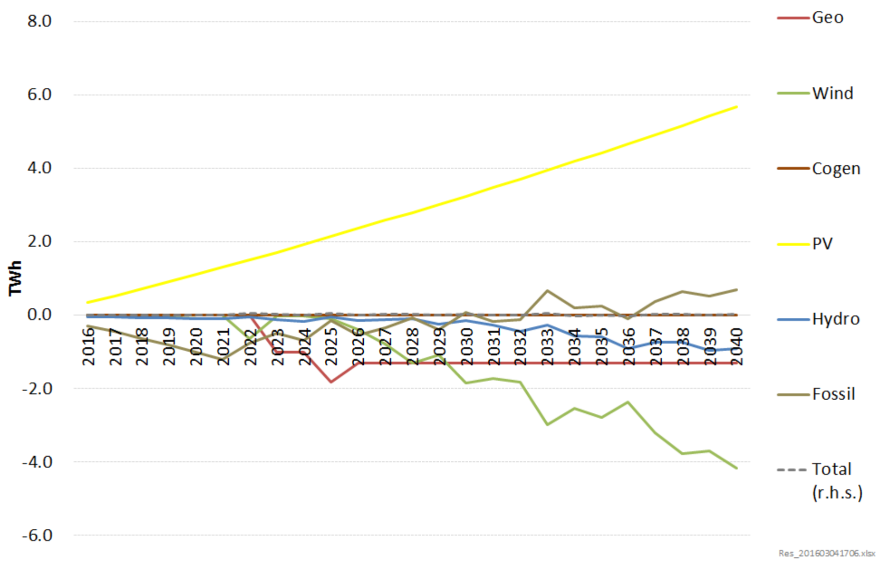


Figure 11 shows the difference in generation outcomes between the two projections shown in Figure 10.

Figure 11: Difference in generation due to solar PV uptake



This illustrates that in the early years solar PV is displacing fossil-fuelled generation – as indicated by the 'fossil' line being below the x-axis in these early years.[18] However, from 2022 onwards, solar PV is displacing wind and geothermal that would otherwise have been built.

Further, from 2033 onwards, there is slightly higher generation from the fossil stations than would otherwise have been the case. As described in more detail in Appendix C, this is due to solar PV

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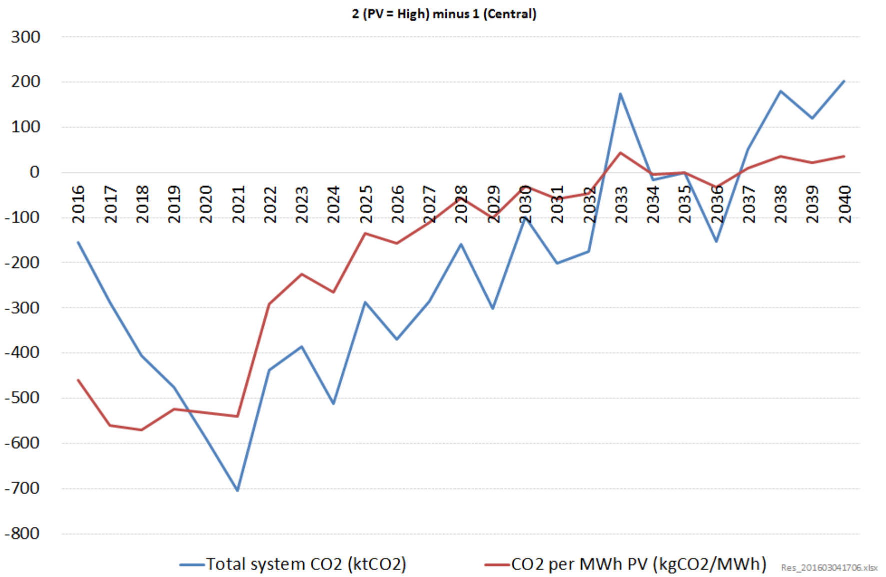
[18] The fossil line is the combined output of the CCGTs, Huntly Rankine units, and OCGTs. They have been combined into this single line for ease of reader interpretation.

amplifying the summer/winter differentials in demand, giving rise to an increased demand for low-capacity factor generation to operate in this seasonal firming mode – which hydro schemes are limited in their ability to further undertake.

The overall impact for electricity sector emissions is shown in Figure 12 – both in terms of overall electricity sector emissions (expressed in $ktCO_2$, and in terms of $kgCO_2$ per MWh of PV generation.

Figure 12: Difference in projected total system emissions between scenario with PV uptake and scenario without PV uptake



This shows that in the early years, solar PV is resulting in less emissions (through displacing fossil generation), but in the medium to long term it is resulting in an increase in emissions – through increasing the demand for low-capacity factor generation to operate in seasonal firming mode.

The year-on-year 'jaggedness' is caused by the binary aspect of some of the plant investment and retirement decisions made by the model. This is discussed further in section 2.8 below. However, while the reality may result in 'smoother' outcomes, this is not considered to alter the fundamental nature of the results.

2.7.4 New technology uptake scenarios

Because the purpose of this exercise is to establish the likely nature of the emissions impact of a new technology, relatively simple uptake scenarios were developed.

For any given year, the level of uptake is expressed in terms of the percentage of households with that specific technology. A constant yearly rate of growth was assumed, starting from effectively zero uptake in 2014, through to the following levels of household penetration by 2040:

- Solar PV = 60% of households
- EVs = 80% of households have an EV[19]
- Stand-alone batteries = 60% of households.

These values were chosen as representing the upper range of plausible outcomes based on observed outcomes overseas (e.g. in some parts of Australia, 40% of households have solar PV, and in Norway EVs have already reached 20% of new vehicle sales).

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[19] Note that on average there are more than 2 vehicles per household in New Zealand. Thus 80% of households having an EV corresponds to roughly 35% of the total light passenger fleet being an EV.

In reality the uptake of these new technologies is more likely to follow an ‘s-curve’ pattern of penetration among households, and the level of penetration by 2040 could be less.

However, given that the purpose of the exercise is trying to understand the implications of a technology if there were significant levels of uptake, trying to simulate such ‘s-curves’ would not only be subject to significant levels of uncertainty, but it could detract from understanding the nature of the issue.

Each technology uptake scenario was compared to a counterfactual which assumes zero uptake of the relevant technology.

This counterfactual is applied because the purpose of the analysis is to gauge the effect of technology uptake on emissions. Neither of the uptake scenarios is intended to be a prediction of what is likely to occur in the future.

The model is set up to assess different technology uptake scenarios on a sensitivity basis, including:

- Higher, and lower rates of uptake
- Different patterns of uptake (i.e. linear, s-curve, etc) – noting that only linear uptake scenarios were considered for this study.
- Different combinations of technologies being taken up together (e.g. solar PV in combination with stand-alone batteries).

2.8 Key caveats

Although the model takes account of the key variables affecting power station operation and investment decisions, there are some key caveats to bear in mind:

- The model makes plant operation and investment decisions based strictly on the cost assumptions in its ‘menu’ of options. In reality, owners of stations may sometimes make decisions based on other ‘strategic’ considerations. In particular, this may affect the relative timing of some retirements of the existing CCGTs and Rankine units. However, we do not consider that these factors will fundamentally alter the nature of the results, particularly with respect to the relative investment and operation of low emission and fossil generators.
- Some detailed operational issues are not represented in the model, or are addressed in simplified form. For example, fuel conversion efficiency (and hence cost) can vary with output for some power stations, whereas average fuel efficiency values for each station are adopted in the model. Similarly some thermal power stations incur significant costs when starting up units from cold, and are also constrained to not generating below certain minimum levels. These start-up and minimum-generation constraints are simulated in a simplified fashion when determining which plant to operate to meet a peaky residual demand. However, testing of this simplification has established that this will not fundamentally alter the nature of the results.
- The model implicitly assumes perfect foresight - it treats the input data for demand and generation as being known at the beginning of the 20 year period – and then develops the lowest cost mix of plant to meet demand. In reality there is inherent uncertainty over such factors, and it is unlikely that any one factor (e.g. gas prices) will permanently follow a ‘High’ or ‘Low’ path as is expressed in the various scenarios for the model.

However, the purpose of the model is to shed insight into the nature of outcomes if a particular set of circumstances were to arise. Accordingly, such factors are not considered to alter the fundamental nature of the results from the model.

- One aspect of this inherent uncertainty which may alter investment decisions is the potential closure of the Tiwai aluminium smelter.
  - In reality this may have the potential to delay low emission investment as parties may be reluctant to commit significant capital to a market which may become over-supplied. As currently configured, the model doesn't take into account such potential strategic considerations.
  - However, given that the impact will alter the timing of investment not the fundamental direction of investment, and scenarios are also run which project the closure of the Tiwai smelter and its impact, it is not considered that this will fundamentally affect the nature of the results.
- There can be some 'binary' outcomes between scenarios - particularly with respect to which fossil-fuel plant wins among existing gas-fired and coal-fired plant as a set of cost drivers reach a threshold whereby one plant (e.g. a coal-fired unit) is suddenly more expensive than another (e.g. a gas-fired plant). This can sometimes make some aspects of the results quite sensitive to certain assumptions as the model will project significant changes in output for certain years between these fossil options as these cost thresholds are reached. However, this principally affects the precise timing of when a particular plant becomes more or less expensive than alternatives. It is not considered that this will affect the fundamental nature of the results from the model.
- A similar factor is that plant investment and retirement is assumed to happen at the beginning of each calendar year. This can result in some step change outcomes on a year-to-year basis, particularly in combination with the binary phenomena above. However, again, this is not considered that this will affect the fundamental nature of the results from the model.

3 Results of the analysis

This section sets out the key findings from our analysis.

3.1 Electric vehicles – key results

Recharging of EV batteries requires an increase in electricity generation, and this increase can affect emissions, depending on the source of additional generation. We have looked at two different within-day charging regimes:

1) 'Smart': EVs are predominantly charged at times of the day when there is lower grid demand (largely overnight), and not at times of higher grid demand
2) 'Simple': EVs are predominantly charged based on the time when people tend to finish their journeys.

3.1.1 Effect of EVs on residual grid power demand

Figure 13 shows projected demand in 2036 for the basecase scenario without EV uptake (or without PV or battery uptake). The chart shows how demand is expected to vary across each day, and over months of the year.

Figure 13: Projected 2036 grid demand without EVs (basecase)

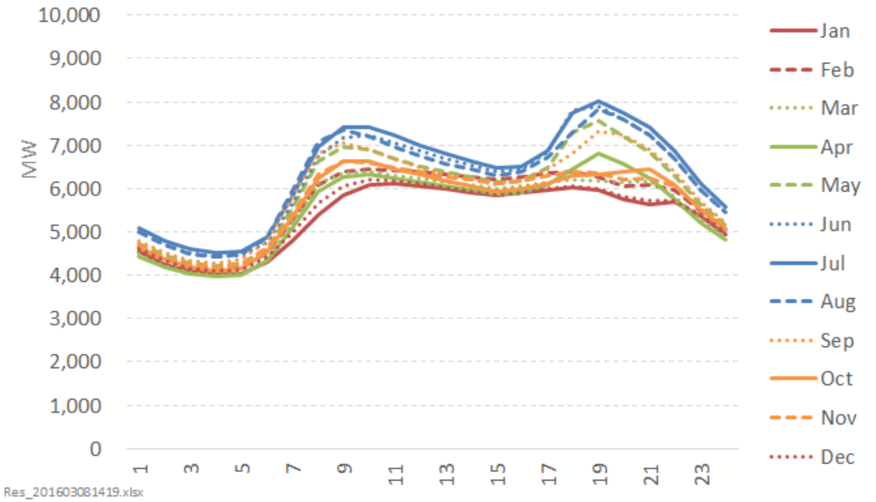

Figure 14 shows the corresponding demand projection with high EV uptake (and smart charging).

Figure 14: Projected 2036 grid demand with EVs (smart charging)

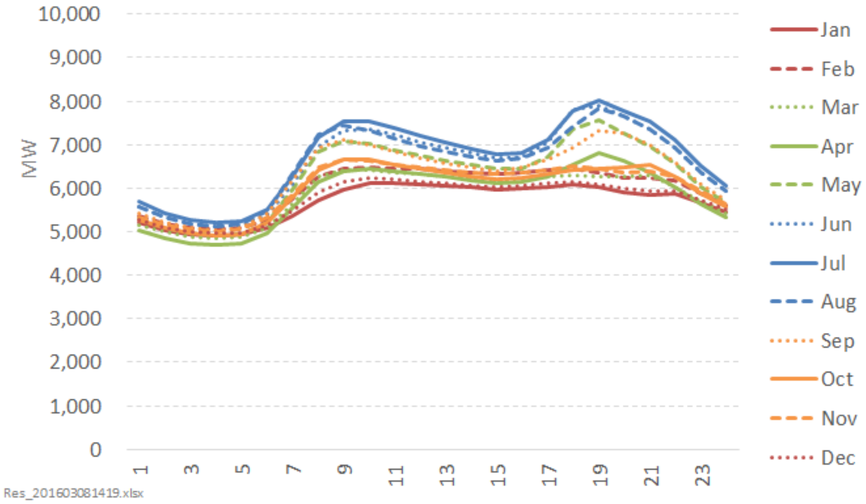

Figure 15: Comparison between with and without EV demand for 2036 for Summer (Jan) & Winter (Jul)

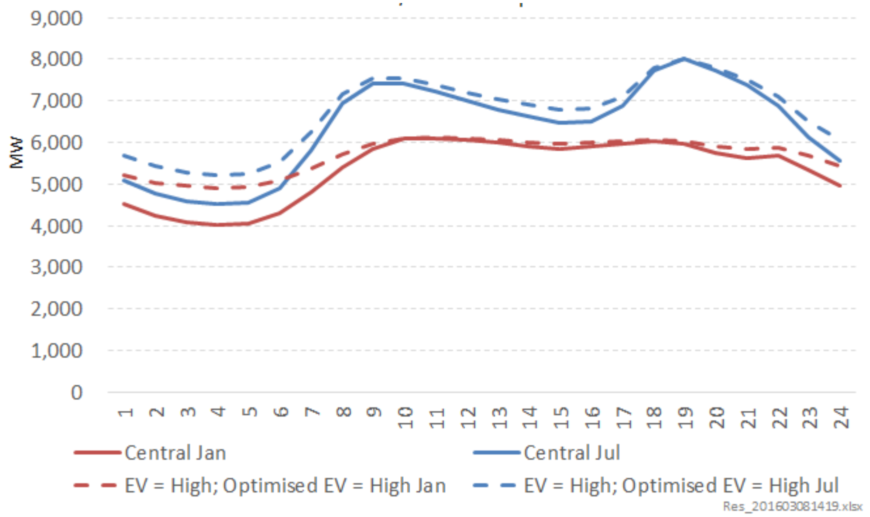

Figure 15 combines the information for the above two figures for only a summer (January) and winter (July) month to illustrate the impact of EV uptake.

This information for 2036 has been used to calculate the projected change in grid demand over the next 20 years. Figure 16 shows the projected demand change under the basecase (top chart) and EV uptake scenario (bottom chart).

Figure 16: 20-year change in demand – basecase and with EVs (smart charging)

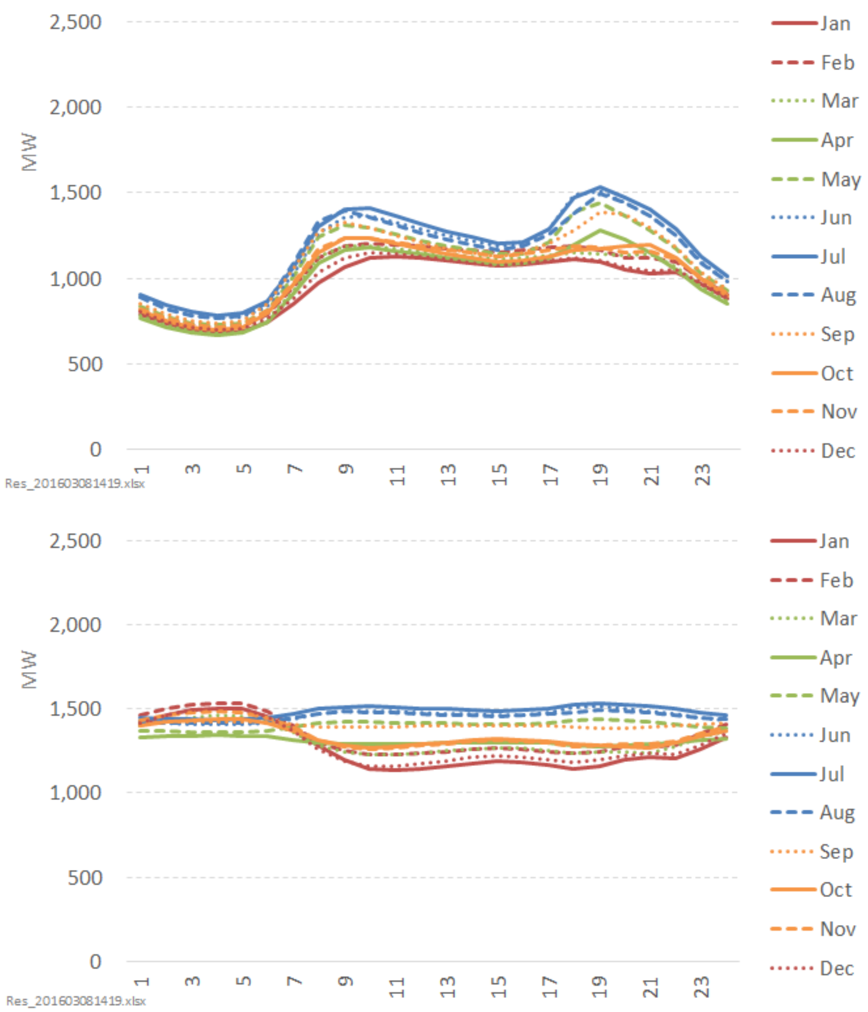

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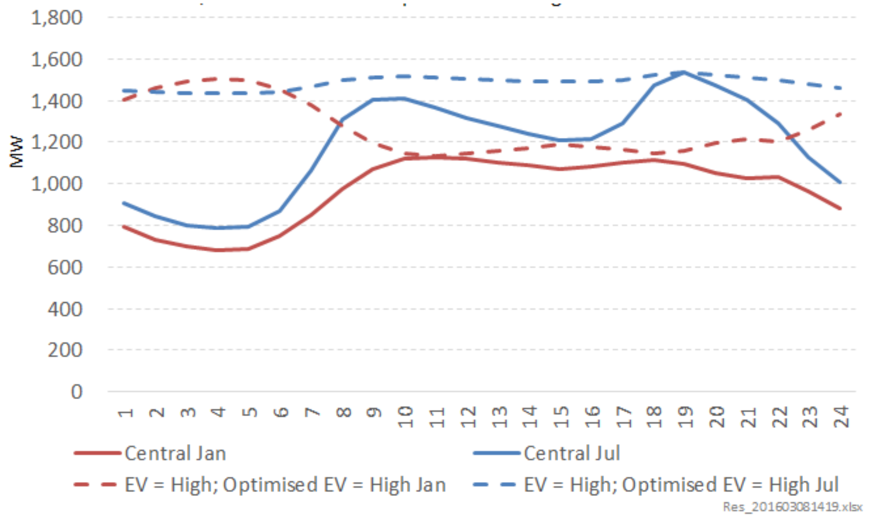
Figure 17 combines the information for the above two figures in Figure 16 for only a summer (January) and winter (July) month to illustrate the impact of EV uptake on demand growth.

Figure 17: Comparison of 20-year change in demand with and without EV uptake for Summer (Jan) & Winter (Jul)



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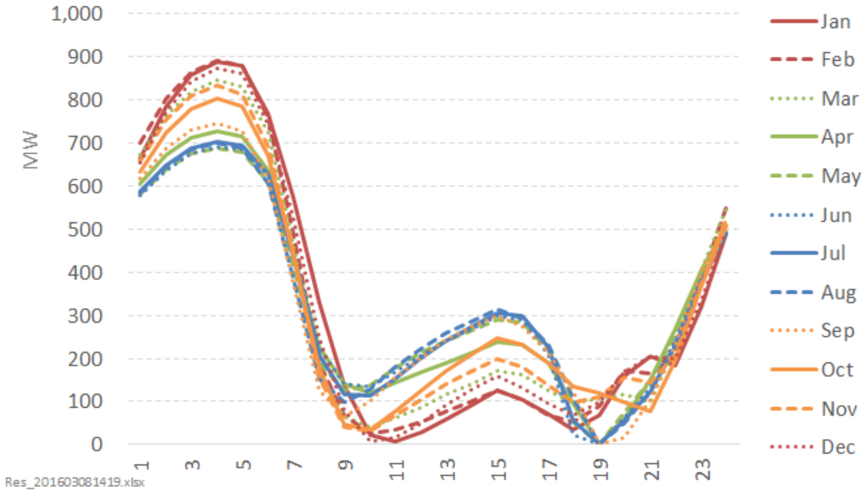
Relative to the basecase, there is a clear increase in average demand due to EV charging. Not surprisingly, this increase is concentrated in the offpeak periods, and demand during peak periods is relatively unchanged.

This is because of the assumed fully optimised EV charging profile which is shown in Figure 18.

Figure 18: 2036 Smart EV charging profile



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A smart EV charging profile has the effect of both growing *and* flattening the daily demand profile. However, EV charging has little effect on seasonal demand patterns. The monthly differences in demand are projected to remain much as they are today.

For the reasons set out in Appendix C, this projected change in demand is expected to be met mainly by new low emission baseload plant, such as wind and geothermal.

This is illustrated in Figure 19 which, in the top graph, shows the projected output from the different types of generation in the basecase scenario with no EV (or other technology) uptake, and in the bottom graph the projected generation output in a scenario with high EV uptake.

Figure 19: Projected generation – basecase (top) and with high, smart-charged EV uptake (bottom)

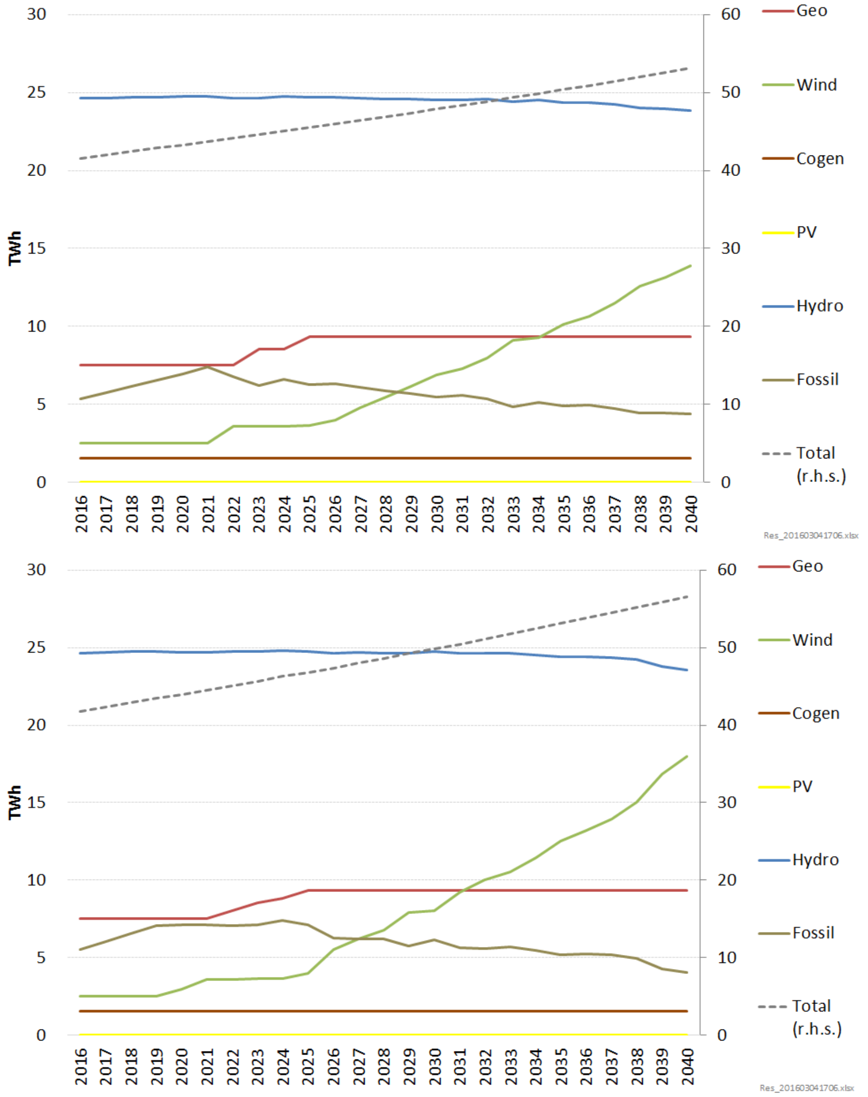

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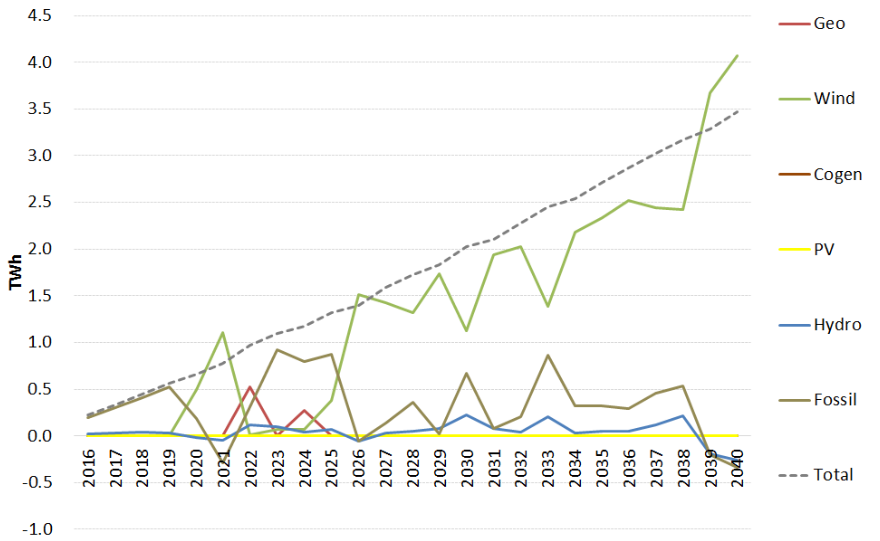
Figure 20 shows the difference between the two graphs. It highlights that

- In the near-term (i.e. the next couple of years) increased EV demand is met by increased fossil generation.
- In the medium to long term (i.e. from 2020 onwards), increased EV demand is projected to come predominantly from new wind generation projects.

Figure 20: Difference in projected generation output due to high EV uptake (smart charging)



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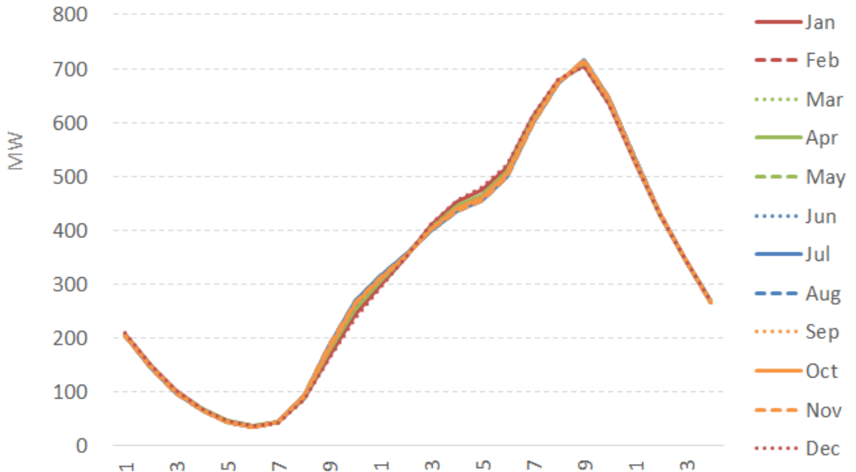
Analysing the outcomes in this fashion also allows calculation of the change in total sector CO_2 emissions.

Impact of EV charging regime

Page 52 of Appendix C details how the model was also run with EVs being charged under a 'simple' approach. In this approach, the timing of EV charging was driven by the time that people finished their journeys – particularly those journeys which finished at home. This resulted in a strong evening peak to EV charging as shown in Figure 21.

Figure 21: 2036 Simple EV charging profile



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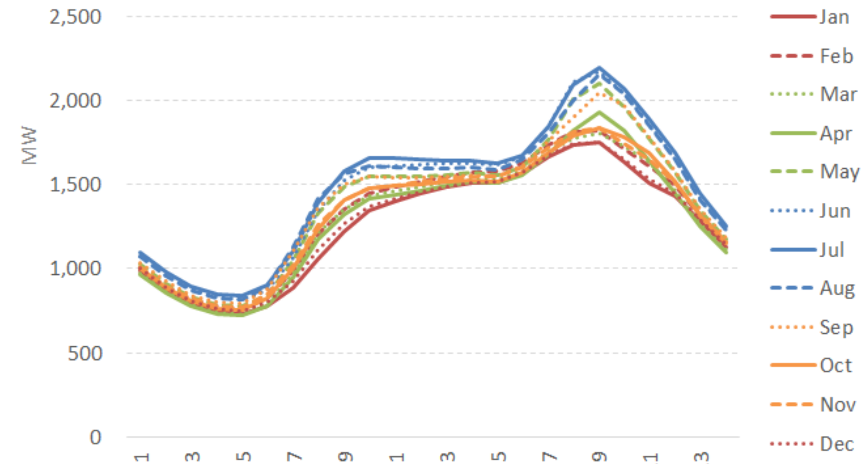
As is shown in Figure 22, this results in the 20-year change in demand being peakier because of EV uptake.

Figure 22: 20-year change in demand with high EV uptake and a 'simple' EV charging approach



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For the reasons set out in Appendix C, some of this growth in peaky EV demand will be met by new low emission baseload plant, such as wind and geothermal (with altered hydro generation helping compensate for the increased peakiness). However, some of this peaky demand growth will be met by increased operation of fossil generators such as OCGT peakers.

3.1.2 Effect of EVs on electricity sector emissions

Figure 23 below shows the electricity sector emissions impacts of EVs for three 'snapshot' years (noting this chart *excludes* non-electricity sector impacts, such as the reduction in 'tailpipe' emissions). The years indicate the results for EV charging this year ('near-term'), and in five ('medium-term') and fifteen ('longer-term') years' time. The impacts are expressed in terms of emissions caused / (displaced) per kWh of EV charging demand:[20]

- In the near term with a generation relative surplus, increased demand from EVs is met mainly by higher generation from existing fossil power stations, with a consequent increase in electricity sector emissions
- Over time, as the system returns to a more balanced position, power demand for EV charging increasingly affects new power station investment decisions. With smart charging over-night (i.e. at times of low demand), this increased demand from EVs is expected to be met predominantly by new baseload generation options which have low emissions (wind and geothermal).

There is a similar dynamic for simple charging. However, while some of the increased demand in the long-term is met by new baseload low emission plants, the fact that much of the charging occurs at times of evening peak means that there is also increased demand for low-capacity factor generation – and ultimately an increase in fossil generation to meet additional demand in the evening peaks.

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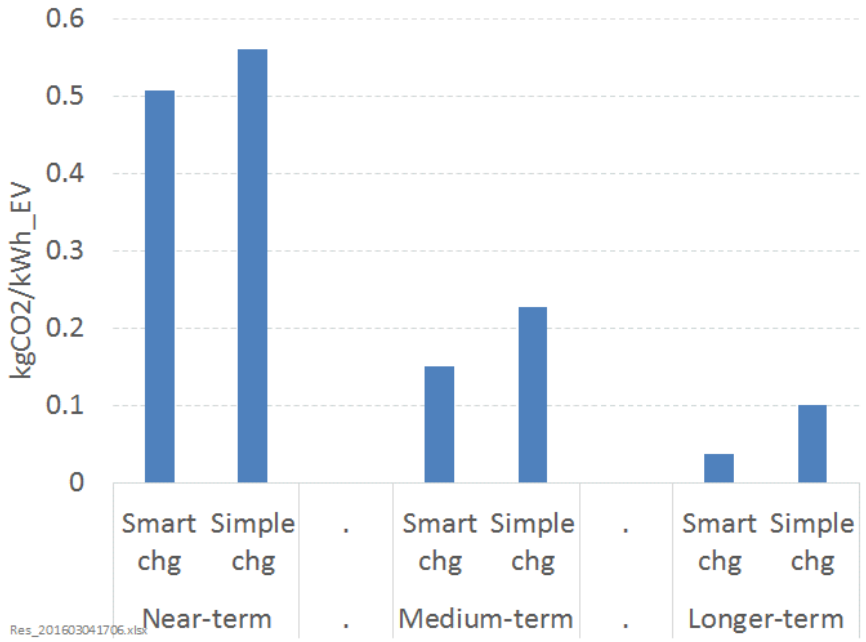
[20] With reference to Figure 20 previously, the impact is calculated as the increase in sector CO_2 emissions between the with-EV and without-EV scenarios, divided by the increase in demand between the two scenarios.

Figure 23: 'Snapshot' effect of EVs on electricity sector emissions[21]

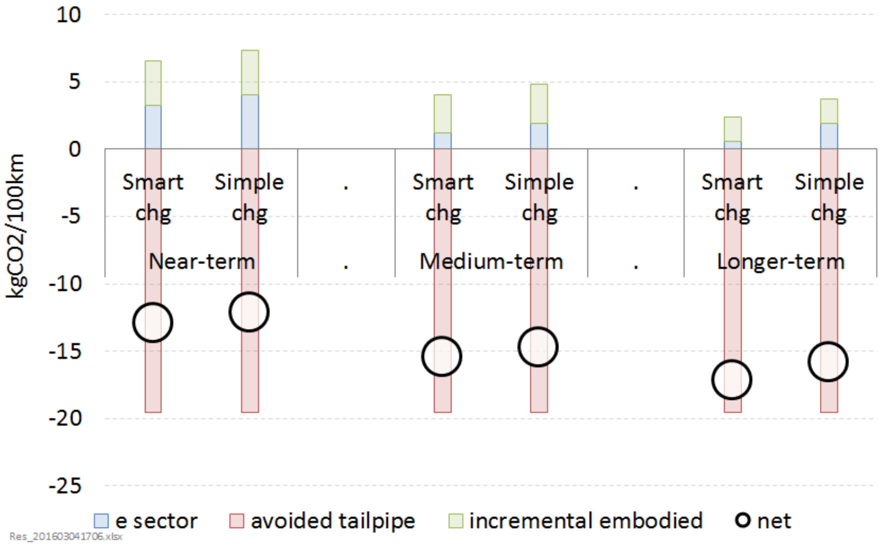


3.1.3 Effect of EVs on total emissions – lifetime impact

Figure 24 shows the overall lifetime emissions impact of EVs, taking into account the avoided 'tailpipe' emissions from internal combustion engine (ICE) vehicles, plus differences in the embodied emissions associated with each vehicle type's manufacture (noting that EVs result in greater embodied emissions than ICEs – as set out in section Appendix A). Because of the changing electricity sector impact of EVs illustrated in Figure 23, the electricity sector emissions impacts are the *cumulative* emissions impacts over the life of the vehicle.

The emissions impacts are also expressed in $kgCO_2$/100km. This allows comparisons between these different factors.

Figure 24: EV total emissions impacts over a vehicle life



Savings in tailpipe emissions from EVs more than offset their electricity sector emissions and the higher embodied emissions associated with their manufacture.[22]

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[21] It is important to note that these are estimates of the *marginal* emission factors, i.e. the emissions effect of the increase in demand due to EV charging. The *average* emissions per kWh for all demand sources will be much lower, because renewables are expected to continue to be the predominant source of electricity generation in New Zealand.

[22] As battery technology improves, and overseas battery manufacturers increasingly source their energy from renewable sources, the higher embodied emissions relative to ICEs should decline. A simple estimate of this decline has

EVs are expected to provide net emissions savings based on current conditions, and these are expected to grow over time. EVs are also expected to produce emission savings under both smart and simple charging regimes, although they will be higher for smart charging.

3.2 Solar panels – key results

3.2.1 Effect of PVs on residual grid power demand

Figure 24 shows projected grid demand for 2036 with high PV uptake. Relative to the basecase projection for 2036 (shown previously in Figure 13), it is much lower through the mid-part of each day (especially in summer months).

Figure 25: Projected 2036 grid demand with PVs

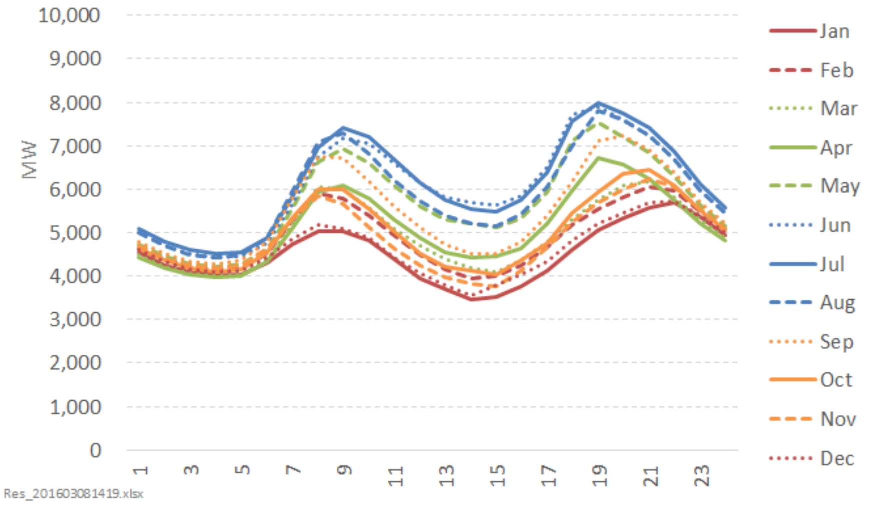

Figure 26 combines the information for Figure 13 and Figure 25 for only a summer (January) and winter (July) month to illustrate the impact of PV uptake.

Figure 26: Comparison between with and without PV uptake for 2036 for Summer (Jan) & Winter (Jul)

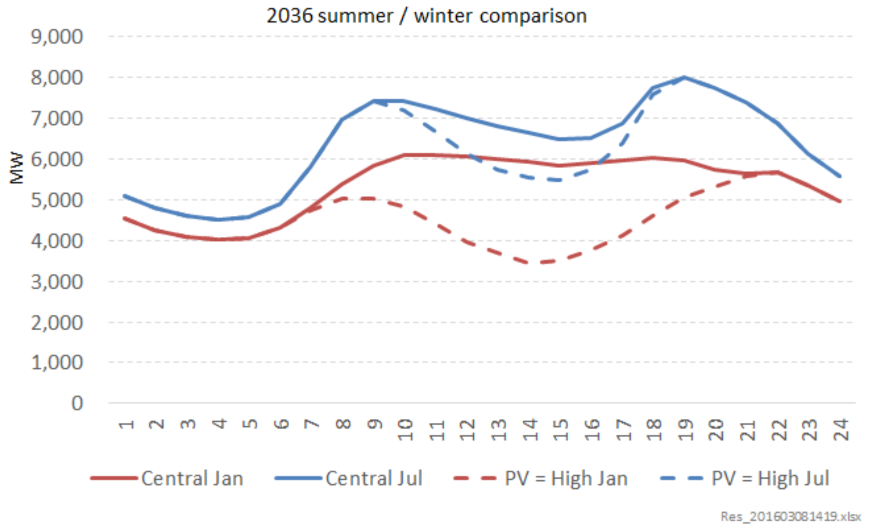

Figure 27 shows the projected change in grid demand over the next 20 years under the basecase[23] (top chart) and PV uptake scenario (lower chart).

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been used to reflect this. However, it should be noted that this factor is subject to material uncertainty.

[23] The basecase is the same as Figure 13 shown in the previous section on EVs.

Figure 27: 20-year change in demand – basecase and with PVs

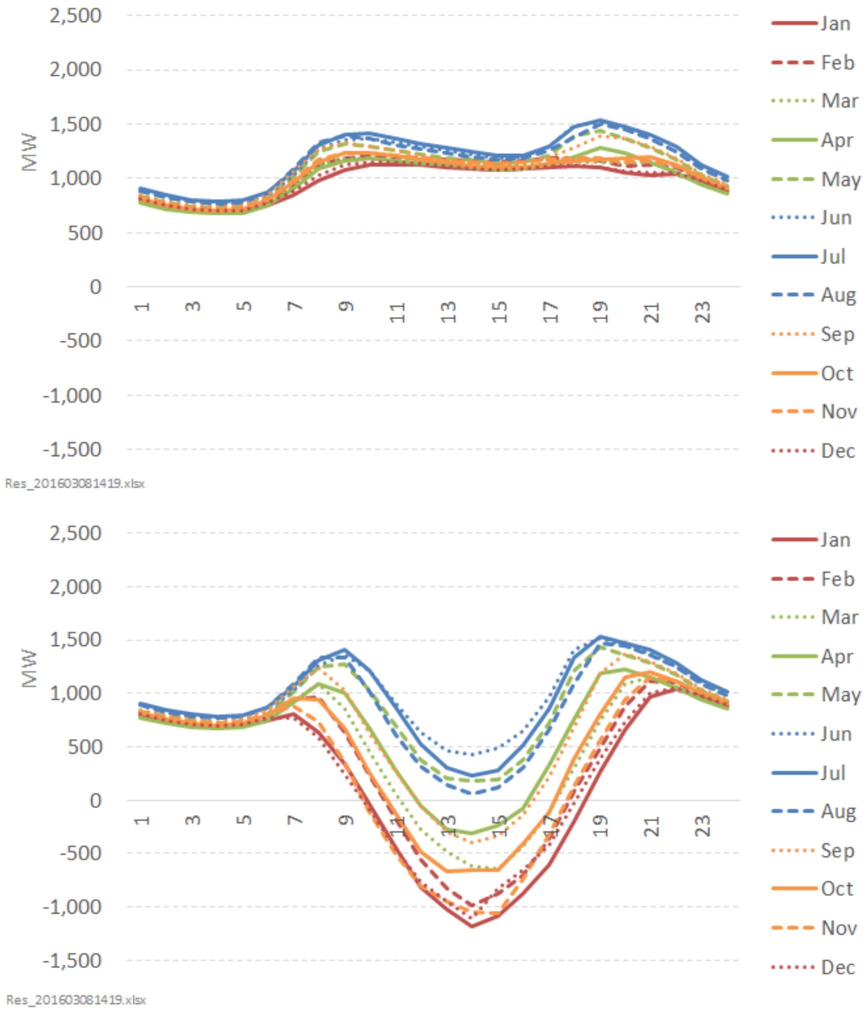

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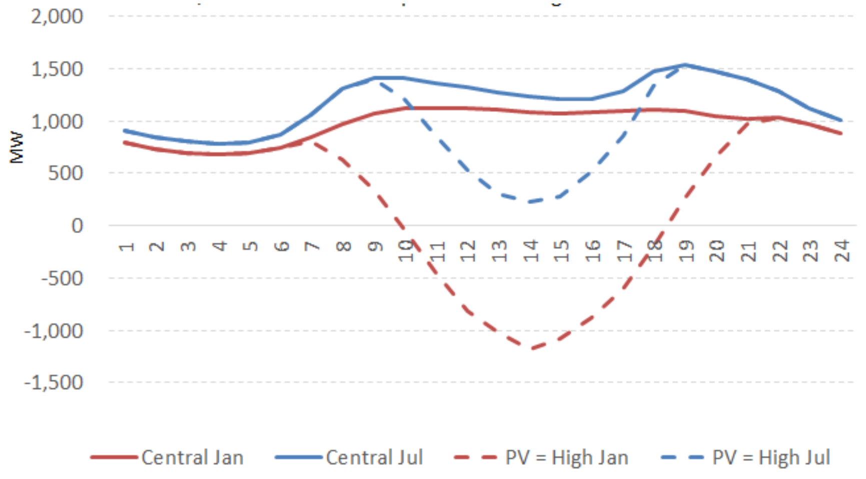
Figure 28 combines the information for the above two figures in Figure 27 for only a summer (January) and winter (July) month to illustrate the impact of EV uptake on demand growth.

Figure 28: Comparison of 20-year change in demand with and without PV uptake for Summer (Jan) & Winter (Jul)



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High PV uptake will reduce the overall growth in grid demand relative to the basecase (as indicated by less area under the curves for the PV uptake scenario). This reduction is not surprising, given that solar PV will be meeting a large proportion of electricity demand growth in this scenario.

The more surprising feature is that the growth in peak grid demand is the same in the basecase and high PV uptake scenarios (both show a demand growth of around 1,500 MW). High PV uptake also results in a widening of the seasonal demand differentials between winter and summer.

This means there would be no reduction in the total grid-scale capacity held on the system. However, there would be a change in the type of plant required at the grid level, with an increase in the requirement for lower capacity-factor generation (i.e. plant that only runs when required).

For the reasons set out in Appendix C, this flexibility requirement is expected to be met mainly by increased use of fossil-fuelled plant in the longer term.

This change in generation outcomes is illustrated in Figure 29 which, in the top graph, shows the projected output from the different types of generation in the basecase scenario with no PV (or other technology) uptake, and in the bottom graph the projected generation output in a scenario with high PV uptake.

Figure 29: Projected generation – basecase (top) and with high PV uptake (bottom)

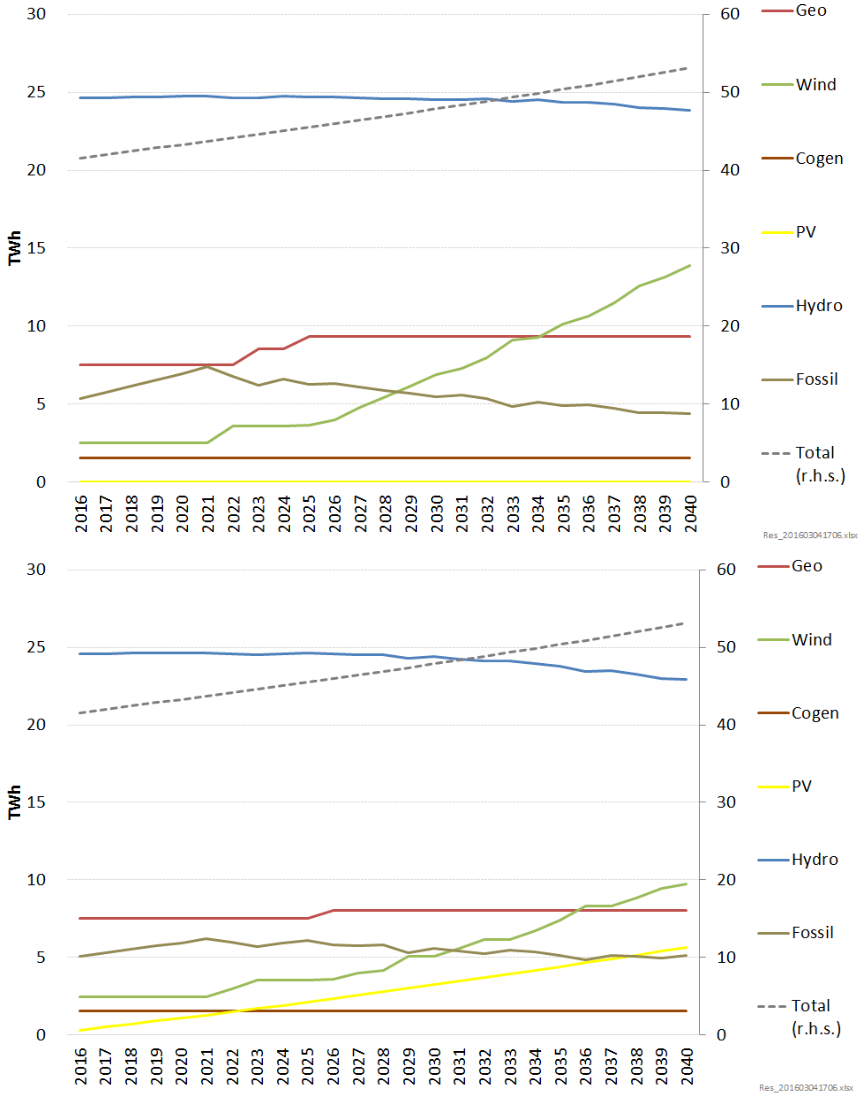
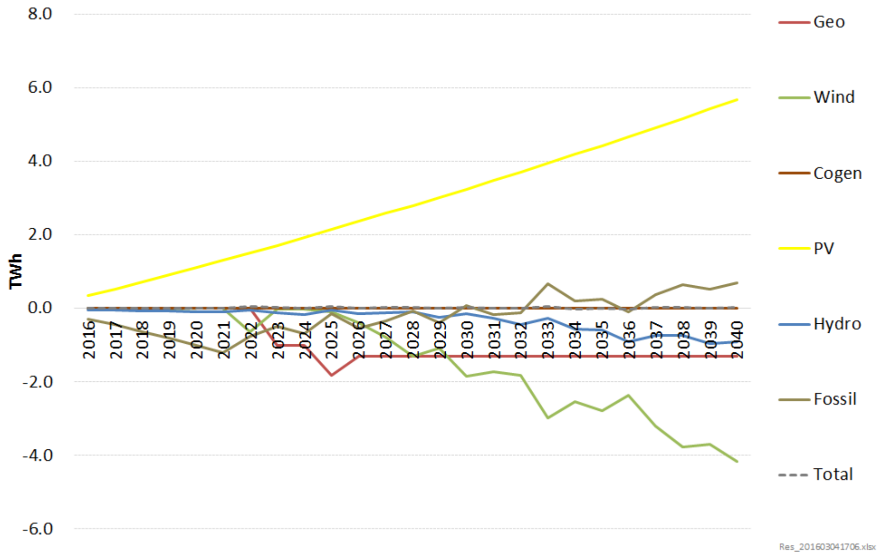


Figure 30 shows the difference between the two graphs. It highlights that

- In the near-term (i.e. the next couple of years) increased PV generation results in fossil generation being displaced.
- In the medium to long term (i.e. from 2022 onwards), increased PV generation is projected to displace wind and geothermal plant that would otherwise be built.
- In the long term (i.e. from 2033 onwards), increased PV generation is projected to increase fossil generation.

Figure 30: Difference in projected generation output due to high PV uptake



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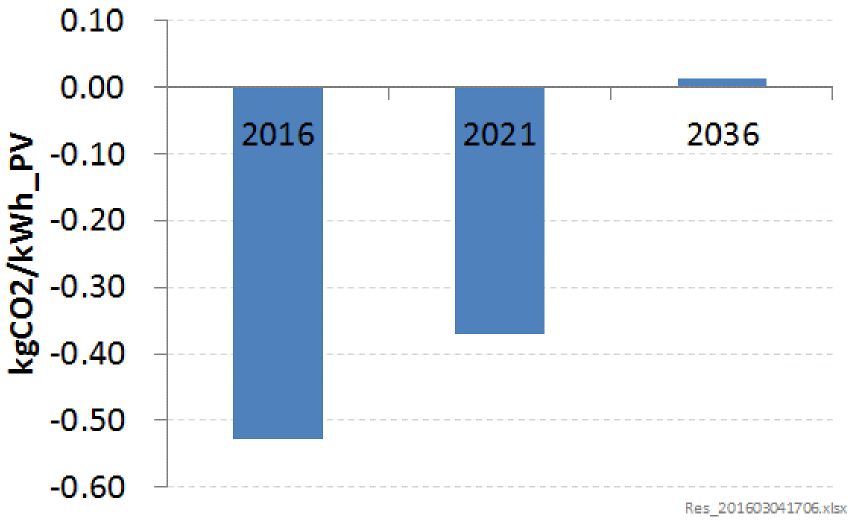
3.2.2 Effect of PVs on electricity sector emissions

Figure 31 shows the impact of a solar PV uptake on electricity sector emissions for three snapshot years. The chart shows the results for a solar PV panel operating this year, and in five and fifteen years' time.

Figure 31: 'Snapshot' effect of PV on electricity sector emissions



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With the current situation of generation relative surplus, additional solar PV in 2016 will predominantly displace generation from existing fossil-fuelled power stations. Additional solar PV generation will therefore lower electricity sector emissions in the near term.

However, as the system returns to a more balanced position over time, PV uptake will progressively alter the investment decisions of *new* plant that would otherwise have been built to meet the growth in demand.

Increasingly, the displaced power will be from low emission power stations (wind and geothermal) that would otherwise have been built, rather than new fossil-fuelled stations. This means that solar PV is expected to have little beneficial effect on emissions in this period.

In the longer-term, we expect additional solar PV to cause a need for more fossil-fuelled generation than would have been the case without solar PV. As a result, we expect solar PV generation to modestly increase electricity sector emissions in these later years.

This is because solar PV generates more power in summer than winter – the opposite of New Zealand's demand needs. Existing hydro will be unable to fully counteract this.[24] This seasonal effect is slightly offset by solar PV having a favourable day/night pattern of generation – generating in the middle of the day, potentially allows more hydro generation to be targeted into morning and evening peak periods – although this too is limited by the physical capacity of hydro stations.

Other new power sources will be required to counteract an increasing seasonal imbalance between supply and demand. This is most likely to be from thermal generation, because it has a lower overall cost than the alternatives.[25]

For example, geothermal and wind are not cost-effective for seasonal duty. They have high fixed costs that are incurred even when the plant is not running. In addition, wind generation is intermittent, reducing its effectiveness as a controllable power supply source.

The net effect is that in the longer term, we expect solar PV uptake won't only displace new low emission options (i.e. wind and geothermal), it will also slightly add to emissions by increasing the requirement for fossil-fuelled generation.

3.2.3 Effect of PVs on cumulative emissions

Figure 32 shows the electricity sector emission consequences of solar PV panels installed at different times, based on their cumulative emissions over 20 years from being built. (Note the different scale in comparison with Figure 31.)

For a panel installed in 2016, the early years where PV is operating in a system with relative surplus (and therefore reducing emissions by displacing fossil generation) offsets the later years where PV is operating in a more balanced system (and having little impact on emissions).

For a panel installed in 2016, we expect a modest net reduction in electricity sector emissions over its lifetime. However, panels installed at later dates will increasingly displace new low emission

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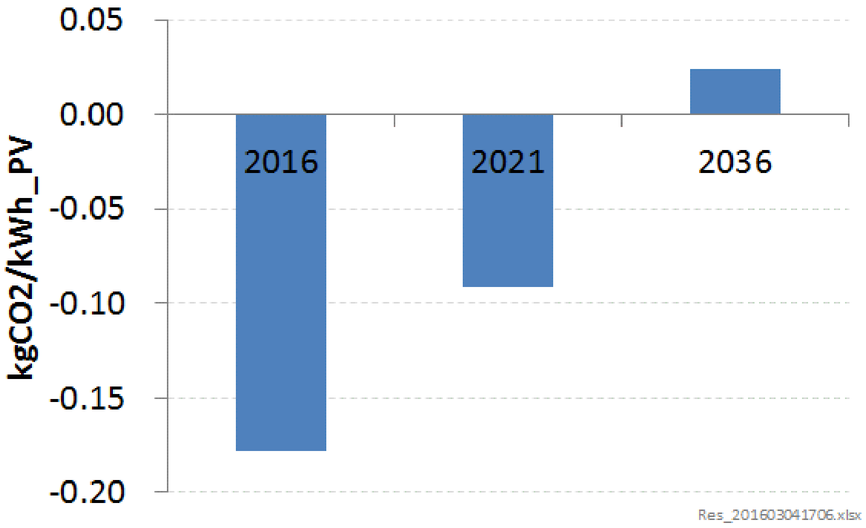
[24] While existing hydro can adjust to meet changes in the general within-day pattern of demand, its storage capacity limits the extent to which it can additionally store water in summer to release in winter more than it is currently doing.

[25] These include options such as pumped storage, and non-fossil fuelled thermal options such as biomass. These technologies are unlikely to be cost-effective for seasonal operation because they have high fixed costs.

plants, and therefore provide lower electricity sector emission benefits over their life. Ultimately, we expect that additional solar PV will modestly increase electricity sector emissions for the reasons noted above.

Figure 32: Altered electricity emissions over a 20-year life for PV panels built at different times[26]



3.2.4 Effect of PV and batteries on emissions

In some countries it has been suggested that the *combination* of PV plus battery uptake will deliver more favourable emission outcomes than solar PV by itself. This is because batteries allow 'solar electricity' to be stored for use at a later time, when it is more likely to displace fossil-fuelled generation.

We looked at this issue for New Zealand by running scenarios with combined uptake, as well as scenarios with just PV or just battery uptake.

While batteries by themselves reduce emissions (as detailed in section 3.3), combining them with PV panels does not make them any more effective. Similarly, the incremental emissions impact of adding PV generation to a world with high battery uptake is very similar to adding such PV generation in a world with no battery uptake. In both cases, a significant amount of the generation being displaced by PV over the long-term is wind and geothermal plant which would otherwise have been built.

Further, as detailed on page Figure 39, if batteries are operated in such a way as to minimise export from consumers with PV panels, their effectiveness at reducing emissions is impaired compared to a situation where batteries are operated to minimise overall electricity sector costs.

3.2.5 Effect of PVs on total emissions – lifetime impact

Figure 33 shows the life-cycle emissions of PV panels built at different times taking account of cumulative electricity sector impacts over the life of the panels (discussed in section 3.2.3) and embodied emissions, which are the emissions resulting from the manufacturing process for PVs (detailed in Appendix A).

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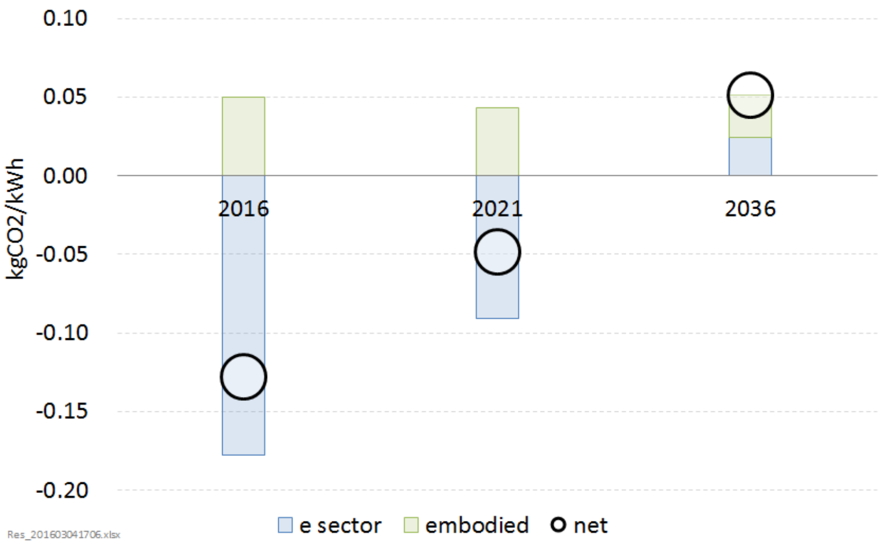
[26] To interpret this graph, a panel built in 2016 will result in some significant savings in 2016 – as illustrated in Figure 31 previously. However, as also shown in Figure 31, by 2021 the savings will be a lot less, and by 2031 the panel will be resulting in an increase in emissions. The number shown in Figure 32 for a panel built in 2016 represents the sum of all the years from 2016 to 2035, and for a panel built in 2021, the number shown in Figure 32 represents the sum of all years from 2021 to 2040. And so on.

The chart shows these impacts for PV panels installed in 2016, 2021 or 2031. The circle represents the combined effect of electricity sector and embodied emissions.

For PVs installed in 2016, the benefit of the early years of offsetting fossil generation outweighs the embodied emissions associated with their manufacture. However, in the medium-term the net effect of PV generation moves to being neutral, and then ultimately panels built in the long-term are projected to increase CO_2 emissions. This is because PV generation increasingly displaces low-emissions wind and geothermal generation that would otherwise be built, and starts to increase the need for low-capacity factor fossil generation to perform seasonal firming.

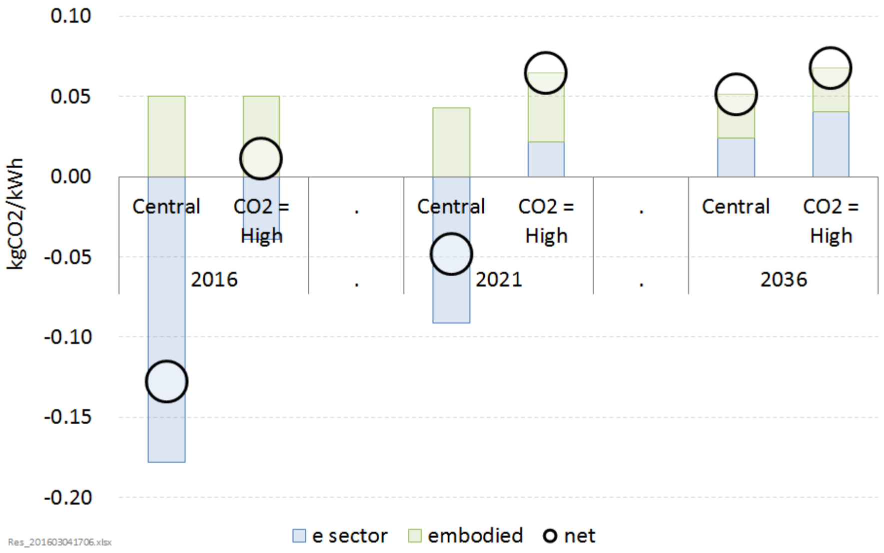
Figure 33: Lifetime emissions impact of PV – Central scenario



The above analysis was repeated for various different scenarios of key electricity sector drivers including demand growth, fuel prices and CO_2 prices.

This revealed that the magnitude of the emissions effect of PV uptake is sensitive to future CO_2 prices. Ironically, it appears that in a future of High CO_2 prices (indicative of a scenario where global warming is acknowledged to be a serious problem), PV uptake has a particularly bad emissions impact in New Zealand. This is shown in Figure 34 which compares the lifetime emissions impact of PV for the Central scenario, and also for a scenario with High CO_2 prices.

Figure 34: Lifetime emissions impact of PV – Central and High CO2 price scenarios



This outcome occurs because in a high CO_2 price world, we see PV displacing a greater amount of wind than in a medium CO_2 price world.

3.3 Batteries – key results

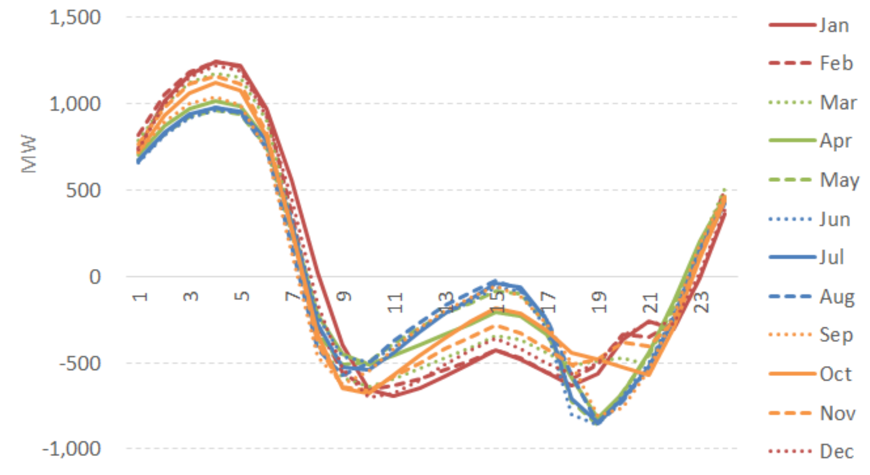
The principal impact of stand-alone batteries (i.e those not part of an EV) is to alter the pattern of grid demand – increasing demand when batteries are being charged-up, and decreasing demand when they are discharged again. There is a secondary impact from a small net increase in grid demand due to battery charging losses.

We have modelled a scenario where batteries are used to optimise and flatten overall grid demand.

Batteries were assumed to charge and discharge once per day. No batteries were assumed to provide seasonal demand shifting (i.e. charge up once in summer to release once in winter) or perform more than once cycle per day (e.g. charge overnight to release in the morning peak, then charge during midday to release in the evening peak). This is because these modes of operation appear unlikely to be financially attractive.

This results in a charging profile illustrated in Figure 35.

Figure 35: 2036 battery charge/(discharge) profile



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The impact on overall grid demand is illustrated in Figure 36. This shows that, although batteries don't materially alter the overall quantity of grid demand (the area under the lines), they do act to materially reduce the peakiness of demand.

Figure 36: Projected total grid demand - basecase and with high battery uptake

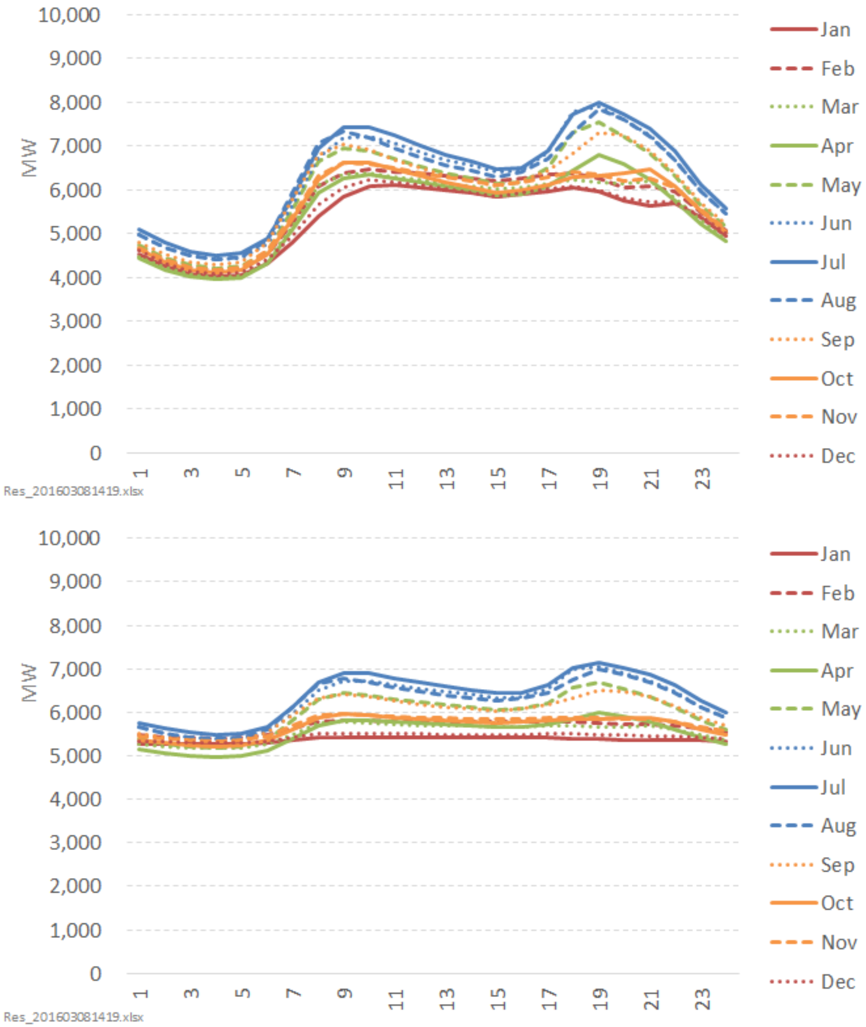
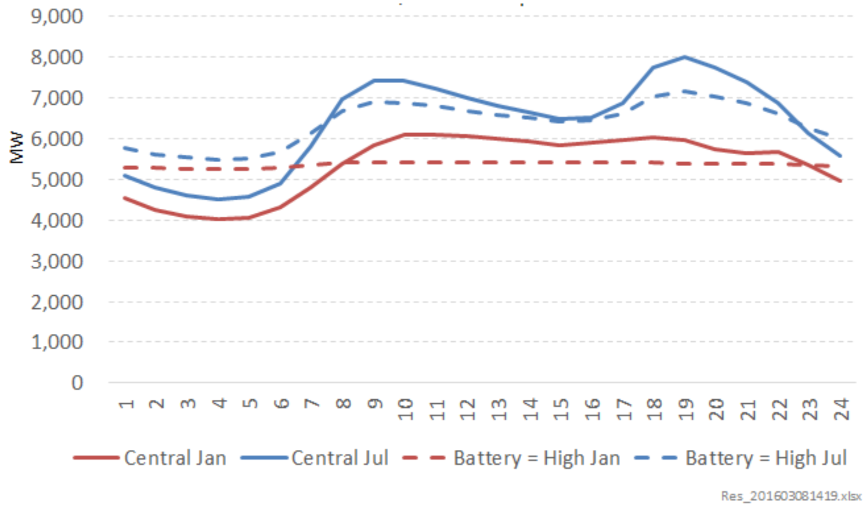


Figure 37 combines the information from the two graphs in Figure 36 for only a summer (January) and winter (July) month to illustrate the impact of battery uptake.

Figure 37: Comparison between with and without battery uptake for 2036 for Summer (Jan) & Winter (Jul)



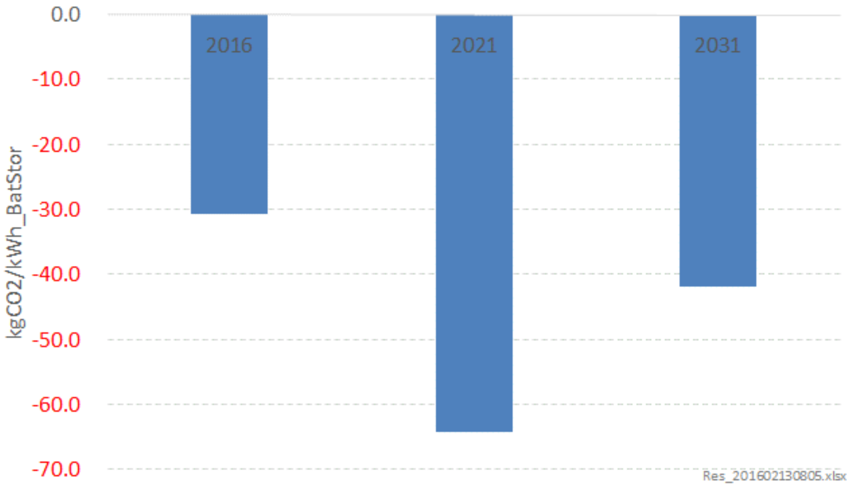
The results shown in Figure 38 indicate that with this pattern of battery charging and discharging, batteries have a beneficial impact in terms of reducing CO_2 emissions throughout their life.

However, the nature of the benefit is different in the early years, compared to the later years:

- In the early years when the system has some relative surplus, the benefit occurs through the flattening of demand, which allows lower cost gas-fired thermal stations to run more often, and reduces use of higher cost coal-fired thermal stations

- As the system becomes more balanced, batteries start to impact on the type of new plant that will be built. The flattening of the demand curve means that more low emission baseload plant (wind and geothermal) is built than otherwise, resulting in existing thermal plant running less.

Figure 38: Electricity sector emissions impacts of battery storage



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In scenarios that combine the uptake of PVs and batteries, the within-day charging/discharging regime was optimised from a ‘New Zealand Inc.’ perspective – i.e. to flatten the within-day shape of net grid demand – taking into account any change in shape of such demand due to high solar PV uptake.[27]

As set out on page 26, this combination doesn’t result in an emissions-reduction ‘whole’ that is radically different to the sum of its parts. i.e. the Only battery + Only PV emissions reductions ≈ Battery + PV emissions reductions.

Another PV + battery charging regime was examined where the within-day charging of batteries was optimised from the consumer’s perspective, based on existing price signals that reward consumers for minimising exports. This is the way that many residential battery + PV systems are being designed to operate, given the current price signals that such households receive.

The outcome of such a charging approach is for batteries to be predominantly charged during the middle of the day, whereas a ‘New Zealand Inc’ demand-optimising approach would mainly charge such batteries overnight.

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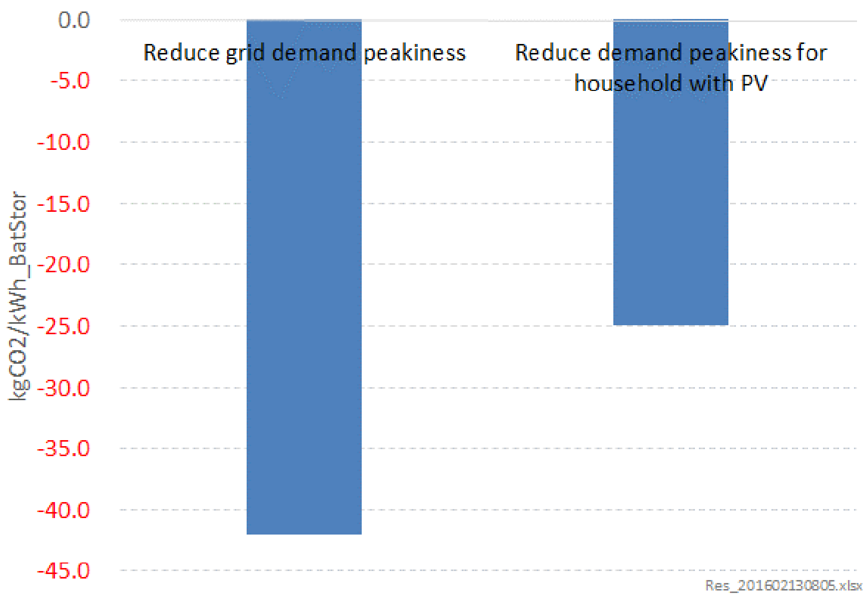
[27] Strictly speaking, the objective is to minimise the difference in the costs of producing electricity across each day – this is expected to result in a flatter demand profile because demand and costs are correlated.

Figure 39: Long term electricity sector emissions impacts of battery storage for two different charge optimisation approaches



As Figure 39 indicates, this reduces the effectiveness of batteries at reducing emissions than would be the case if battery charging was optimised for the system as a whole.

3.4 Comparison between technologies

Some consumers may consider the purchase of EVs, PVs or batteries to reduce their carbon footprint. Accordingly, the above analysis has been used to compare the emissions consequences of purchasing a typical 'residential-scale' version of the three different technologies: [28]

- A 4 kW rooftop PV panel
- A standard EV
- A stand-alone battery with 7 kWh storage capacity.

For a household with discretionary 'green' dollars, investment in these technologies is likely to require similar levels of net upfront cost. A 4 kW solar PV unit currently retails at around $12,000 - $14,000[29] – and a 7 kWh storage battery is expected to have a similar price. [30] This is also roughly the price difference between an EV and its conventional equivalent. [31]

As shown in Figure 40, we expect each EV operating in 2016 to reduce carbon emissions by around 1.2 tonnes per year. Looking at the longer term, we expect the emissions reduction per vehicle to increase to around 1.5 tonnes per year. This is because charging of

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[28] Of course this is a very simplified comparison, as consumers are likely to consider a range of factors, such as affordability, ease of use, etc. We have not considered other factors, nor have we looked at alternatives which could reduce their carbon footprint, such as improving their home's insulation.

[29] Based on advertised prices at whatpowercrisis.co.nz in February 2016, plus installation costs.

[30] Based on the price disclosed by AGL for a 6kWh battery storage device in Australia, adjusted for the exchange rate, and scaled to 7kWh capacity. See www.agl.com.au/about-agl/media-centre/article-list/2015/may/agl-is-first-major-retailer-to-launch-battery-storage

[31] Based on the price difference between conventional and hybrid electric Mitsubishi Outlander models. A similar price difference exists between second hand EVs and conventional ICE vehicles of comparable size and age.

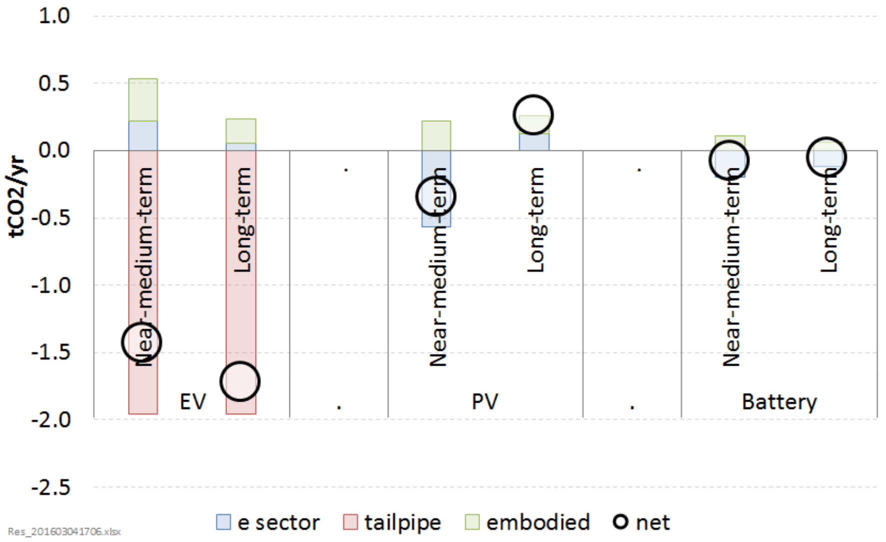
EVs will increasingly be met from new low emission electricity sources.[32]

By comparison, we expect a 4 kW solar PV panel installed in 2016 to have almost no net reduction on emissions – because the saved electricity sector emissions largely offset the embodied emissions in the manufacture of the PV panel.

As discussed earlier, we expect the electricity sector emissions saving with PVs to decline over time, as solar PV panels increasingly substitute for new low emission plants. As a result, over the longer term, we expect a solar PV panel installed in 2031 to increase emissions by about 0.6 tonne per year.

For batteries, we expect emissions reductions of around 0.2 to 0.3 tonnes per year, and this does not change much over time.

Figure 40: Annualised emissions impact of typical EV, PV, and battery



These results are not surprising given New Zealand's carbon footprint. At present, the average New Zealand household is estimated to directly cause annual emissions of approximately 7 tCO_2. As Figure 41 below illustrates, the vast majority of these direct household emissions are from vehicles.[33]

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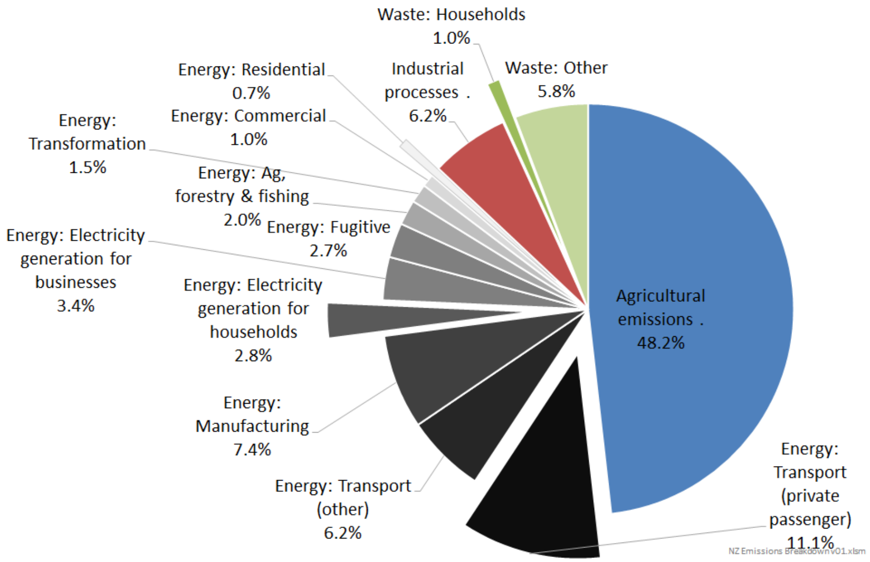
[32] This is based on the 'smart' charging of EV largely at offpeak times. The emissions savings are modestly reduced if charging occurs at other times (i.e. 'simple' charging).

[33] The 7 tCO_2 figure, and the numbers shown in Figure 41, are from Concept analysis using data from the Ministry for the Environment, the Ministry of Business, Innovation and Employment, and Statistics New Zealand. 'Agricultural' emissions are largely methane from livestock. 'Energy' emissions are largely from burning fossil fuels to provide heat energy or motive power. 'Industrial process' emissions relate to processes which cause emissions (e.g. the chemical reactions associated with cement production). 'Waste' covers emissions from landfill and the like.

Figure 41: Breakdown of New Zealand's total greenhouse emissions - 'splitting out' those directly attributable to households



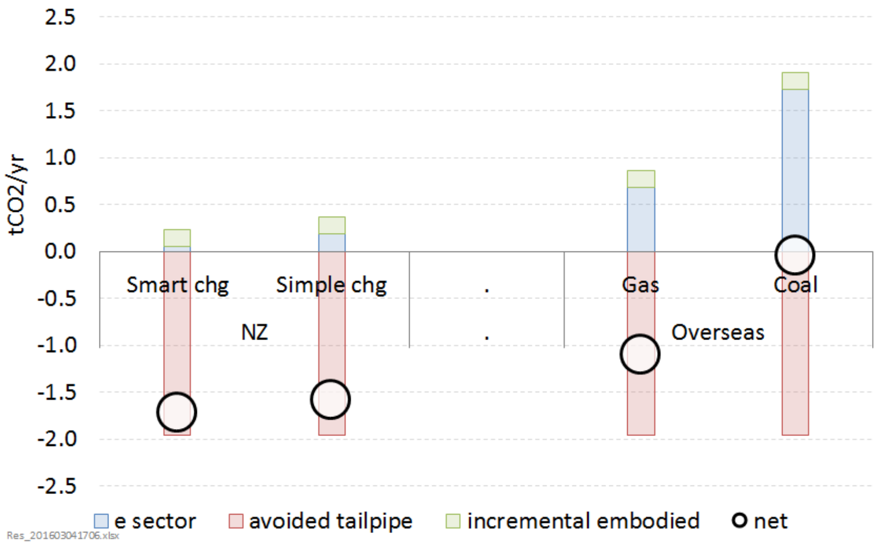
Overall if consumers wish to spend money on new technologies to deliver environmental benefits, by far the biggest emissions saving can be achieved from investing in EVs, whereas batteries and solar PVs have less benefit, and PVs may even increase net emissions in the longer term.

3.5 Comparison with other countries

The projected emissions impacts shown in Figure 40 are markedly different to those expected in many other countries, such as Australia and the United States where coal or gas-fired power stations are the predominant source of grid electricity.

Figure 42 compares the results for EVs in New Zealand with countries where gas or coal-fired power stations are the main sources for existing and new power supply. There will still be an emissions benefit from EVs for countries reliant on gas-fired generation, but much less than the benefits in New Zealand. And for countries that are largely dependent on coal-fired generation, EVs are expected to provide no net emissions benefit.[34]

Figure 42: Emissions impact of EV - NZ and overseas



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[34] These emission impacts are consistent with those estimated by the United States Department of Energy for EV uptake in that country (after allowing for international differences in average vehicle travel distances and fuel efficiency). See www.afdc.energy.gov/vehicles/electric_emissions.php

Figure 43: Emissions impact of 4 kW solar PV - NZ and overseas

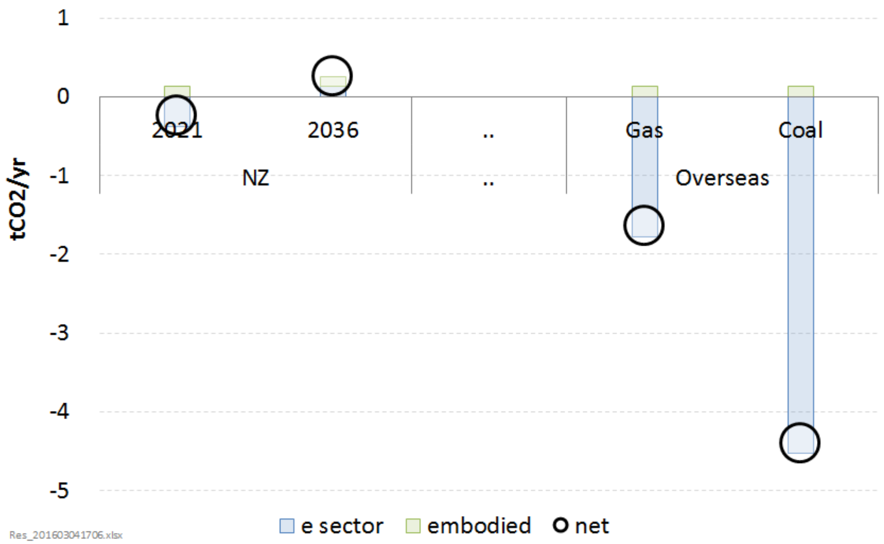

Figure 43 compares the results for solar PVs in New Zealand with countries where gas or coal-fired power stations are the main sources for existing and new power supply. In those countries, solar PV will substantially reduce emissions.

The key reason for the differences in national results is that low emission sources in New Zealand (such as wind and geothermal) provide the lowest cost source for new baseload power supply.[35] This is unusual by international standards.

As a result, new EVs will mainly be charged from low emission power sources in New Zealand. This contrasts with many other countries where EVs alter the rate of investment in gas or coal-fired power stations – and hence emissions. Likewise, PVs will mainly displace investment in new gas and coal-fired stations – resulting in emissions reductions.

3.6 Sensitivity testing

We have tested to see whether the results change with different input assumptions. Almost 90 different scenarios have been tested, including combinations of the different technology uptake scenarios and key market input drivers.

For example, we have considered a scenario in which the Tiwai smelter closes from 2018. Our analysis indicates this would prompt additional closures of fossil-fuelled power stations, to establish a broad balance between power supply and demand. As a result, ongoing uptake of new technology would continue to impact mainly on investment in new wind and geothermal plant – and therefore have the types of emissions impacts described above.

The only scenarios where the ranking of emission impacts among new technologies differ markedly from Figure 40 are:

- If system conditions mean that no appreciable investment in new grid-connected generation is required for the next 15 years. This implies that older plant does not need to be replaced upon retirement, and that there is zero growth in power demand at the grid level. While we have assumed lower rates of growth than in the past (roughly 1% prior to any impact of PV), it appears very unlikely that zero growth would prevail on a long term basis, given the rising

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[35] The ability of the existing hydro fleet to alter its pattern of generation to meet changes in demand also provides some benefit in New Zealand which isn't available in other countries. However, there are limitations to the extent to which New Zealand's hydro generation can react in this way.

population and per capita income growth that are predicted by most forecasters. A flat demand outlook appears especially unlikely if EV uptake occurs.

- If the cost of power from new gas and coal-fired power stations is materially below that of wind and geothermal on a sustained basis. This seems improbable given the historic and current competitive position of wind and geothermal. Nor are there factors on the horizon to suggest this will change. Indeed, the more likely outcome is that low emission options will become more competitive as carbon prices rise over time, and wind generation costs continue to fall at a faster rate than other more mature technologies.

Accordingly, we consider that the results in Figure 40 provide a robust picture of the likely relative impacts of new technologies on emissions in New Zealand.

Appendix A. Embodied and direct emissions

This appendix looks at:

- 'Embodied' greenhouse gas emissions – i.e. greenhouse gases emitted during the *manufacture* of technologies such as solar PV panels or EVs
- Direct emissions – i.e. CO_2 (or other greenhouse gases) directly emitted by a technology as part of its operation. This only applies to fossil power stations and geothermal plant.

Net effect on embodied emissions

The uptake of EVs, solar panels and batteries will result in the release of some emissions when they are manufactured. We also recognise that these new technologies will displace conventional alternatives in many cases (e.g. EVs displace *new* petrol powered cars).

We have taken this effect into account when calculating emission impacts where they are relevant. For example, the embodied emissions factor for an EV is based on the difference, relative to manufacturing a petrol-powered car.

Sources of information

To compile emissions estimates, we have drawn on New Zealand and international sources. These sources largely report contemporary emission factors based on prevailing technologies and energy sources.

Over time, embodied emission factors are likely to decline, as regions with strong manufacturing bases (such as China, Europe and the United States) derive an increasingly high proportion of their electricity from non-carbon emitting sources.

We have not sought to account for this effect in our analysis because there is insufficient information to make reliable predictions. Furthermore, the declining trend is likely to affect embodied emissions for all technology types.

Electricity generation technologies

Solar photovoltaics

The manufacture of monocrystalline and polycrystalline solar PV panels is a relatively energy intensive process.

There can be significant variation in the embodied emissions depending on the nature and location of manufacturing. The main (but not only) parameters that affect the variability of the lifecycle emission factor are:

- Emission intensity of energy sources used in manufacture (i.e. plant efficiency and fuel used)
- Efficiency of the process to produce silicon wafers (this affects the energy required to produce panels)
- The location where the panels are installed (this affects kWh energy production and is necessary to consider given that embodied emissions are typically expressed in $kgCO_2$/MWh).

The results of various life cycle emission factor assessments for solar PV are shown in Table 2.

Table 2: Life cycle emission factors for solar PV panels

Source	Monocrystalline ($kgCO_2/MWh$)	Polycrystalline ($kgCO_2/MWh$)
EPE Centre[36]	80	50
IPCC[37]	73	55
Journal of Industrial Ecology[38]	40	45

These results are remarkably consistent given the level of variation within any one study. For example, life cycle emission factors over 200 $kgCO_2/MWh$ have been noted in specific instances for solar PV in some studies. For this study, we have adopted an emission factor of 50 $kgCO_2/MWh$ based on the average for polycrystalline panels.

Wind generation

The life cycle emission factors for wind energy in New Zealand are estimated at approximately 6.5 $kgCO_2/MWh$,[39] an order of magnitude lower than for solar PV.

This is mainly due to the lower energy intensity of manufacturing wind turbines, and the much higher capacity factor of wind generation compared to solar PV. In New Zealand's case, the emission factor is even lower because of our very good wind resource, compared to the rest of the world.

Geothermal generation

Embodied emissions associated with the *manufacture* of new geothermal plant are estimated at around 5 $kgCO_2/MWh$ on average.[40],[41] This emissions factor is relatively low due to the high capacity factor of geothermal generation, and comparatively long asset lifetimes in New Zealand.

Geothermal stations also directly emit CO_2 from their operation (releasing CO_2 in the geothermal fluid which is extracted from under the ground). These direct emissions vary considerably by plant. For example, Wairakei is about 30 $kgCO_2/MWh$. At the higher end of the range, the Ngawha plant has an emission factor of 600 $kgCO_2/MWh$ – almost double that of a CCGT.[42] Operational emissions are estimated to be of the order of 124 $kgCO_2/MWh$ on average for existing plants. This is similar to the level for proposed new geothermal stations, such as Tauhara which has an estimated operational emission factor of 100 $kgCO_2/MWh$.[43i]

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[36] 'Environmental Aspects of Photovoltaic Solar Power' 2015.

[37] 'Special Report on Renewable Energy Sources and Climate Change Mitigation' 2011 http://srren.ipcc-wg3.de/

[38] 'Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation'

[39] Journal of Industrial Ecology 'A Simplified Life Cycle Approach for Assessing Greenhouse Gas Emissions of Wind Electricity' 2012, and 'Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power' 2012.

[40] This figure may be conservative. For example embodied emissions for construction (and later decommissioning) of the proposed Tauhara plant are estimated at around 2 $kgCO_2/MWh$ by Scion (Drysdale).

[41] International comparisons for geothermal life cycle emissions can be seen at Argonne National Laboratory, 'Life-Cycle Analysis Results for Geothermal Systems in Comparison to Other Power Systems Part II', 2011.

[42] This field-specific data is from the NZ Geothermal Association (http://www.nzgeothermal.org.nz/).

[43] Drysdale, D, 'Carbon footprint for the Tauhara Stage II Geothermal Development Project', Scion, Wellington

Gas-fired and coal-fired generation

Direct emissions from a combined-cycle gas-fired turbine (CCGT) are approximately 380 $kgCO_2/MWh$, and those of a Huntly Rankine unit operating on coal are approximately 990 $kgCO_2/MWh$. These numbers are primarily dependant on the assumed plant efficiency, but also the specific fuel properties in the case of coal.

In addition, embodied emissions for these plant types are estimated at approximately 62 $kgCO_2/MWh$ and 52 $kgCO_2/MWh$ respectively[44]. However, given that these plant are existing and the electricity market modelling doesn't project the building of new CCGTs or coal-fired Rankine plant, such embodied emissions are not considered in the analysis of the impact of new technologies.

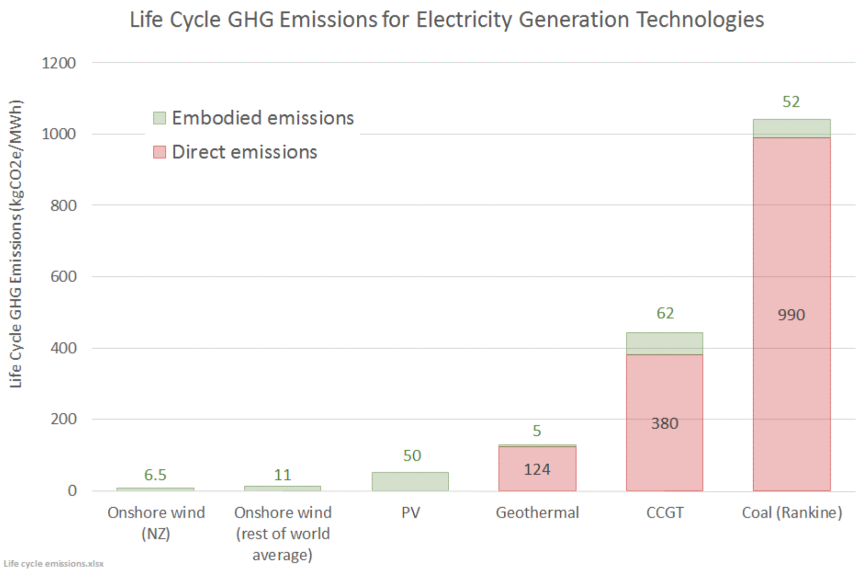
Generation type – embodied emissions

Figure 44 shows a comparison of embodied emissions for different generation types.

Solar PV systems fall between geothermal energy and wind generation in the hierarchy of life cycle emissions. They also have significantly lower emissions than gas- or coal-fired generation plants.

Note that this figure does not include potential indirect electricity sector emissions effects discussed elsewhere in this report.

Figure 44: Comparison of embodied and direct emissions



Electric vehicles

Electric and internal combustion engine (ICE) vehicles vary across a range of different components. For example, emissions associated with the manufacturing of the EV's drive trains may be materially different to those for conventional ICE vehicle drive trains.

There are a variety of studies in this area, but few are specific to New Zealand. Three relevant papers of interest are the following studies:

- ARUP report 'Life Cycle Assessment of EVs' 2015 (for EECA)

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[44] Ibid. Note that these embodied emissions are somewhat higher than for geothermal due to additional fuel production and transport, and fugitive emissions.

- Journal of Industrial Ecology[45] 2013
- Argonne National Laboratory 'Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid EVs' 2009

These studies are in general agreement, and indicate that all-electric battery EVs (BEVs) and plug-in hybrid EVs (PHEVs) do have materially lower emissions than ICE vehicles over the vehicle life. The operating phase is the main source of emissions for ICEs with between 80% and 85% of emissions arising from direct (i.e. 'tailpipe') emissions from operation, and approximately 15%-20% arising from embodied emissions associated with manufacture.

The first two studies listed also largely agree that the manufacturing component of embodied emissions for EVs are about twice that of ICEs (this issue is not covered in the Argonne study).

The ARUP study suggests that a BEV will have approximately 45% of the ICE lifetime emissions, and a PHEV approximately 55% of the ICE lifetime emissions. While these are material emission reductions, they are potentially significantly understating the relative emissions benefit from EVs in New Zealand.

The underestimation of the emission reductions[46] is mainly due to the way EV charging emissions are estimated in the ARUP report. The ARUP study uses the average emissions from the electricity sector in the 2013 year (and thereafter assumes them to be constant) rather than assessing the marginal emission impact of EVs (i.e. what change in emissions arises from adding EVs to New Zealand's electricity system).

As set out in section 3 and 2, this aspect of the impact of EVs has been modelled directly for this report, and established that in the long-term EV demand is likely to be met by predominantly low emission generation. [47]

A secondary issue is that the ICE counterfactual used in the ARUP study is a relatively efficient Euro 5 compliant vehicle with a manufacturer's stated efficiency of about 6.6L/100km (or 'real world'[48] efficiency of about 8.4L/100km). However, vehicles entering the New Zealand light passenger fleet have an average fuel consumption higher than this (of the order of 7.7L/100km manufacturer's efficiency as noted in the ARUP report).

Using the following reported factors from the above studies, a value of the embodied emissions from manufacture of ICE and EV vehicles has been estimated:

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[45] Journal of Industrial Ecology 'Comparative Environmental Life Cycle Assessment of Conventional and EVEVs' 2013.

[46] Note that this is not a criticism of the ARUP study, but simply noting that the study is conservative due to assumptions in the analysis.

[47] The modelling highlights that EV demand will be predominantly from wind and geothermal sources if a 'smart' charging regime is followed – i.e. charging the battery at times of lowest system demand (e.g. overnight). If a 'simple' charging regime is followed whereby charging is undertaken as soon as the journey is finished (e.g. immediately after returning home in the evening), the modelling indicates that a significant proportion of this demand will be met by fossil stations.

[48] It is now accepted that vehicle manufacturers stated fuel efficiency numbers are not reflective of real world driving conditions. Hence an adjustment factor (of about 20%-30%) is used to inflate the manufacturer's efficiency number if real-world fuel consumption is required. More information can be seen on page 50 of MOT's Annual Fleet Statistics: http://www.transport.govt.nz/assets/Uploads/Research/Documents/NZ-Vehicle-Fleet-2014-final.pdf .

- Proportion of lifetime ICE emissions from ‘tailpipe’ emissions reported for the studies = 82.5%
- Assumed ICE efficiency for the studies = 6.6 l/100km
- Emissions intensity of petrol = 2.365 kgCO_2/l
- Back-calculated implied ICE embodied emissions from manufacture using the above factors = 3.3 kgCO_2/100km
- Reported EV/ICE ratio of embodied emissions from manufacture = 2
- Estimated EV embodied emissions = 6.6 kgCO_2/100km

After accounting for all these issues, we estimate the operational emissions from EVs could be almost zero (see section 3 of this report), and the tailpipe emissions from operating an ICE could be about 15% higher than reported in these studies. This would result in about an 85% emission saving from a BEV compared to an ICE over the full life cycle.

Appendix B. Analysis of transport sector emissions

When considering the impact of EVs (EVs) it is necessary to consider their impact relative to the main alternative – i.e. internal combustion engine (ICE) vehicles.

This is expressed in terms of emissions increased / (avoided) per km of travel, and is comprised of three parts:

- Electricity sector emissions per km of travel
- Avoided ICE tailpipe emissions per km of travel
- Any difference in the embodied emissions from manufacture of EVs relative to ICEs – (expressed in emissions per expected km of travel over the life of the vehicle). This is detailed in section Appendix A, and is not described further in this section.

The electricity sector emissions per km of travel are estimated as:

> Emissions intensity of electricity used to charge EVs * Fuel efficiency of EV

Section 2 and Appendix B describe the detailed modelling undertaken by Concept to determine the likely emissions intensity for EV charging demand in New Zealand.

The assumed 'fuel efficiency' of EVs is 0.18 kWh/km – being that typical of an average 5 door hatchback or equivalent small to medium sized vehicle.[49]

The avoided tailpipe emissions are estimated as:

> Emissions intensity of petrol * ICE fuel efficiency

The emissions intensity of petrol is a standard figure, being 2.4 kgCO_2/litre.[50]

The fuel efficiency of ICEs exhibits considerable variation, ranging from inefficient 'gas guzzlers' to much more efficient models.

A value of 8.5 litres/100 km has been chosen as being representative of the real-world[51] fuel efficiency of the type of ICE that would be likely to be displaced by an EV (i.e. an average 5 door hatchback or equivalent small to medium sized vehicle).

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[49] This number is assumed to be broadly representative of the efficiency of both all-electric battery EVs (BEVs) and plug-in hybrid EVs (PHEVs). While there are clearly significant differences between these two types of EV, for the purposes of the analysis this is considered appropriate as the analysis considers the emissions intensity of travel when powered by the electric motor – noting that the vast majority of journeys made by light vehicles are well within the range of batteries for PHEVs.

[50] Diesel-fuelled vehicles are unlikely to be substituted by EVs, and have not been considered in this study.

[51] The test efficiency of such vehicles is approximately 6.5 litres/100 km, however, numerous analyses have demonstrated that the real-world efficiency of drivers undertaking the type of typical around-town driving is approximately 20-25% worse than the efficiency achieved under test conditions. See, for example, http://www.theicct.org/sites/default/files/publications/ICCT_LabToRoad_20130527.pdf

Appendix C. Electricity market model

This appendix provides information on the electricity sector modelling, for readers who want more detail than set out in section 2.

It first describes how electricity demand and generation interact generally, and how the model simulates such interaction to project the likely mix and operation of grid-scale generation going forward.

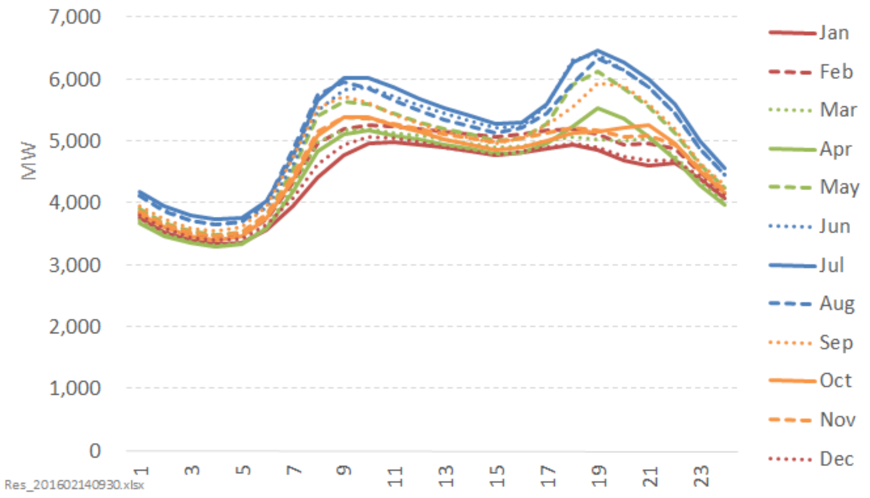
It then describes specifically how new technology uptake is modelled to determine how this is likely to affect the future mix and operation of grid-scale generation – and hence greenhouse gas emissions.

Demand varies throughout the day and year

As shown in Figure 45, demand varies on a within-day ('diurnal') and within-year ('seasonal') basis.[52]

On a within-day basis, demand is lowest at night and highest in mornings and evenings. On a within-year basis demand is higher in winter than in summer.

Figure 45: General patterns of demand/generation[53]



This varying profile of electricity demand affects generation requirements, because it is relatively difficult and expensive to store electricity with existing technologies. For example, based on Figure 45, the minimum level of demand is around 3,500MW. In principle this could be met by generation which runs continuously at full capacity.

At the other end of the spectrum, generation which is only required to satisfy the incremental demand associated with winter peaks will have much lower utilisation. Different types of plant are best suited

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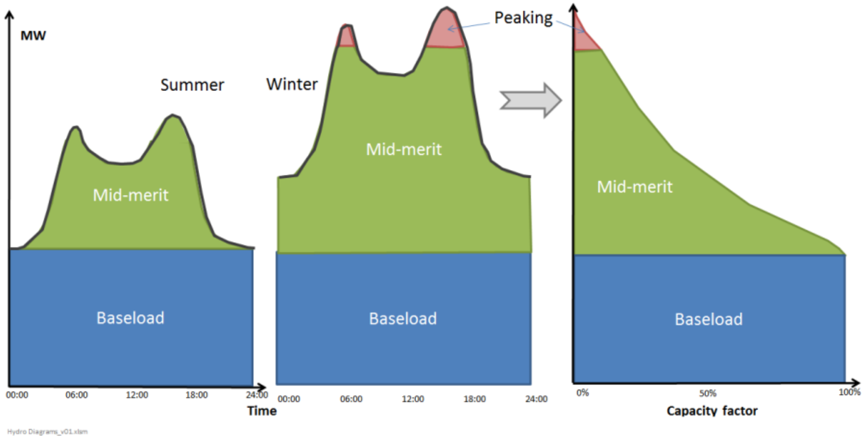
[52] Demand also varies between business days and non-business days, with demand in business days being higher than non-business days. While this phenomenon is captured within the model, it is not shown in the chronological graphs shown in this appendix for ease of viewing clarity.

[53] This chronological representation of demand represents the *average* within-day profile for each month. This average hides the fact that there can be material variation for a given time of day. For example, the lowest demand experienced could be significantly lower corresponding to a short period of unusual conditions (e.g. a combination of weather and public holiday), and likewise for the highest demand.

to meet these differing utilisation rates – or operate at differing ‘capacity factors’ to use industry terminology.

Figure 46 shows how the chronological representation of demand in Figure 45 can be re-ordered to form a so-called ‘duration curve’. This ranks each half hourly demand observation for the year from highest to lowest, with the percentage of time (or capacity factor) represented on the x-axis.

Figure 46: Illustration of different modes of generation operation



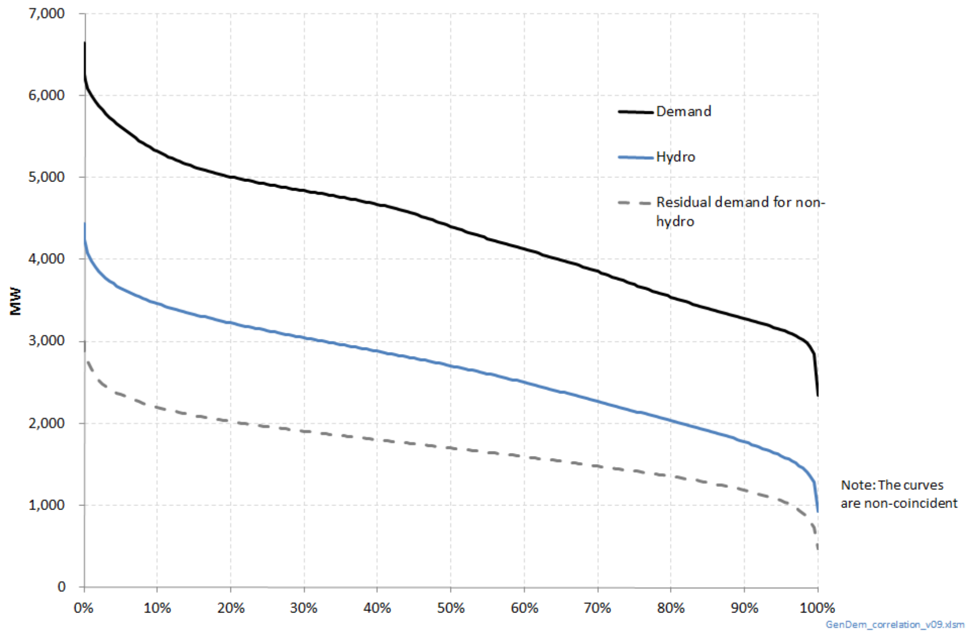
Plant which operates for the vast majority of the time is typically referred to as ‘baseload’, whereas plant which operates very infrequently is referred to as ‘peaking’ generation, and plant which operates for some of the time as ‘mid-merit’.

Hydro generation is very flexible – within limits

New Zealand is fortunate to have significant amounts of hydro generation capacity, much of which has water storage associated with it. This enables water to be stored at times of relative surplus (typically at times of low demand) to be released for generation at times of relative scarcity (often periods of higher demand). As can be seen in Figure 47 below, this has the effect of ‘flattening’ the residual requirement for non-hydro generation.

This is significant because ‘time-shifting’ water from periods of low to high demand reduces the extent to which non-hydro plant is required to operate in lower capacity-factor modes of operation. In other words, a greater proportion of non-hydro plant can operate in baseload mode than would otherwise be the case.

Figure 47: Hydro generation and non-hydro generation duration curves from 1-Jan-2001 to 30-Nov-15



While hydro storage allows water to be sculpted into peak demand periods, there are limitations to this ability due to physical and other constraints. Accordingly, there is still a requirement for some non-hydro generation to operate at lower capacity factors.

Thus, with reference to Figure 47, if hydro was perfectly able to sculpt water into periods of greatest demand, the residual demand for non-hydro would be completely flat at approximately 1,800 MW, and could be met entirely by baseload generation.

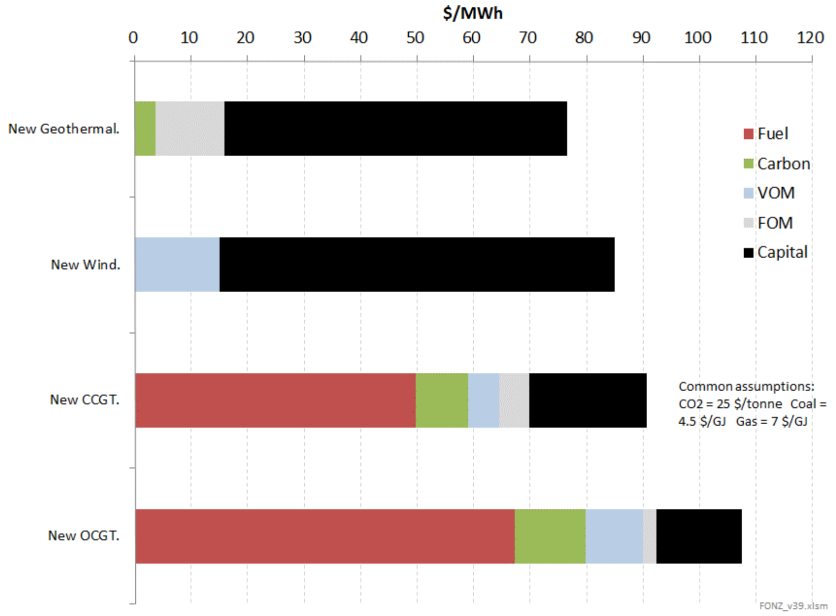
However, because hydro isn't able to perfectly sculpt water, only around 1,000 MW of non-hydro plant can operate in baseload mode, with an additional 2,000 MW of plant being required to operate at lower capacity factors.

Different plant best-suited for differing roles

From a cost perspective, different types of generator are best suited to differing roles. Some plants have relatively low costs to build (i.e. capital costs) but are expensive to operate. These are better suited to meeting peak or low capacity factor requirements. In contrast, plant that is cheaper to operate but more expensive to build may be best suited for baseload operation.

This is illustrated in Figure 48 which shows the components of total cost (also called long-run marginal cost or LRMC) for different types of generator.

Figure 48: Illustrative LRMC for generation types for baseload operation[54]



The LRMC of new low emissions generation, such as wind or geothermal, is dominated by capital costs. Once one of these generators is built, it has relatively low operating costs. This

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[54] There can be significant project-level variation within the geothermal and wind categories based on the specifics of each project – e.g. how windy a site is, the extent of drilling needed for geothermal steam. Nonetheless, the chart gives a reasonable indication of the typical breakdown of cost-structure between different generation types.
VOM = Variable Operating & Maintenance costs – i.e. those non-fuel operating costs which vary with each kWh generated.
FOM = Fixed Operating & Maintenance costs – i.e. non-fuel operating costs which are incurred each year irrespective of generation output (e.g. local body rates)

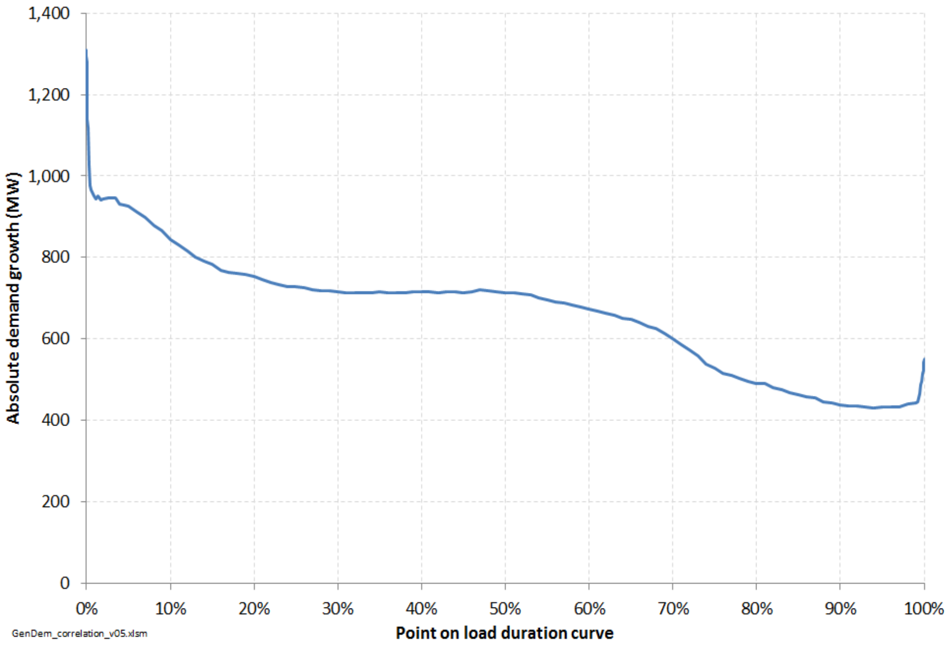
contrasts with gas-fired plants, which are less expensive to build, but have relatively higher operating expenses due to fuel and CO_2 costs.

The information in Figure 48 indicates that new low emission generation has lower cost than new gas-fired plant for baseload operation. This implies that growth in demand should be met by building new low emission plants. And indeed that is what has been happening in New Zealand – *but only for meeting growth in baseload demand*.

Demand growth is not uniform across all hours in the year, but has significant shape to it. This is evident in Figure 49 which shows demand growth in MW between 1998 and 2011 for different points on the duration curve. While the average growth has been around 600MW, during peak demand hours, there has been around 1200MW of growth.

This means that over time, as well as there being an increase in the requirement for baseload generation, 'peaky' demand growth will also give rise to an increased requirement for lower capacity-factor generation.

Figure 49: Duration curve of demand growth from 1998 to 2011[55]



In theory, this growth in peaky demand could be met by increasing the 'sculpting' of existing hydro generation away from periods of low demand to periods of high demand. If practical, this would allow demand growth to be met entirely by new baseload renewables such as geothermal and wind. This is illustrated in the following schematic, with the new baseload low emissions plant represented by geothermal.

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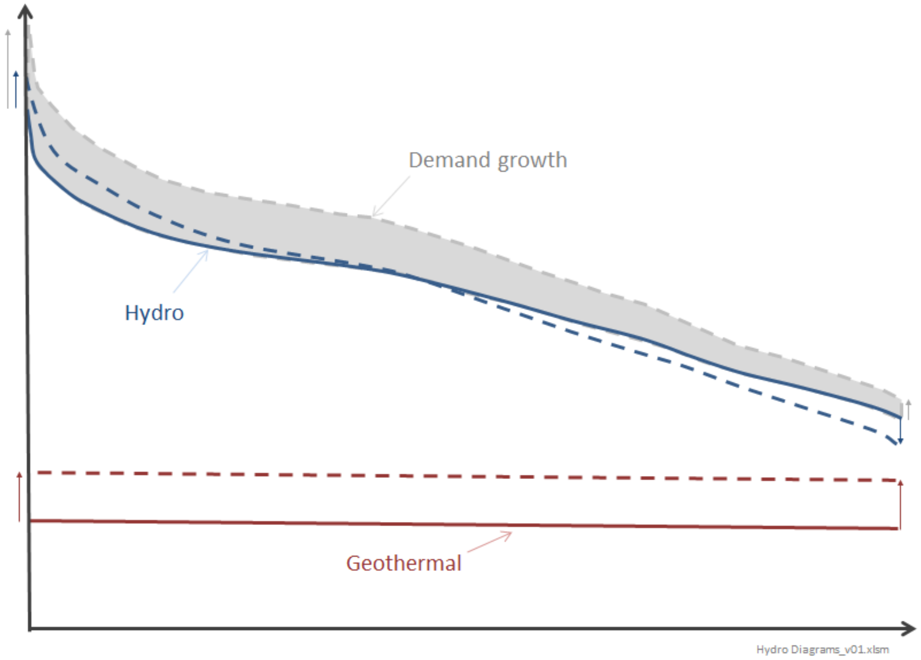
[55] The 'spike' at 100% appears to be due to a few periods of extreme low demand in 1998 that did not recur in 2011 – rather than any ongoing demand trend.

Figure 50: Illustrative example



However, the flexibility from existing hydro generation is already being heavily utilised, with the ability to deliver more flexibility being constrained over a number of time dimensions.

Generally the time-dimension where there still is significant flexibility is on a within-month basis where hydro can shift its generation to meet a changing within-day demand shape and/or balance the day-to-day variability caused by renewables such as wind or solar PV – i.e. increasing generation on cloudy / calm days, and decreasing generation on sunny / windy days.

However, hydro has some limitations on within-month flexibility. In particular:

- There is limited additional scope to generate more at times of peak demand because it already operates at, or close to, full capacity at those times
- Minimum river-flow constraints limit the ability to sculpt more water away from low demand periods.

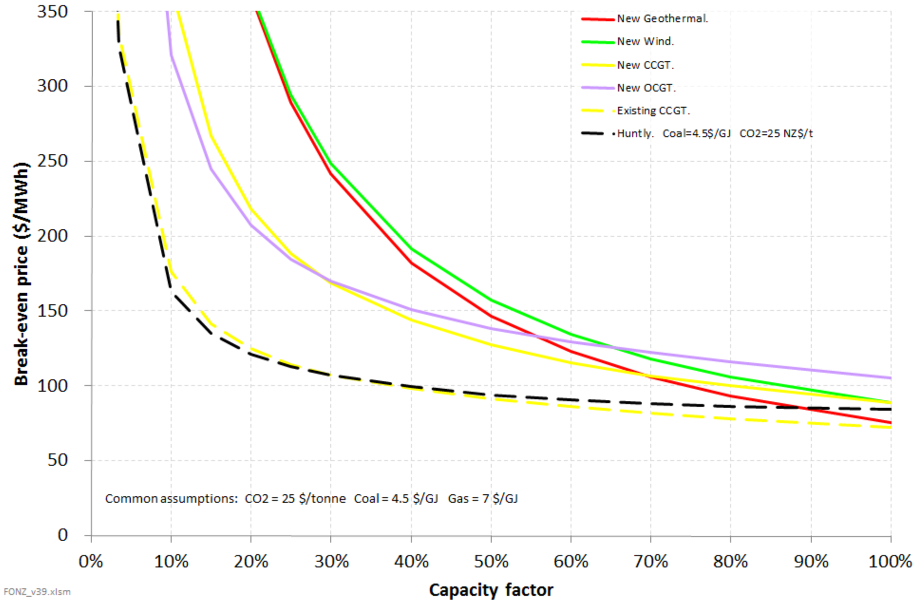
Further, New Zealand's hydro plant are constrained in their ability to store more water in summer to release in winter – at least not without resulting in considerable additional spill.

Due to these constraints, if demand growth is peaky on a seasonal basis, or significantly increases the ratio between day / night demand, it is likely that a significant proportion of this growth will need to be met by non-hydro generation operating at lower capacity factors (absent the use of storage technologies such as batteries).

This is significant, because it means that new low emission generation is not necessarily the lowest cost option to meet 'peaky' demand growth, even though it is the cheapest form of baseload generation. Rather, the mix of low emission and fossil-fuelled plant that is best suited will depend on the 'shape' of electricity demand.

Figure 51 shows how the breakeven electricity price for different generation options is affected by capacity factor of operation. New low emission plants, which are cheapest for high capacity factor operation, rapidly increase in cost if required to operate below full capacity. Conversely, for low capacity factor operation, an open-cycle gas turbine will have a lower breakeven price than low emission plants.

Figure 51: Impact of capacity factor on breakeven price



Electricity model accounts for demand shape and capacity factor effects

The electricity sector model used for this report takes account of all of these effects. For a given year it:

- Projects the level and shape of demand on both a within-month chronological basis, and a monthly duration curve basis. This projection is based on the underlying scenario of demand growth drivers in the absence of technology uptake (i.e. the basecase).
- Adds / subtracts the impact of new technologies such as solar PV, EVs and batteries to these basecase demand projections, on both a chronological and duration curve[56] basis. These demand changes are based on the underlying technology uptake scenario (discussed in section 2), taking account of the shape of such demand (as described from page 48). These provide the residual grid demand functions for each technology uptake scenario.
- Schedules the dispatch of must-run non-hydro grid-scale generation, being geothermal, cogen and wind. The amount of such generation will be based on the starting levels plus, for future years, any new build generation the model determines as being required to meet demand growth. Such dispatch is subtracted from demand to give a revised residual demand – taking account of the variability of wind for the duration curve representations.
- Simulates the storage and release decisions of the hydro fleet across five different representative inflow years – ranging from a ‘very dry’ year to a ‘very wet’ year. This simulated hydro generation is further subtracted from the residual demand curve. On a seasonal basis, there are considerable constraints on the ability to store more water during the summer for release in the winter. However, on a within-month basis it is assumed that there is considerable flexibility for the hydro schemes to alter their diurnal pattern of generation to meet a changing demand shape subject to two key constraints:

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[56] The duration curve representation is necessary to capture the variability of solar PV – i.e. between cloudy and sunny periods.

  - No ability to generate more than the combined physical generation capacity of the schemes. This is a material limitation at times of peak demand.
  - No ability to generate less than a minimum level necessary to meet minimum flow constraints. This is very scheme specific, so a simple approach has been taken where the observed historical coincident minimum generation from hydro schemes has been assumed to be broadly representative of this minimum generation constraint across schemes in general. This is a material limitation on the hydro schemes' ability to meet demand growing day / night differential in demand.
- Simulates the dispatch of the different thermal generators (CCGT, Rankine and Peakers) to meet the residual demand curves across the different months for the different inflow years.
  - The merit order of the options is determined by fuel and CO_2 prices (taking into account must-take fuel contracts, and the flexibility premium associated with delivering fuel to meet low capacity factor operations), plant efficiencies, and O&M costs. This determines the least-cost combination of duties for these different types of plant. (e.g. whether running coal-fired plant harder than gas-fired plant would be lower cost or not.)
  - It also compares whether it would be cost-effective to build a new baseload generator (typically a geothermal or wind plant) rather than running the existing thermals harder. New-build is also driven by the need to have sufficient capacity on the system.
  - If it would be cheaper to build a new OCGT peaker rather than operate an existing CCGT or Rankine unit, it simulates that CCGT or Rankine being retired. This evaluation takes account of the fixed operating & maintenance costs of both the existing and new plant, but only considers the capital costs of the new OCGT as the capital costs of the existing plant are sunk.

The model progressively runs each year, recording which plants are built and retired, and recording the amount of operation from each type of generation for each year.[57]

The model is designed to allow key factors to be varied on a scenario basis – e.g. fuel prices, CO_2 prices, technology uptake, demand growth etc. – thereby allowing examination of the impact of these different sector drivers (individually or in combination) on sector outcomes.

How might new technologies impact on emissions?

As discussed in section 2.7, whereas the investment, retirement and operation of all other generation types are determined explicitly by the model, the new technology uptake scenarios are specified *outside* the model.

In other words, a level of uptake of EVs, solar PV, or batteries (or combination thereof) is externally specified, and the model then simulates how the future investment, retirement, and operation of

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[57] Each year is run for the different hydro inflow states (i.e. wet to dry) in order to determine an average amount of generation from each plant.

grid-scale generation is affected by such uptake – and hence the impact on greenhouse emissions.

The model examines both the effect on *average* annual residual grid demand, and the change to the *shape* of such residual demand.

Impact of EV uptake

The principal impact of EVs is to increase demand while their batteries are being re-charged. There is assumed to be no within-year variation in how much EVs are charged (i.e. it is assumed people drive as much in the summer as in the winter), but there is assumed to be considerable within-day variation in terms of when EVs are charged. In this respect, two re-charging regimes were explored:

1) 'Smart': EVs are predominantly charged at times of the day when grid demand is lowest.
2) 'Simple': EVs are predominantly charged based on the time when people tend to finish their journeys.

In a smart EV charging scenario, EV batteries will tend to be re-charged overnight, and with some limited charging during the middle of the day – basically the inverse shape of grid demand. This is illustrated in the following figures.

Figure 52: Projected 2036 grid demand without EV charging

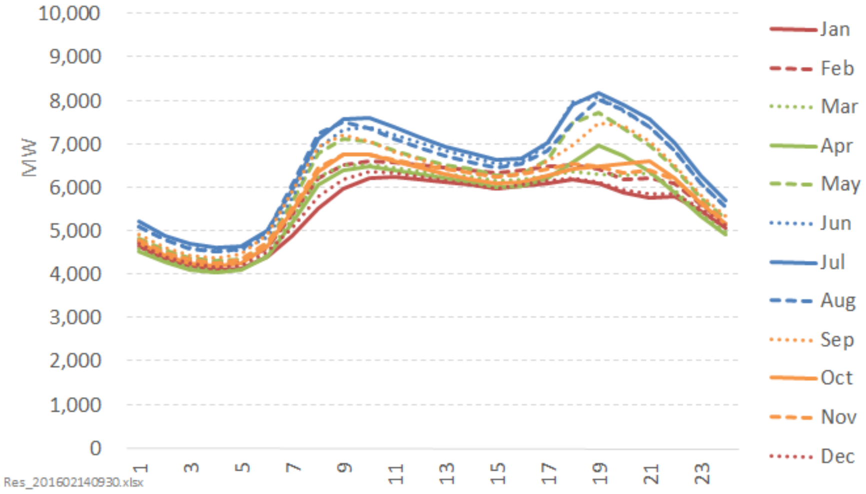
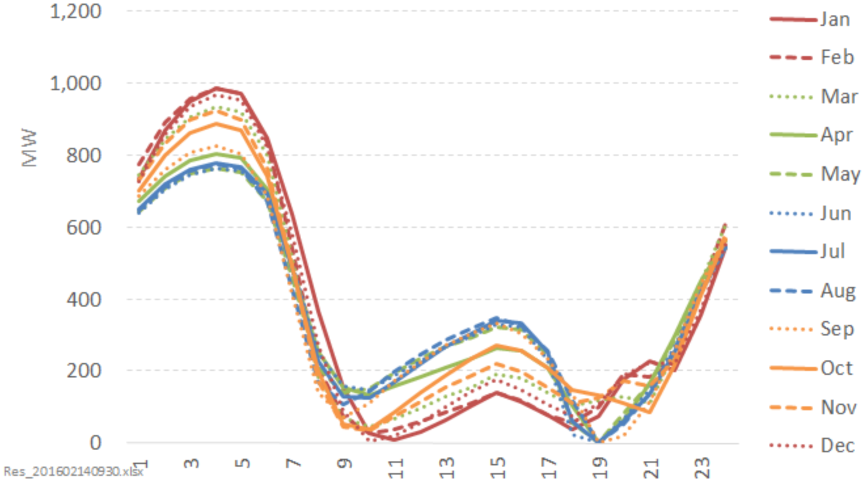


Figure 53: Projected 2036 EV smart charging profile



The smart charging profile would result in a flattening of overall residual grid demand, as illustrated by comparing the post-EV demand shown in Figure 54 below with the pre-EV demand shown in Figure 52 previously.

Figure 54: Projected 2036 residual grid demand after smart EV charging and high EV uptake

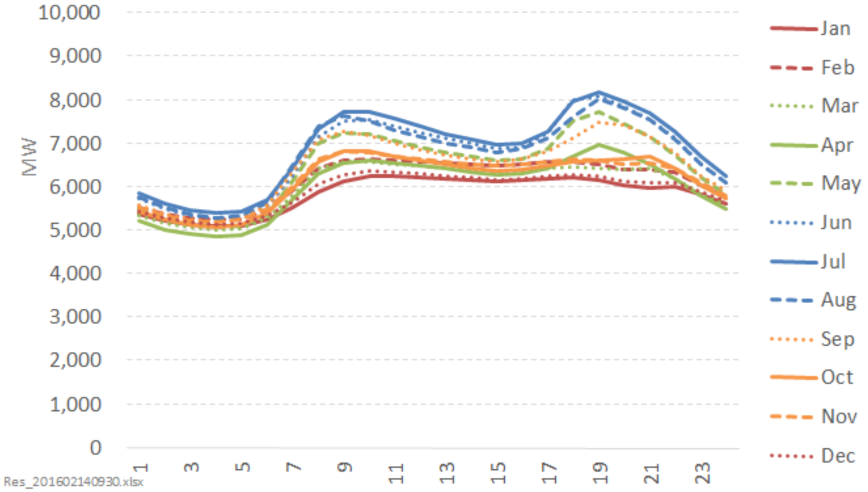
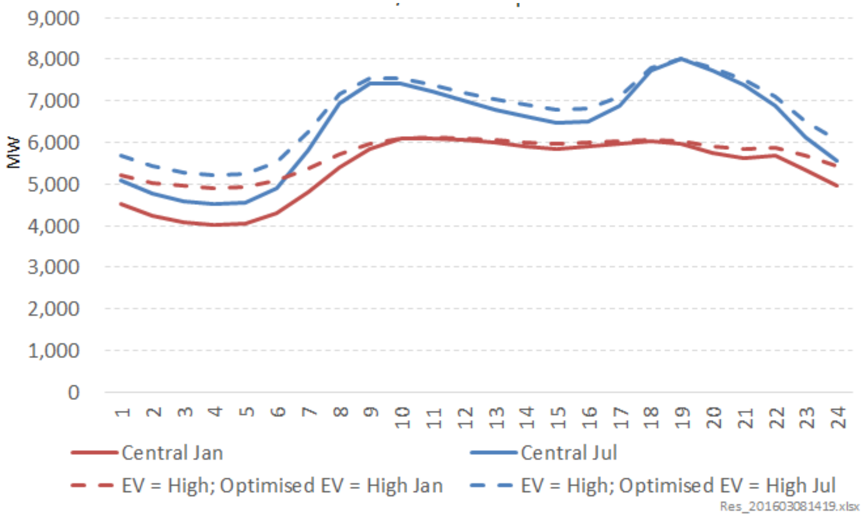


Figure 55 combines the information from the above figures for only a summer (January) and winter (July) month to illustrate the impact of EV uptake.

Figure 55: Comparison between with and without EV demand for 2036 for Summer (Jan) & Winter (Jul)



On a duration curve basis, the following figures illustrate how the 20-year growth in demand is affected by significant amounts of EV uptake – with smart charging.

Figure 56: Projected 2036 demand duration curves (DCs) <u>without</u> EVs: A) Overall DC, and B) Change in DC over 20-year period

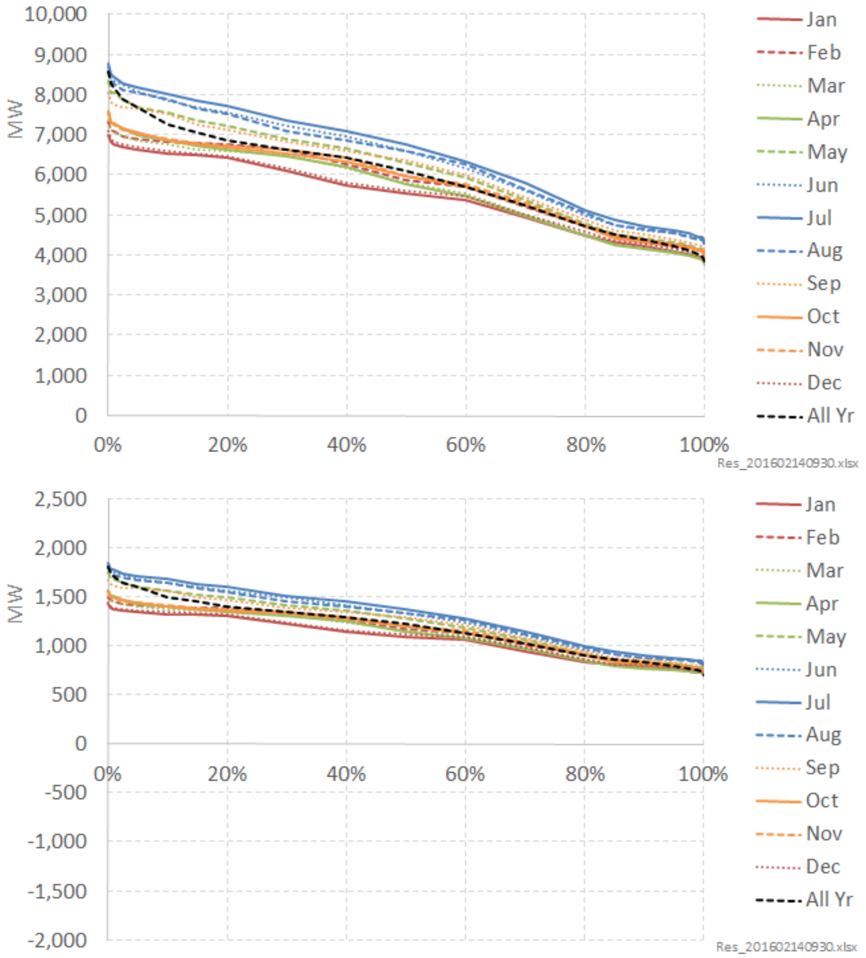
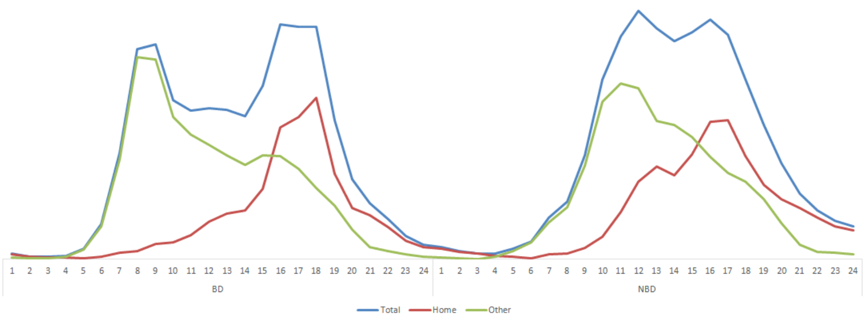


Figure 57: Projected 2036 demand duration curves (DCs) <u>with</u> high uptake of smart-charged EVs. A) Overall DC, and B) Change in DC over 20-year period

Turning to the alternative, 'simple', EV charging regime, this assumes that EVs are re-charged based on when they finish their journey. The following figure illustrates the number of light vehicles on the road at different times of the day, differentiating between whether the destination is the vehicle owner's home, or another destination (e.g. work). This shows that there are clear morning and evening peaks to travel times, with the evening peak dominated by journeys home.

Figure 58: Light passenger vehicles on the road at different times of the day



Source: Concept analysis using MoT household travel survey data

A model was developed to translate this travel data into an estimation of the likely amount of EV demand if EVs were charged immediately after they finished their journey. In developing this model it was assumed that charging didn't occur for half of non-home journeys – and that this vehicle would instead be charged in the evening once the driver arrived home. An assumption was also made as to the amount of charging that would be required for different vehicles according to how far they had travelled that day.

The resulting pattern of EV demand is illustrated in Figure 59 below.

Figure 59: Simulated within-day EV charging profile from 'simple' charging

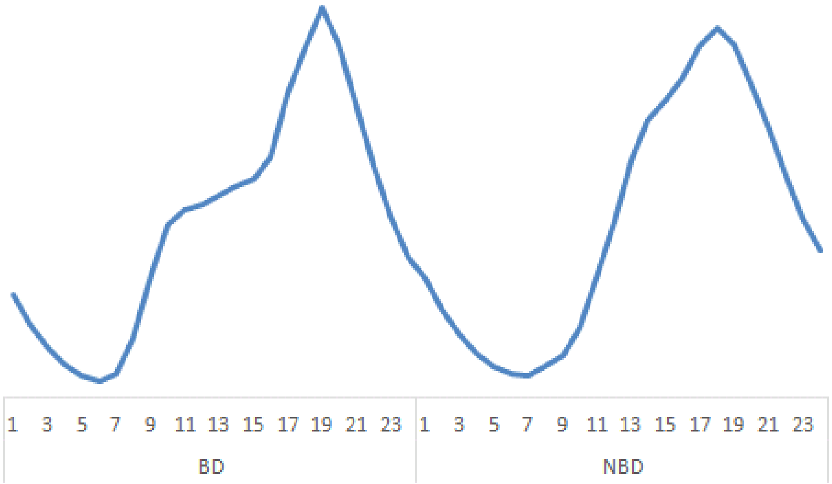


Figure 60 to Figure 62 below show the consequences of this EV demand charging profile on a chronological basis and duration curve basis.

Figure 60: Projected 2036 demand: A) Without EV charging, and B) with high uptake of simple EV charging

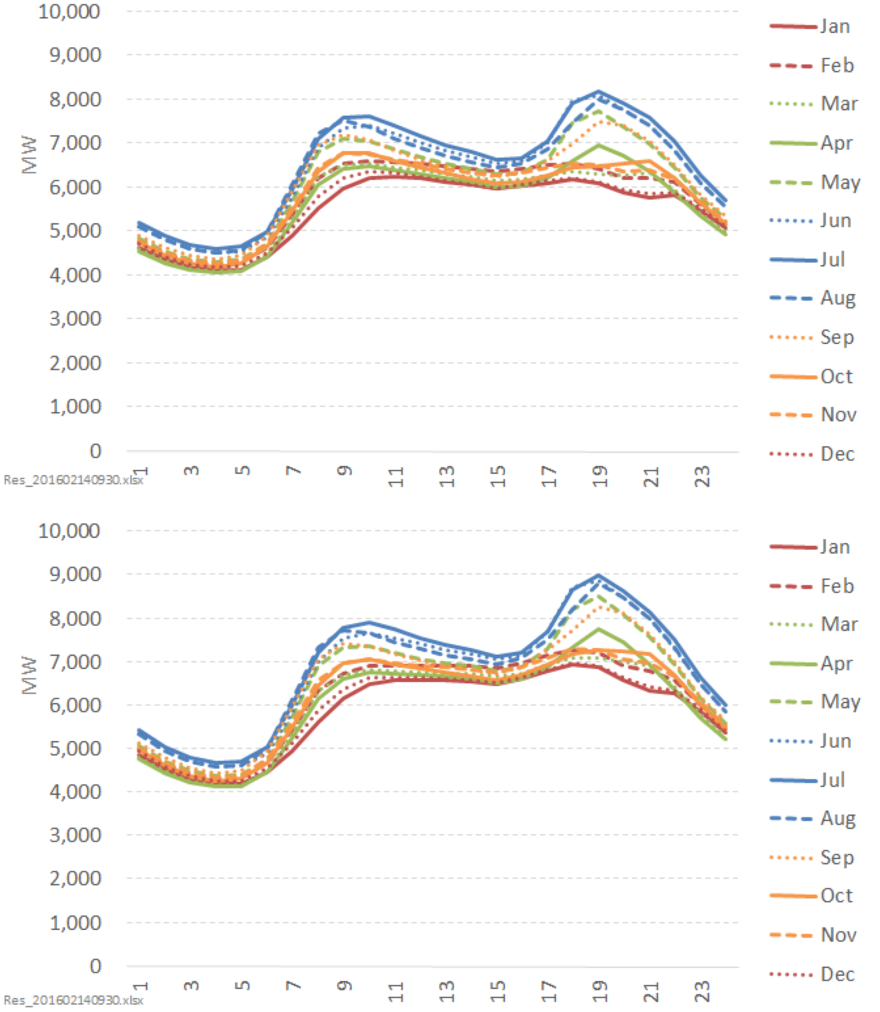


Figure 61: Projected 2036 demand duration curves (DCs) <u>without</u> EVs: A) Overall DC, and B) Change in DC over 20-year period

Figure 62: Projected 2036 demand duration curves (DCs) with high-levels of uptake of simple-charged EVs. A) Overall DC, and B) Change in DC over 20-year period

The above analysis shows that, whereas smart charging flattens the residual demand curve, simple charging increases the peakiness of the residual demand curve – particularly on a day/night basis. This increases the requirement for low capacity factor generation. Thus, by 2036 under the high EV uptake scenario with simple charging, the model is projecting a 20% increase in the demand for generation to operate at capacity factors of 80% or less.

Flexibility from hydro generation can counteract some of this. However peak capacity limitations, and limitations to go below minimum generation levels, constrain the ability of hydro plant to completely counter-balance this increased demand peakiness. As a consequence, the model projects a 14% increase in the demand for non-hydro generation to operate at capacity factors of 80% or less.

Impact of solar PV uptake

In the case of solar PV, as Figure 63 and Figure 64 show, there is a strong within-day shape to average output (nothing overnight, and peaking during the day), as well as a strong seasonal shape to production (lower during winter, and higher during summer).

Figure 63: Typical within-day profiles of solar PV output across the year

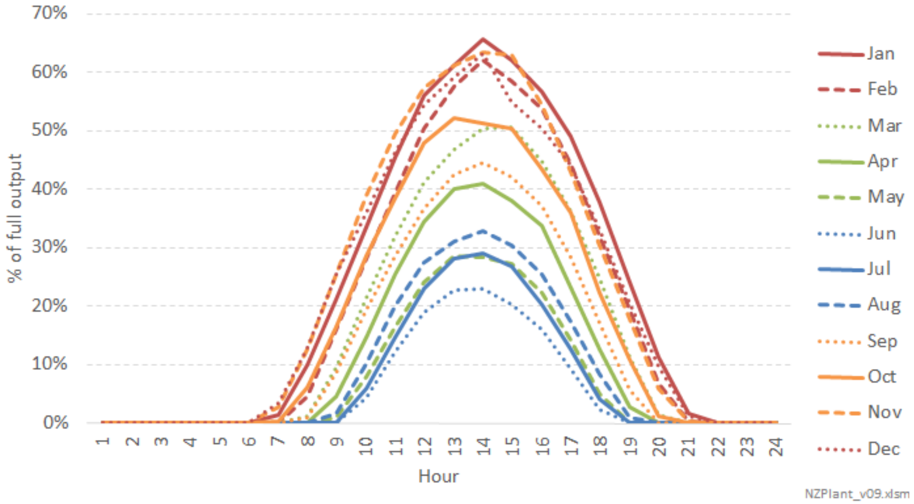
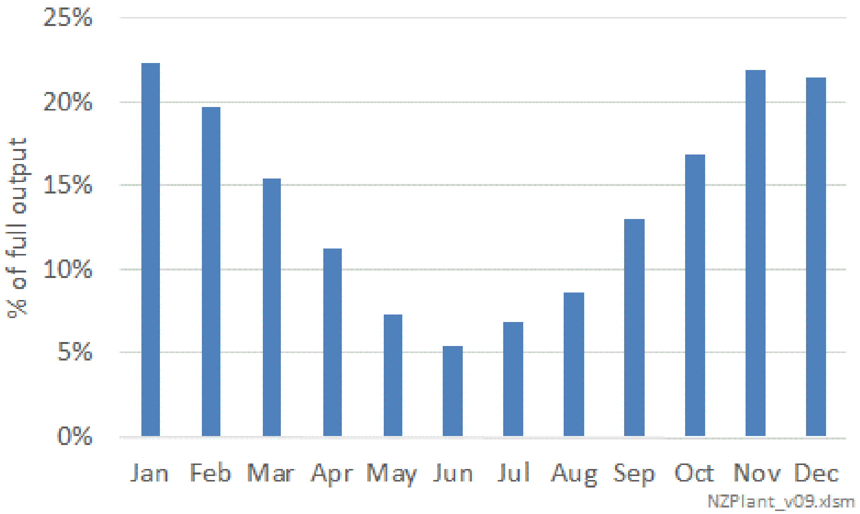
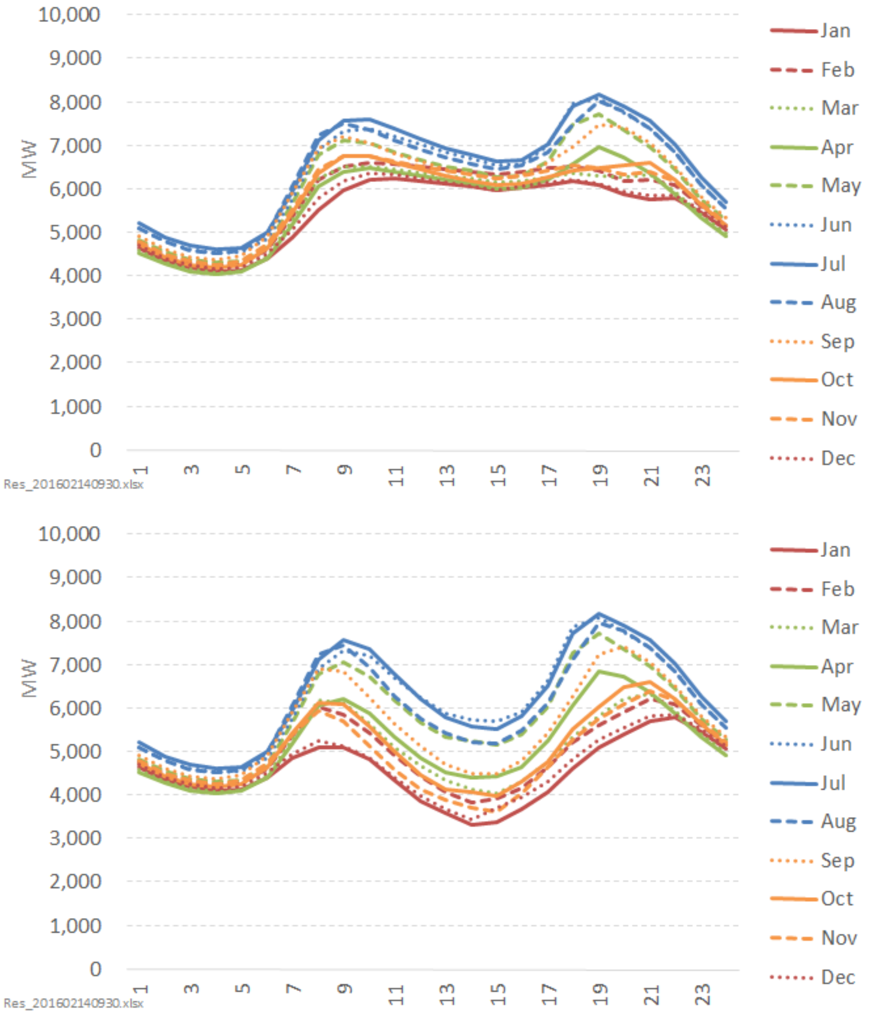


Figure 64: Typical within-year profiles of solar PV output



If there is widespread uptake of solar PV, this will affect the shape (as well as the level) of residual grid demand. As is illustrated in Figure 65, this change will alter the diurnal pattern of demand – significant reductions in the middle of the day, but no change overnight – and also change the seasonal pattern of demand: significantly amplifying the differential between winter and summer demand.

Figure 65: Modelled 2036 grid demand: A) without solar PV, B) with high levels of solar PV



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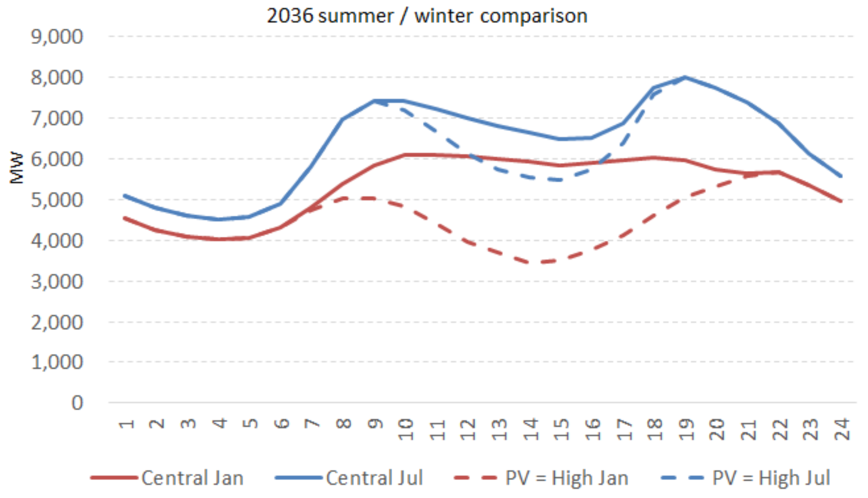
Res_201602140930.xlsx

Figure 66 combines the information from the two graphs in Figure 65 for only a summer (January) and winter (July) month to illustrate the impact of PV uptake.

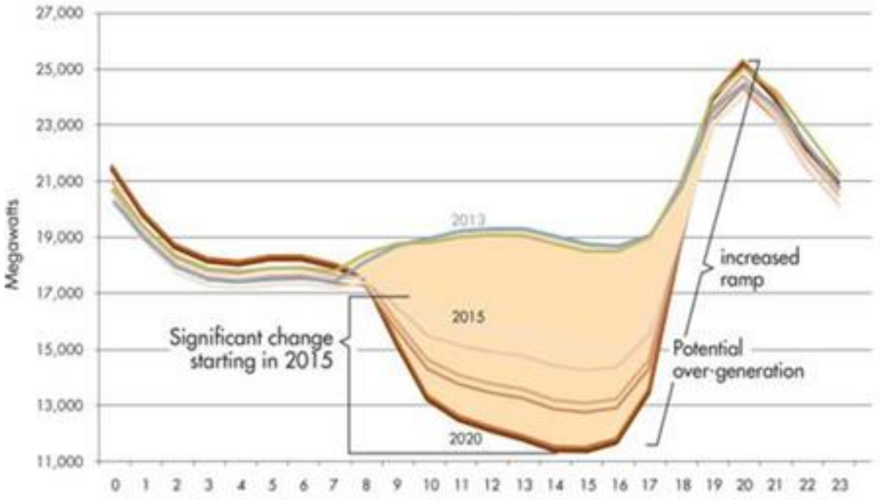
Figure 66: Comparison between with and without PV uptake for 2036 for Summer (Jan) & Winter (Jul)



Res_201603081419.xlsx

As can be seen in Figure 67, this type of change in the shape of residual demand is being experienced in countries with significant levels of solar PV uptake.

Figure 67: Impact of solar PV uptake on the within-day grid demand curve for California



Source: California ISO

Figure 68 shows how high levels of uptake of solar PV will affect the projected growth in demand over a 20 year period.

Figure 68: Projected 20 year growth / (reduction) in demand: A) Without solar PV, and B) With high levels of solar PV

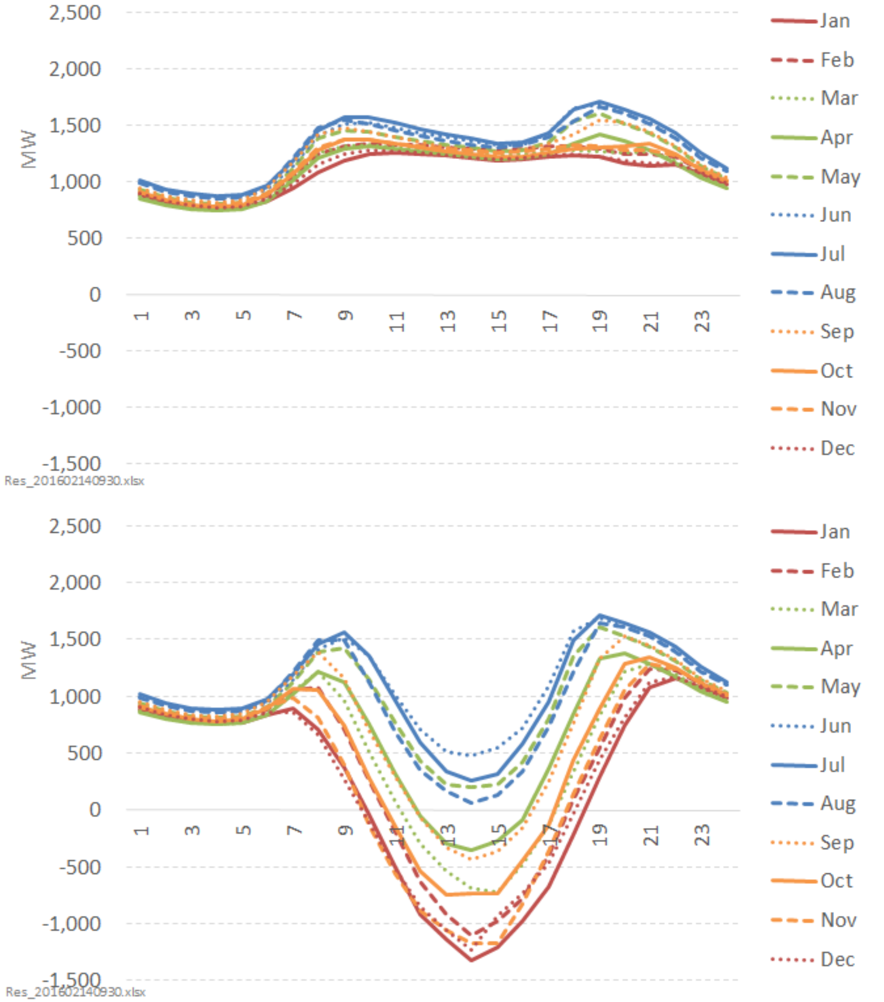
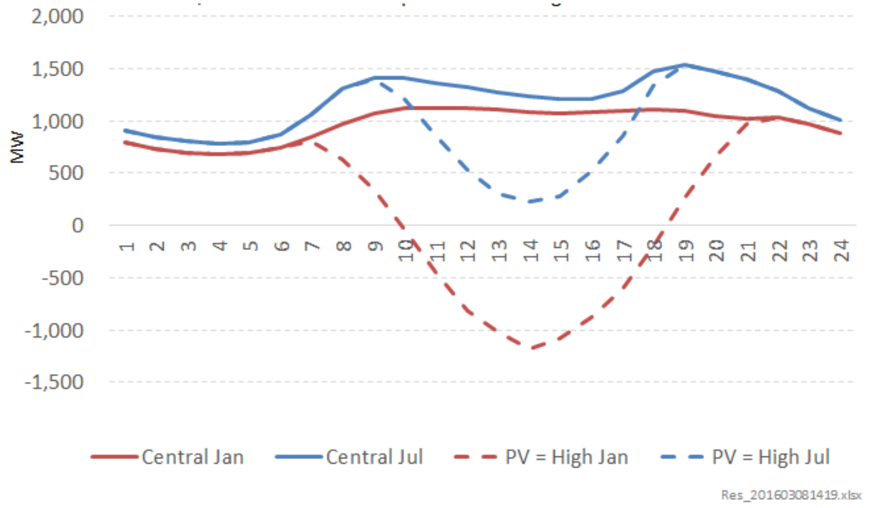


Figure 69 combines the information for the above two figures in Figure 68 for only a summer (January) and winter (July) month to illustrate the impact of EV uptake on demand growth.

Figure 69: Comparison of 20-year change in demand with and without PV uptake for Summer (Jan) & Winter (Jul)



Res_201603081419.xlsx

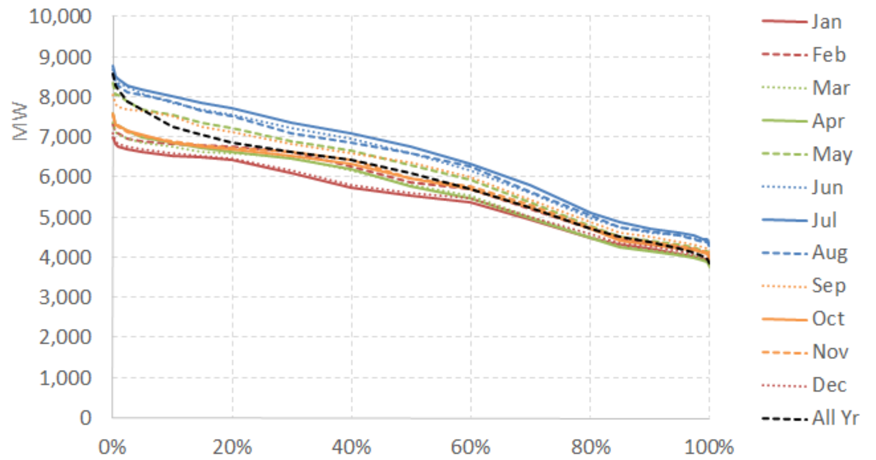
While underlying demand is projected to grow for all time periods over this 20 year period, high levels of solar PV uptake are expected to result in grid demand falling during daytime periods (particularly during summer), but be unchanged overnight.

These figures show the projected effect of solar PV uptake in terms of *average* impacts on grid demand for different times. While these average impacts are important, they do not capture the fact that solar can also exhibit significant hour-to-hour and day-to-day variability due to cloudy versus sunny periods.

The electricity model addresses this dynamic by converting each within-day chronological curve into a within-day duration curve. This allows the range of solar PV variability for each hour of the day to be accounted for in the model.[58]

The following charts illustrate the long-term impact of solar PV on residual grid demand, expressed in duration curve terms.

Figure 70: Projected 2036 demand duration curves (DCs) __without__ solar PV. A) Overall DC, and B) Change in DC over 20-year period



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[58] This duration curve calculation takes account of the fact that there can be significant geographic diversity benefits from having solar PV spread across New Zealand, e.g. if it is cloudy in Auckland, it may not be cloudy in Wellington.

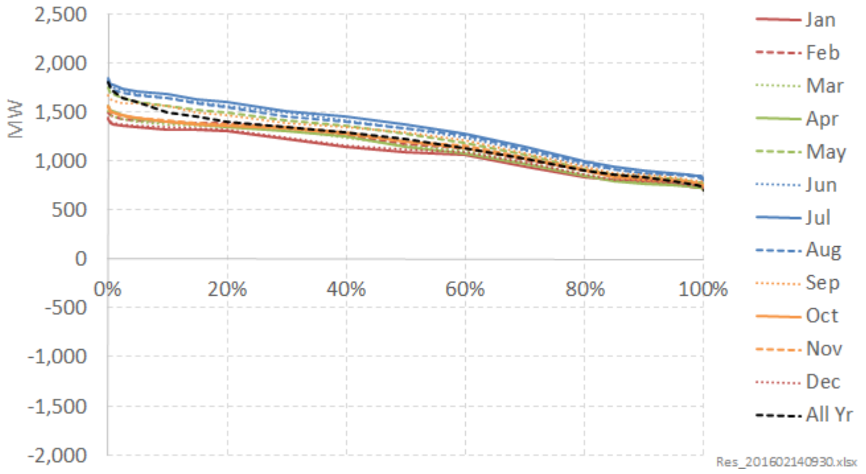

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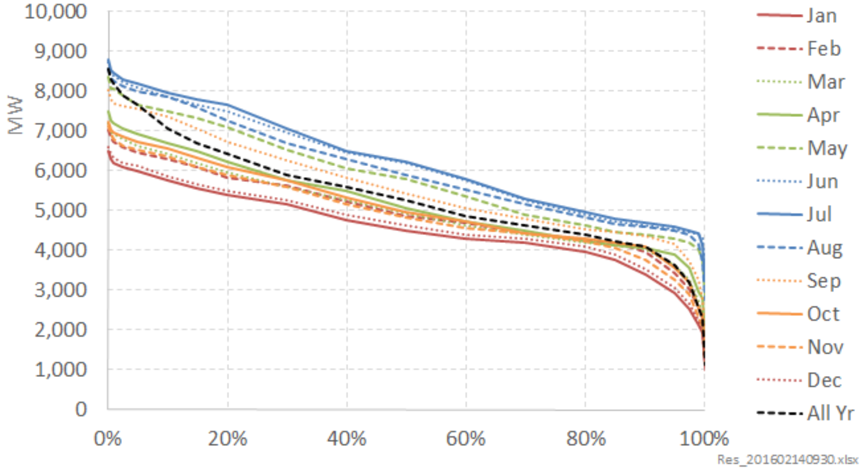
Figure 71: Projected 2036 demand duration curves (DCs) with high solar PV. A) Overall DC, and B) Change in DC over 20-year period



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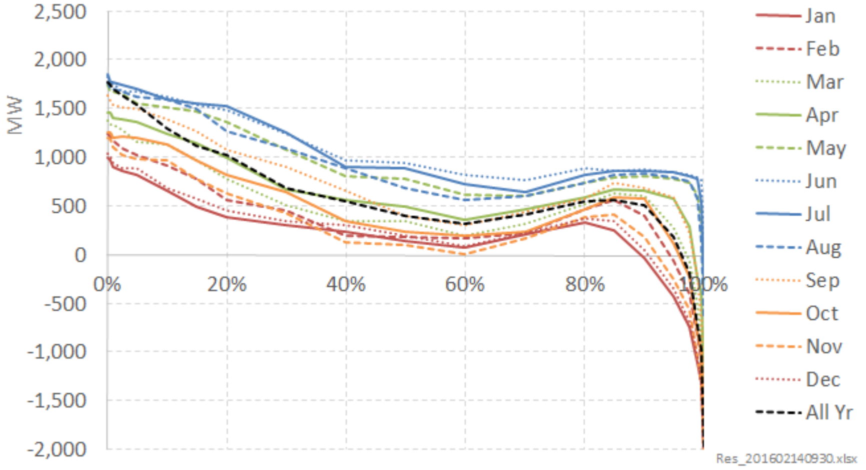

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Figure 71 B) illustrates that high solar PV uptake will reduce grid demand growth, with much less area under the duration curves than in Figure 70 B). This general decline in grid demand growth is not surprising, given that solar PV would be meeting a large proportion of electricity demand growth in this scenario.

The more surprising feature is that the growth in peak residual grid demand is the same in the basecase and high solar PV uptake scenario. This means there would be no reduction in the total grid-scale capacity held on the system. However, there would be a change in the type of plant required at the grid level, with an increase in the requirement for lower capacity-factor generation.

Indeed, the above scenario results in a 30% increase in the requirement for plant to operate at capacity factors of 60% or less. This is particularly due to the widening of the seasonal differential between winter and summer demand, but is also due to an increased peakiness of the within-day curve.

New Zealand’s hydro plants have some flexibility to adjust for this altered grid demand shape. However, as is described on page 46 earlier, there are constraints on the ability of hydro plant to further alter their pattern of generation – particularly on a seasonal dimension.

As such, the modelling indicates that although hydro plant can address some of the increased peakiness associated with solar PV, some 80% of this increased requirement for lower capacity factor generation would need to be met from other sources. Given that fossil-fuelled generation is more economic for meeting such lower-capacity factor generation, in the long-term this means that significant uptake of PV can increase the requirement for fossil-fuelled generation than would otherwise be the case.[59]

Impact of battery uptake

The principal impact of stand-alone batteries (i.e. those not part of an EV) is to alter the pattern of grid demand – increasing demand when batteries are being charged-up, and decreasing demand when they are discharged again. There is a secondary impact in that there will be a small net increase in grid demand due to battery charging losses.

Batteries are assumed to charge and discharge once per day. Because of the significant costs involved, batteries are assumed to not provide seasonal demand shifting (i.e. charge up once in summer to release once in winter), or perform more than one cycle per day (e.g. charge overnight to release in the morning peak, then charge during midday to release in the evening peak).

The model looks at two potential modes of battery operation:

- Optimising the within-day charging and discharging to minimise the within-day peakiness of overall system demand[60]
- Operating the battery to flatten the within-day net demand profile of a consumer with solar PV.

The following figures first illustrate the impact of battery charging to minimise the peakiness of overall system demand. Figure 72 shows the projected profile of grid demand in the basecase without battery use.

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[59] It is possible that new sources of seasonal flexibility could emerge over time, such as energy stored as compressed air in disused gas wells, or conversion of surplus power to hydrogen for storage and use at a later time. However, technology has not advanced sufficiently for these options to be viable at present, and any option will need to have relatively low fixed costs to be cost-effective.

[60] Strictly speaking, the objective is to minimise the difference in the costs of producing electricity across each day – this is expected to result in a flatter demand profile because demand and costs are correlated.

Figure 72: Projected 2036 grid demand without battery charging

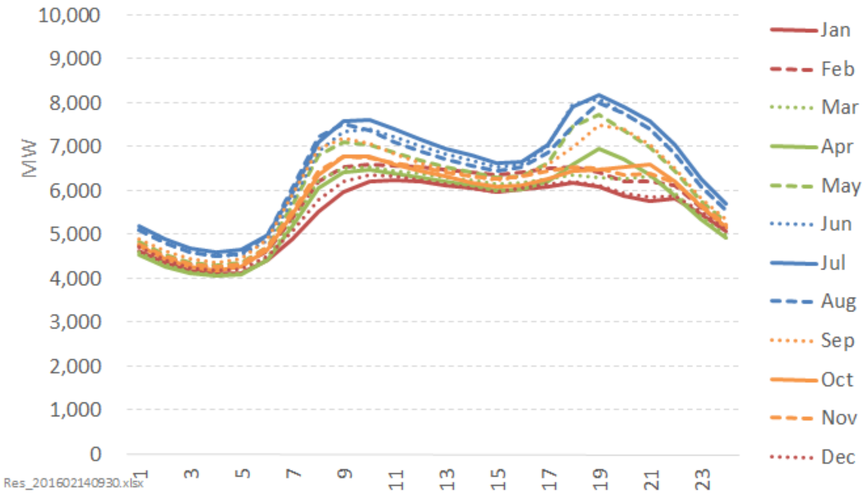

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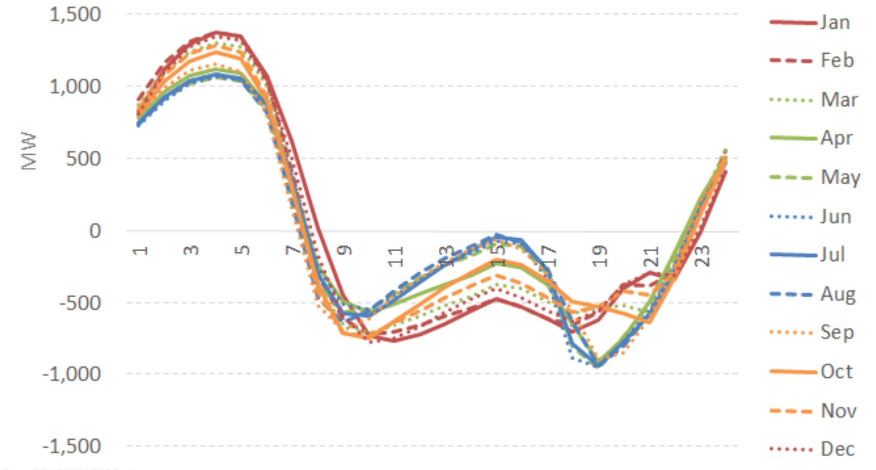
Figure 73 shows the projected profile of battery charging/discharging, based on a regime that is intended to provide the maximum benefit from a 'NZ Inc.' or national perspective, by minimising price differentials and flattening demand across each day. It shows how batteries would be charged during off-peak periods (e.g. mainly overnight) and discharged during morning and evening peaks.

Figure 73: Projected 2036 battery charging profile to minimise system demand



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This results in a flattening of overall residual grid demand as shown in Figure 74 below.

Figure 74: Projected 2036 residual grid demand after high uptake of batteries that are charged to minimise system demand

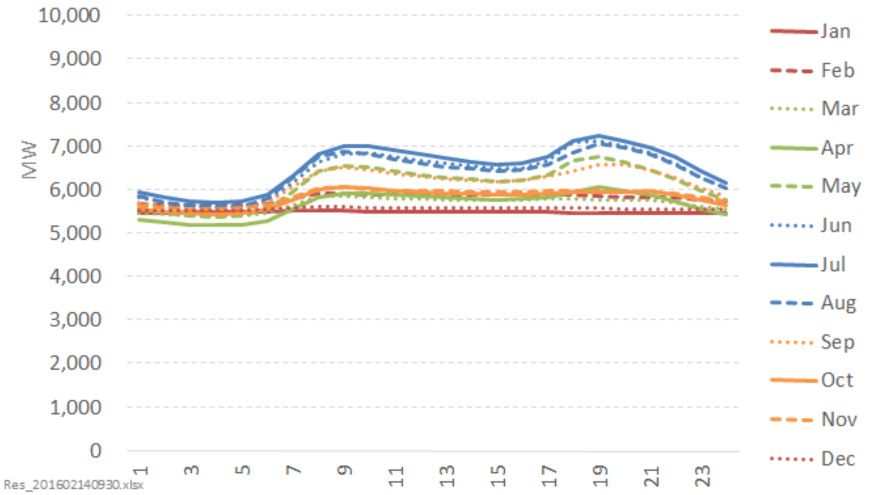
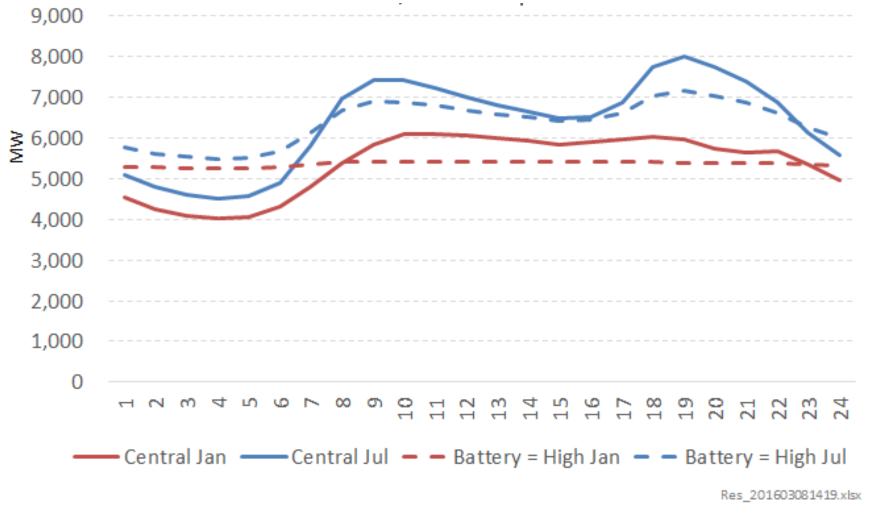


Figure 75 combines the information from the above graphs for only a summer (January) and winter (July) month to illustrate the impact of battery uptake.

Figure 75: Comparison between with and without battery uptake for 2036 for Summer (Jan) & Winter (Jul)



On a duration curve basis, the following figures illustrate how the 20-year growth in demand is affected by significant amounts of battery uptake – with a system-demand optimisation charging approach.

Figure 76 shows the demand duration curve without battery uptake (A), and the change in residual grid demand, relative to the basecase (B).

Figure 76: Projected 2036 demand duration curves (DCs) without Batteries: A) Overall DC, and B) Change in DC over 20-year period

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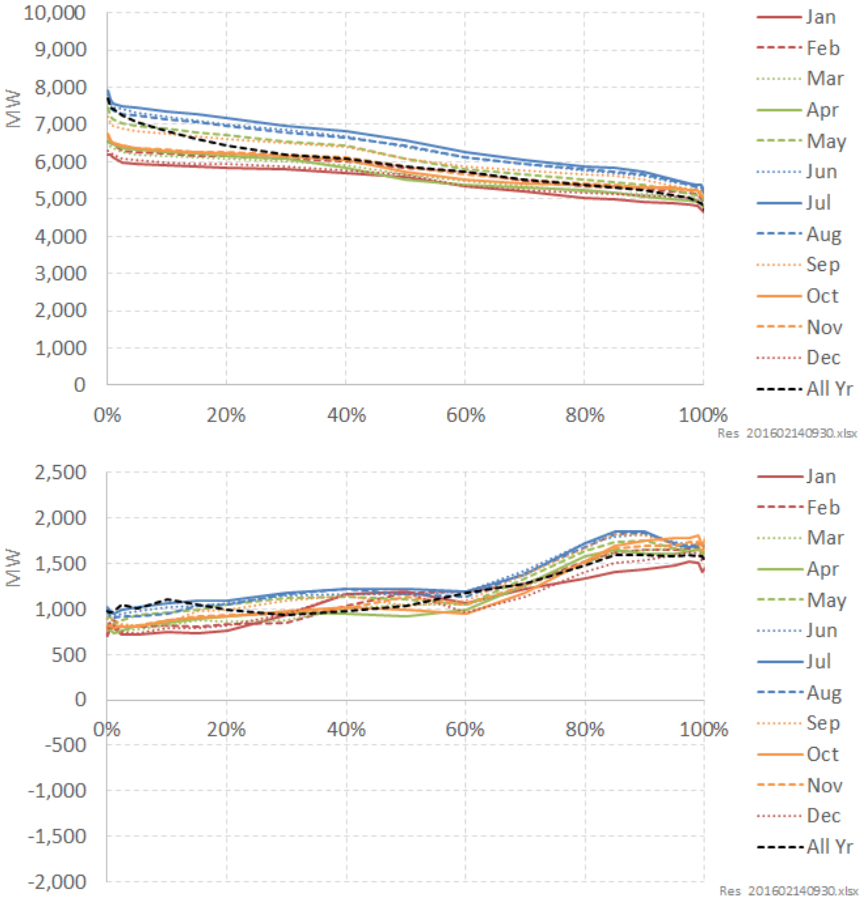
These charts can be compared with the demand duration curve data with battery uptake shown in Figure 77. These show how battery uptake acts to flatten the overall demand duration curve (A). This is even more apparent when considering changes in the demand duration curve (B).

Figure 77: Projected 2036 demand duration curves (DCs) with high uptake of batteries. A) Overall DC, and B) Change in DC over 20-year period



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As can be seen, this charging approach results in a reduction in the requirement for low capacity factor generation, relative to the basecase. It also results in an increase in the requirement for baseload generation.

Impact of combined solar and battery uptake

We have also considered scenarios that combine solar PV uptake with batteries. These recognise the dynamic interactions between solar PV and batteries. In particular, solar PV uptake will alter the residual demand for electricity, which can change the 'optimal' timing of battery charging and discharging. This is illustrated by the following charts.

Figure 78 shows the projected battery charging profile in 2016 when there is little PV on the system. This is fundamentally the same as the charging profile shown in Figure 73 previously, and shows that charging predominantly occurs overnight, with batteries releasing their charge during morning and evening peaks.

Figure 78: Projected 2016 battery charging profile to minimise system demand in a system with little solar PV

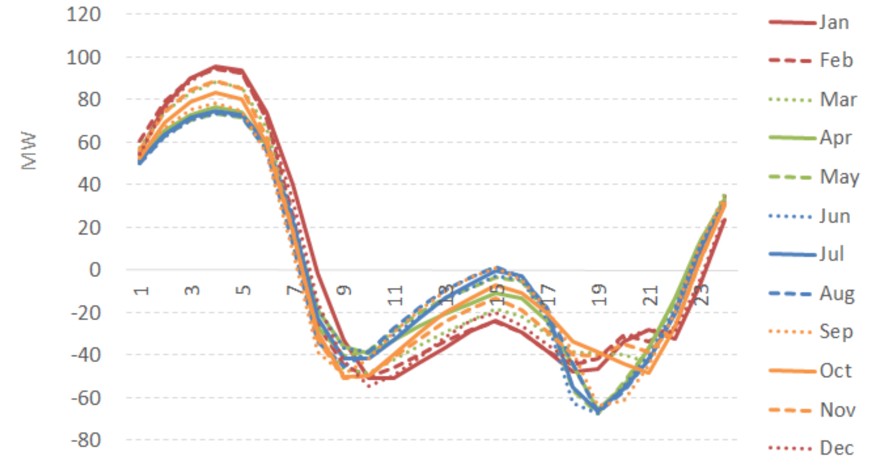

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Figure 79: Projected 2036 battery charging profile to minimise system demand in a system with high levels solar PV

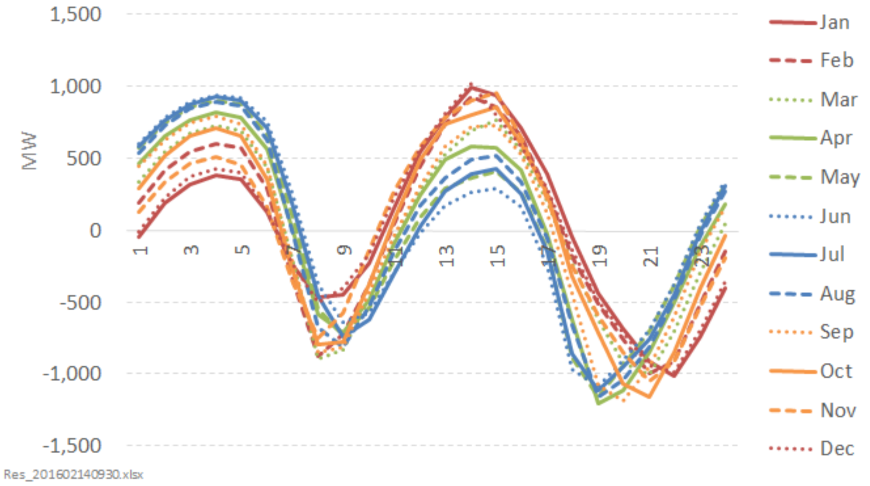
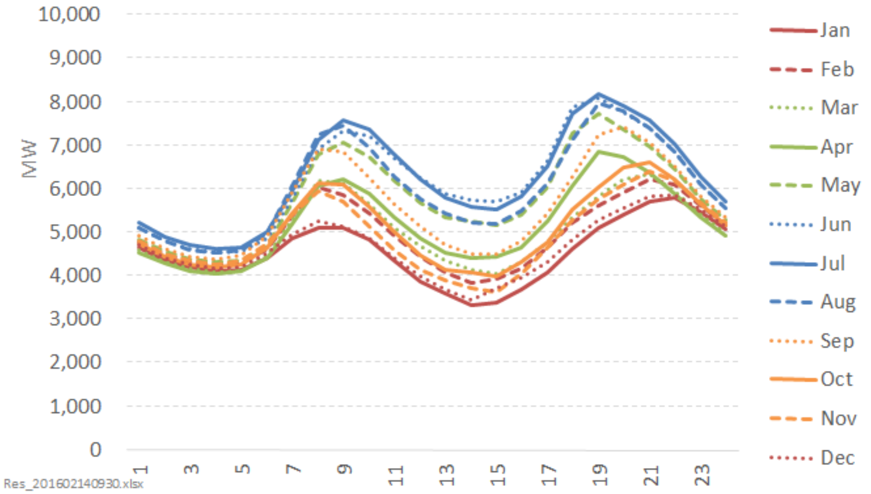


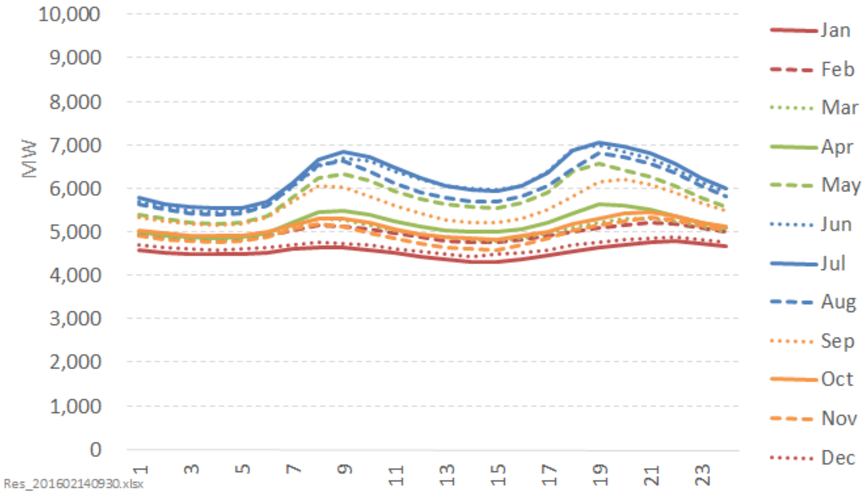
Figure 79 above shows change to the charging profile of batteries, with a significant amount of charging now occurring in the middle of the day. This is because, as is illustrated in Figure 80 below, the post-PV residual demand has significant relative surplus during the middle of the day – indeed, in summer months the post-PV demand during the middle of the day is now lower than the demand overnight.

Figure 80: Projected 2036 post-PV residual demand with high levels of solar PV



The operation of batteries shown in Figure 79 previously, counter-acts the effect of solar PV, with the result that the final residual grid demand (i.e. post-PV and post-batteries) is a lot flatter. This is shown in Figure 81 below.

Figure 81: Projected post-PV and post-batteries 2036 residual grid demand with high levels of solar PV and batteries



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The overall impact of this combined technology uptake is shown below in Figure 82 (which shows the impact on demand growth) and Figure 83 (which shows the impact on the overall grid demand duration curve in 2036).

Figure 82: Projected 20-year grid demand growth: A) without PV or batteries, B) with high uptake of PV + batteries

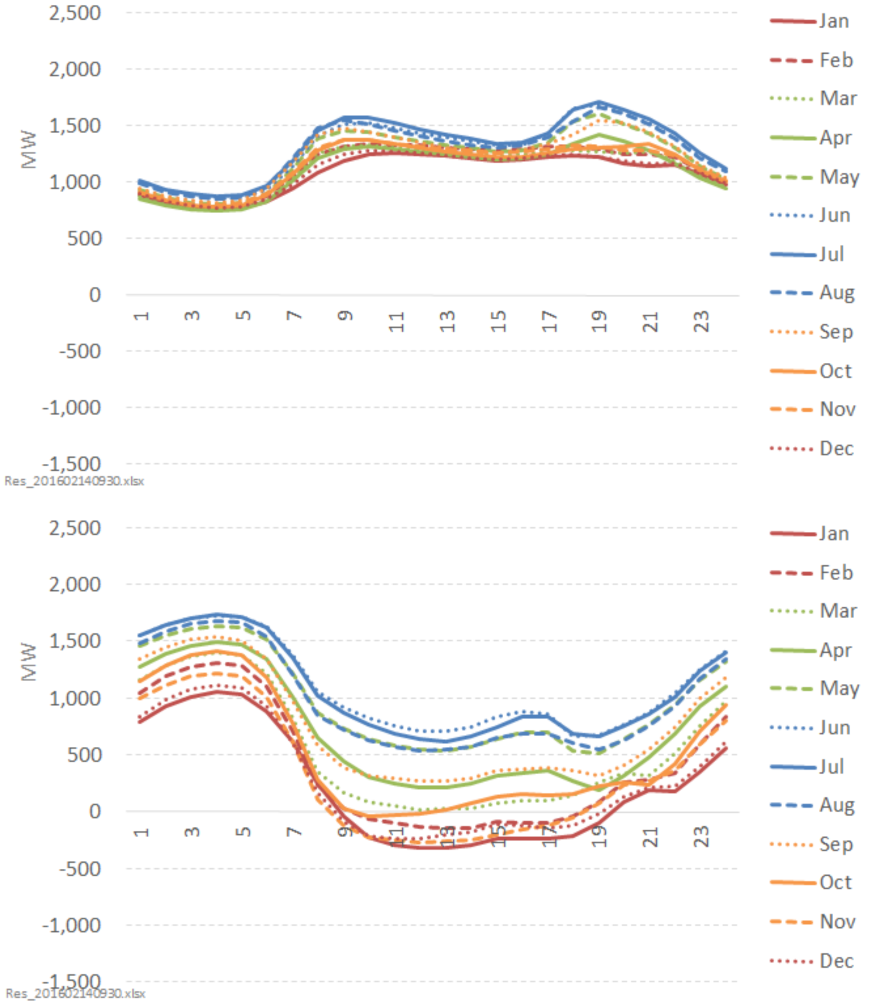
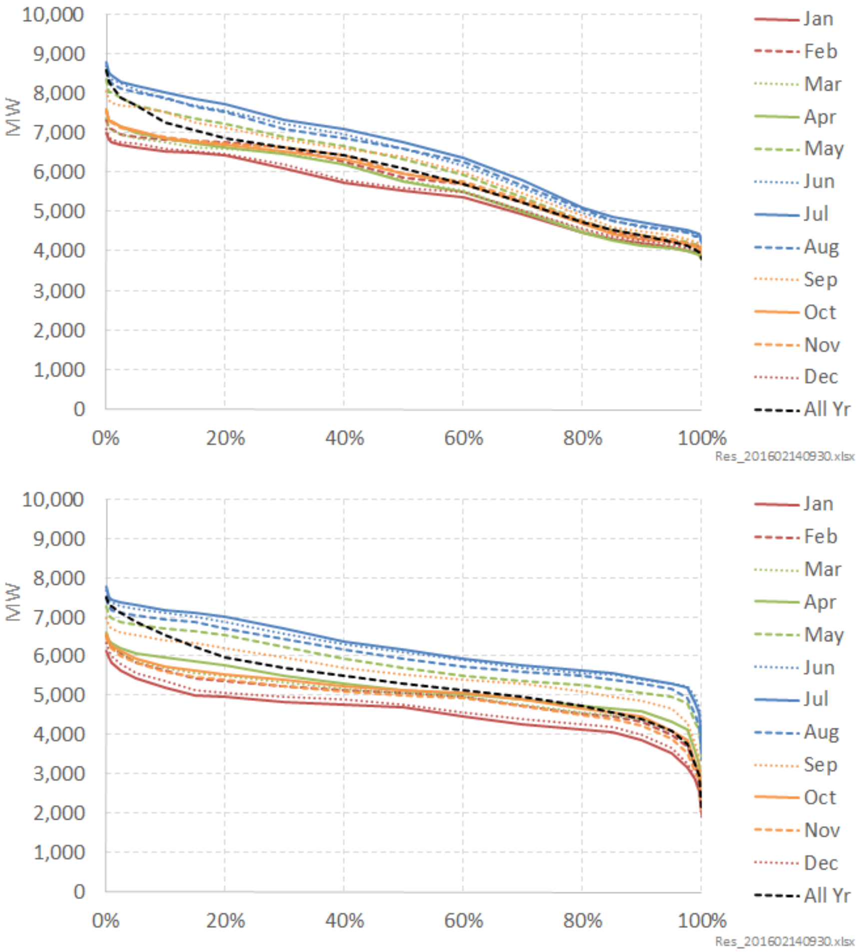


Figure 83: 2036 residual demand curve: A) without solar PV + batteries, B) with high solar PV + high battery uptake



As described on page 59, solar PV uptake on its own can cause the residual demand curve to become peakier, resulting in an increased need for low capacity factor generation (i.e. fossil) in the long run.

The analysis describes above shows that solar PV + battery uptake can reduce the extent of this increased peakiness.

However, it is not considered that an uptake of PV plus batteries will fundamentally alter the conclusions as to whether solar PV uptake will increase the requirement for low-capacity factor (i.e. fossil) generation in the long-run.

To understand this, the following charts show the duration curve in 2036 for four different scenarios:

- No technology uptake
- High PV uptake
- High battery uptake
- High PV + battery uptake

Figure 84: 2036 duration curve in a future with no new technology uptake

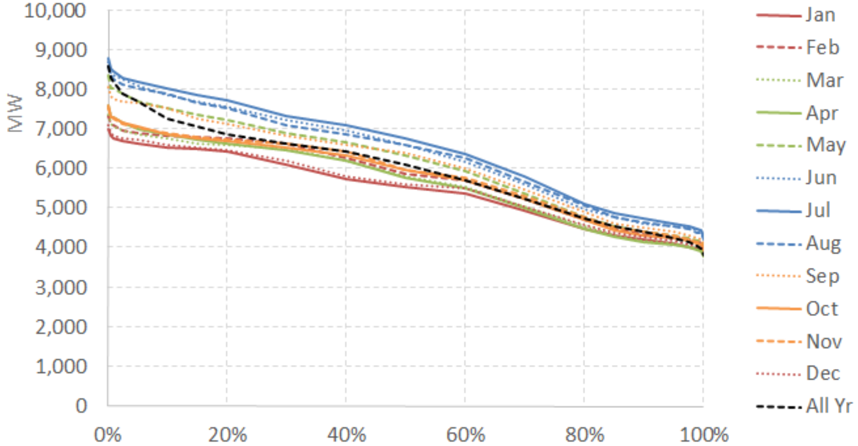


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Figure 85: 2036 duration curve with high solar PV uptake

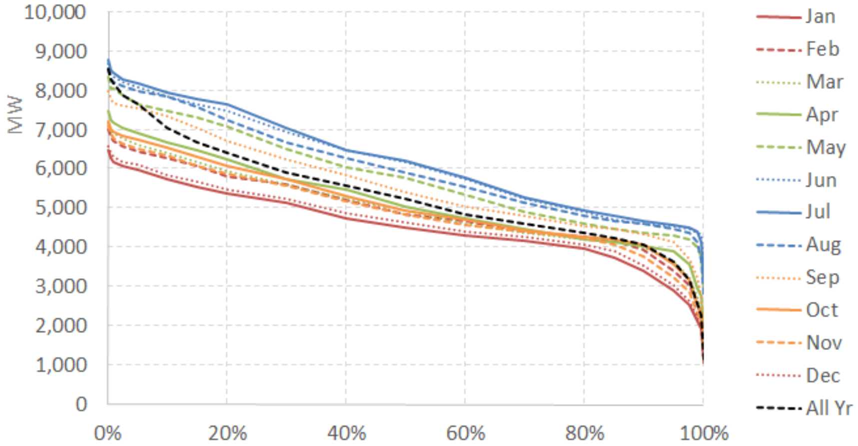

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Figure 86: 2036 duration curve with high battery uptake

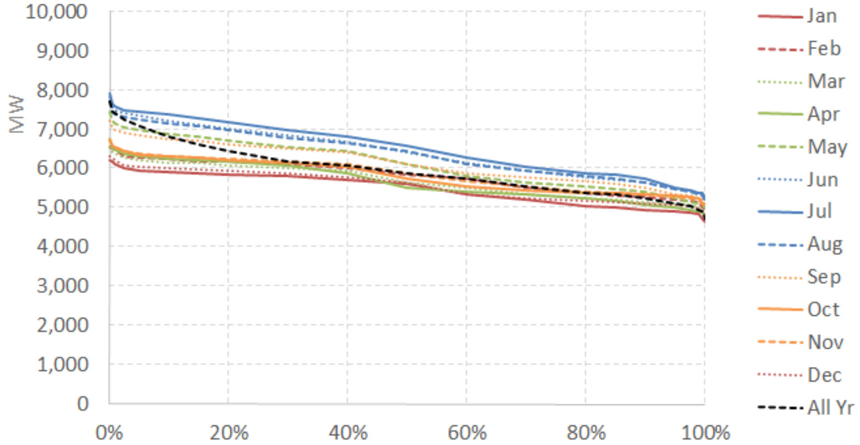

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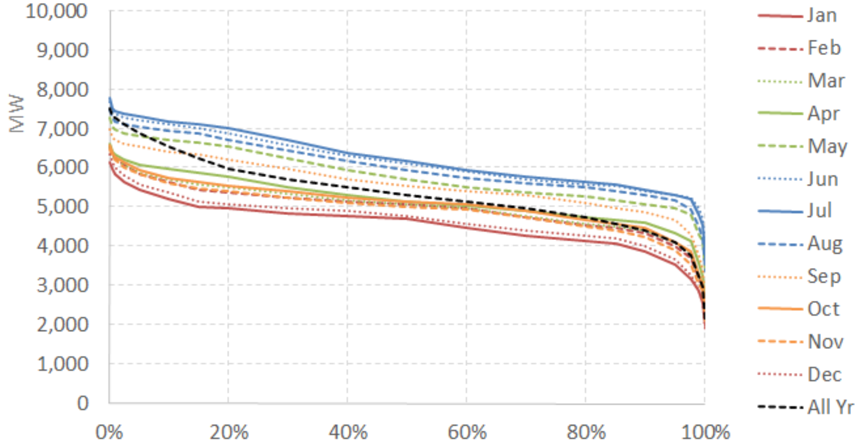
Figure 87: 2036 duration curve with high solar PV and high battery uptake



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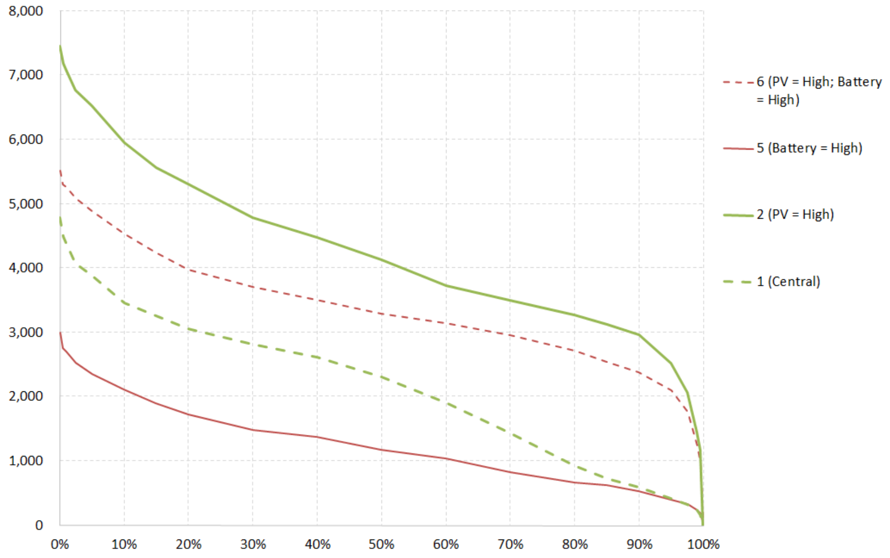
The following chart shows the "All Yr" duration curve for each of the four scenarios (the dotted black line in the above charts), but only for demand above the minimum point – being a measure of the demand for low-capacity factor generation.

Figure 88: 2036 duration curves above minimum demand for four different scenarios[61]



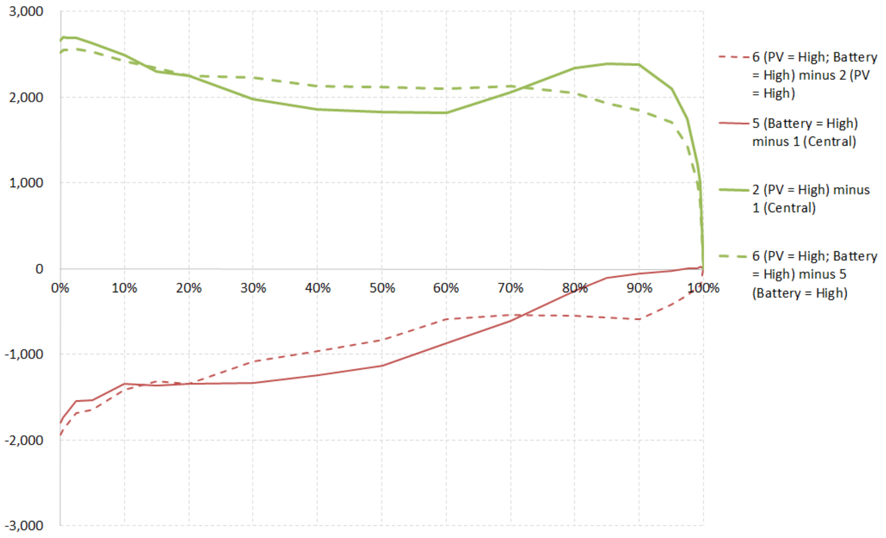
The following chart shows the same data as in Figure 88 but expressed as the difference between pairs of scenarios. The lines coloured red show the impact on the requirement for low capacity factor generation due to batteries:

- Without PV (the solid red line)
- With PV (the dashed red line)

Similarly, the lines coloured green show the impact on the requirement for low capacity factor generation due to solar PV:

- Without batteries (the solid green line)
- With batteries (the dashed green line)

Figure 89: Impact on the requirement for low capacity factor generation due to PV and battery uptake and combinations thereof



The altered requirement for low capacity factor generation is roughly the same for each technology whether it is in combination with the other technology or not. In other words, installing batteries in combination with PV doesn't fundamentally alter the

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[61] The numbers 1, 2, 5, and 6 in the legend refer to scenario reference numbers for the modelling. The "Central" scenario has no new technology uptake.

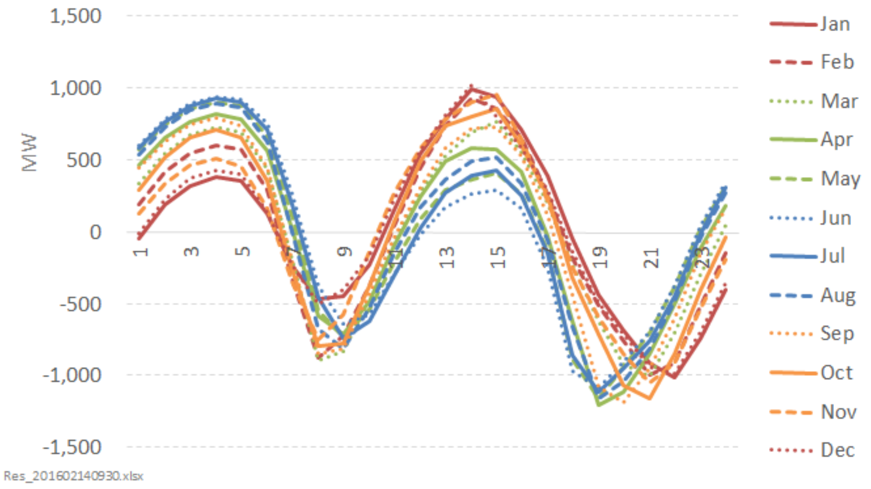
impact of PV in terms of increasing the requirement for low capacity factor generation in the long-term.

This conclusion is intuitively sensible, given that the main long-term challenge with solar PV relates to the amplification of seasonal differentials, for which batteries are unlikely to have a material impact (i.e. it is unlikely to be economic to install a battery to fill up once in the summer to release once in the winter, at least for the foreseeable future).

The modelling also considered the impact of operating batteries to minimise residential demand peakiness for houses with PV. This is because it appears some batteries may be purchased by households with solar PV in order to minimise the extent of any 'export' from their panels at times when their PV generation exceeds household demand. This mode of operation could be driven by the relative export versus demand tariffs that households face. Such outcomes are occurring in many overseas jurisdictions and are starting to happen in New Zealand.

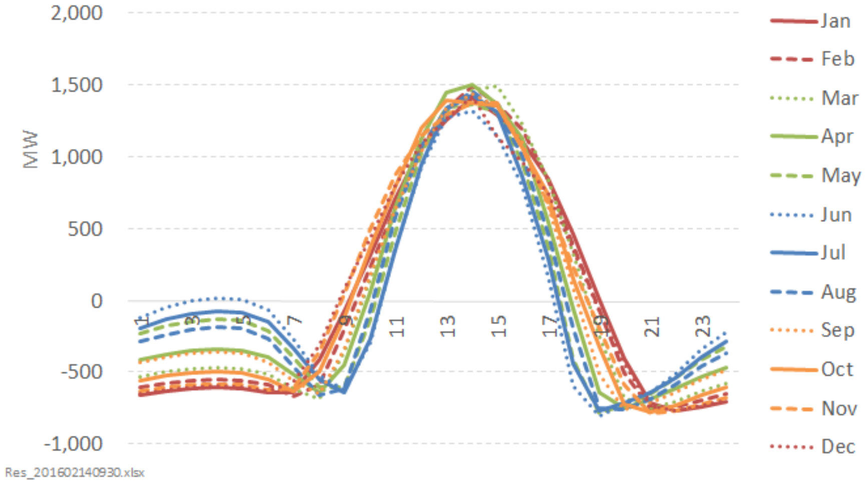
As shown previously in Figure 79, with high solar PV uptake, in order to minimise system demand, battery charge and discharge would have a profile like that shown in Figure 90 below.

Figure 90: Projected 2036 battery charging profile to minimise system demand in a system with high levels solar PV



However, if instead batteries were being operated to minimise export for a residential property with solar PV, their pattern of operation would look like that shown in Figure 91 below.

Figure 91: Projected 2036 battery charging profile to minimise residential export



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This has the effect of increasing the peakiness of residual demand compared to the scenario where batteries were operated to minimise overall system demand. The consequences of this are that more low-capacity factor generation is required than would otherwise be the case.

In other words, operating batteries to minimise export from properties with solar PV has the effect of increasing New Zealand's emissions compared to a future where such batteries were operated to optimise the overall system demand.

Appendix D. The new technologies

This section provides background information about new technologies and the New Zealand electricity sector. While many readers will be familiar with this information, it is provided for completeness.

Electric vehicles

EV technologies have been around since the earliest days of motor vehicles. Until recently, they have not been attractive in mainstream applications due to cost or performance issues.

Recent technology improvements, especially for batteries, have led to EVs becoming more common. A range of technology options are currently available such as Battery EVs (BEVs), series Plug-in Hybrid Electric (PHEVs), and parallel PHEVs.

The range of options reflects factors such as:

2. The role of vehicles in society is relatively segmented (consider the different vehicle requirements for long family holidays, commuting to work, delivery vans, taxis, etc).
3. Vehicle manufacturers face the design problem of trying to optimise vehicles across many parameters such as:
    - Performance of the vehicle (this includes weight minimisation, but also meeting the maximum power demands which are typically for acceleration and hills, not for steady state driving on highways)
    - Capital cost of vehicle
    - Efficiency (minimising running costs and meeting regulatory standards).

It is possible that multiple configurations will persist for some time, with each focused on particular segments of the vehicle market.

Battery EVs

Battery EVs, or BEVs, are powered by electric motors only, and only use electricity as a fuel (i.e. recharging the battery from the electricity network is the sole external energy source).

Compared to other EVs, BEVs have the advantage of less complexity and thus potentially lower capital and maintenance costs (i.e. if battery costs reduce).

However, a BEV’s operational range is limited by the battery capacity. While fast charging (e.g. 80% battery charge in 30 minutes or so) is possible, this still results in materially slower journeys compared to other vehicles (ICE or PHEV) if the journey length exceeds the vehicle range. Using fast chargers also reduces the lifespan of some batteries, so there can be a material cost associated with fast charging. The Nissan Leaf is an example of a BEV.

Series PHEVs

A Series Plug-in Hybrid EV, or ‘Series PHEV’, is an EV powered by electric motors only. It can source the electricity to power the motors from an on-board battery, or from an on-board internal combustion engine that drives a generator. The battery can be recharged from the electricity network when the vehicle is parked.

The internal combustion engine cannot mechanically drive the wheels of the vehicle. It can only generate electricity.

Compared to other EVs, Series PHEVs have the advantages of:

- greater driving range (i.e. similar to as ICEs)
- a battery size better optimised for commuting distance (batteries are a heavy and high-cost component, and BEVs arguably have significantly oversized batteries for 95% of their travel needs)
- no mechanical drivetrain (compared to parallel PHEVs)
- a more efficient 'recharging' engine (for a given capacity) compared to Parallel PHEV - the Series PHEV engine is optimised for a narrow range of power output and is therefore more efficient.

The main compromises of Series PHEVs are:

- Efficiency is lower in non-electric mode (i.e. while the small 'charging engine' is more efficient, this is offset to some degree by inefficiencies in the generator, battery charging and discharging, and in the electric motors)
- They are more complex than BEVs with higher maintenance costs.

The BMW i3 'range extender' model is an example of a Series PHEV.

Parallel PHEV

A Parallel Plug-in Hybrid EV, or 'Parallel PHEV', is an EV that can be powered by electric motors and/or an internal combustion engine. The internal combustion engine can mechanically drive the wheels of the vehicle (either alone or in conjunction with the electric motors).

Compared to other EVs, Parallel PHEVs have the advantages of:

- greater driving range (similar to ICEs)
- better optimisation of peak power demands by spreading the load across the electric and internal combustion engine when under high load
- typically they have lower cost than Series PHEVs.

The main compromises of Parallel PHEVs are:

- They have more a complex drive train than BEVs and Series PHEVs as there is some degree of doubling up on the installed engine/motor capacity as the electric motors alone need to be able to meet all of the driving load. The trade-off here is one of drive train costs (capital and operating) versus engine and motor costs
- Parallel PHEVs often have less battery capacity than Series PHEVs. However, this results in less 'electric range' so may result in lower efficiency (and higher running costs), depending on commute distances.

The Mitsubishi Outlander is an example of a Parallel PHEV.

Key point of difference between PHEVs and BEVs

A key point of difference between PHEVs (of all varieties) and BEVs is that PHEVs offer fuel choice. Consumers can choose to either plug-in their vehicle to charge the battery (using electricity as the fuel), or just fill the tank with petrol.

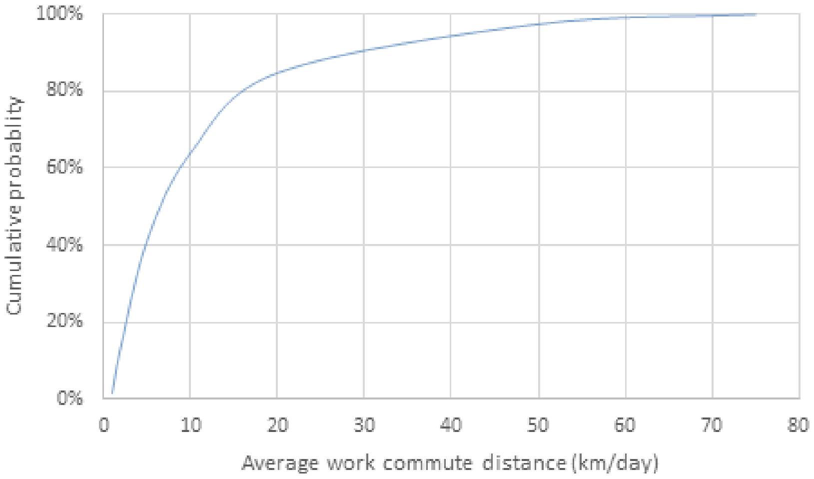
This fuel-switching capability may have a specific benefit to New Zealand, because it could reduce electricity demand during hydro droughts when supply becomes tight and power is more expensive to produce. Only PHEVs have this fuel switching capability, and as such, the benefits that could arise are dependent on PHEV uptake (i.e. versus BEVs).

Daily vehicle usage and EVs

BEVs vehicles typically have less range than ICE vehicles, with the Nissan Leaf having a reported range on a full charge of around 135km.[62] PHEVs have a greater range because the vehicle can switch to petrol if the battery is exhausted. However, the majority of light passenger vehicle use is actually shorter trips that are well within a PHEV's electric-only capability.

New Zealand's relatively small cities result in daily commute distances that are lower than many other countries (even with New Zealand's comparatively low penetration of public transport). For example, about 90% of daily commute distances for work are less than 30km, as shown in Figure 92.

Figure 92: Average daily work commute distances



Source: Statistics New Zealand data

These work commute distances are well within the capability of modern EVs, but also (potentially more importantly) within the 'electric-only' range of PHEVs.

More generally, the daily distances travelled by all light vehicle types is shown in Figure 93. It indicates that the majority of daily travel distances are less than 40km for all vehicle types (well within the range for EVs). Furthermore, around 90% of daily travel is less than 100km in distance, still within the range for a fully charged EV such as a Nissan Leaf.

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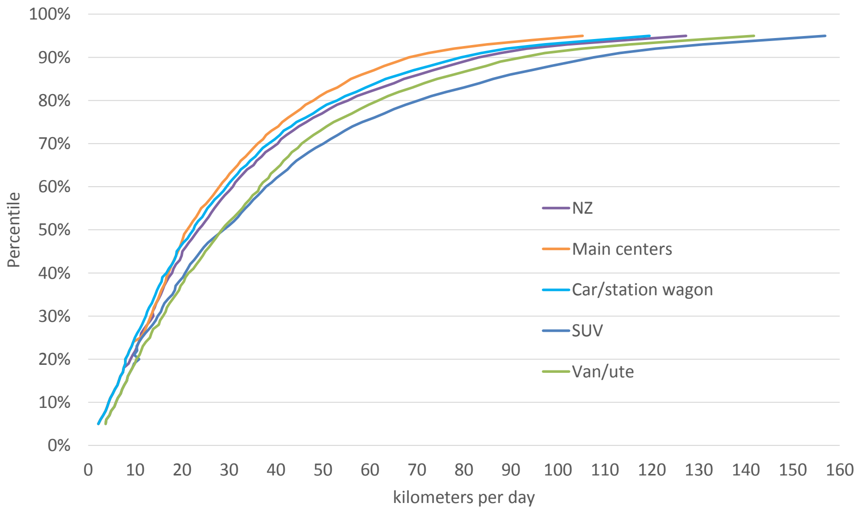
[62] Nissan Motor Corporation estimate.

Figure 93: Daily travel distance by vehicle type



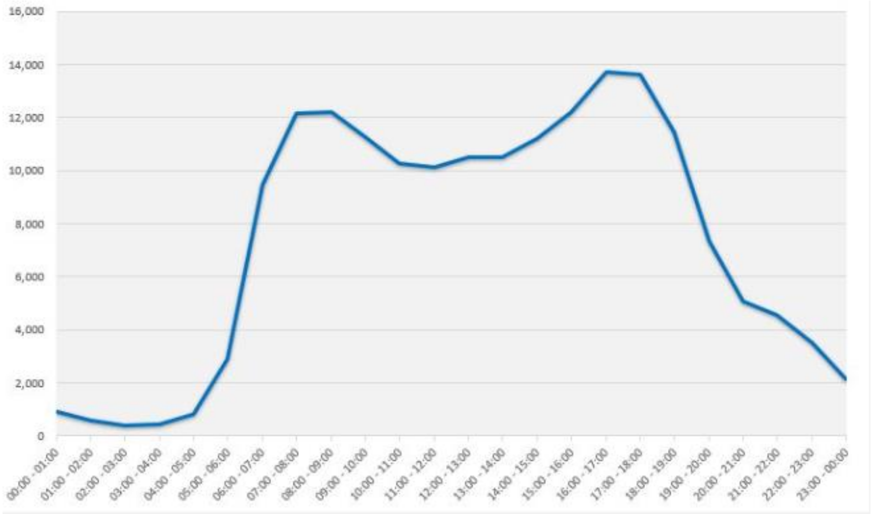
Source: Data sourced from study by Centre for Advanced Engineering, University of Canterbury

Patterns of light passenger vehicle use

EVs (EVs) are, initially at least, likely to substitute for internal combustion engine (ICE) vehicles. For this reason, it is useful to look at existing vehicle usage to how this matches the attributes of the various EV technologies.

As with electricity, travel demand show very regular patterns, due to factors such as work commuting and school travel. The strong diurnal demand pattern is shown in Figure 94.

Figure 94: Diurnal travel demand on Auckland Harbour Bridge[63]



Source: NZ Transport Blog. North and south bound data is shown

Likewise, vehicle usage is higher on business days than at the weekend, as shown in Figure 95.

These patterns of usage mean that unless EV owners face suitable incentives, charging of EVs is likely to amplify existing electricity demand peaks. In particular, commuters are likely to plug in and begin charging their EV as soon as they get home from work in the evening,[64] since this is likely to be a convenient time.

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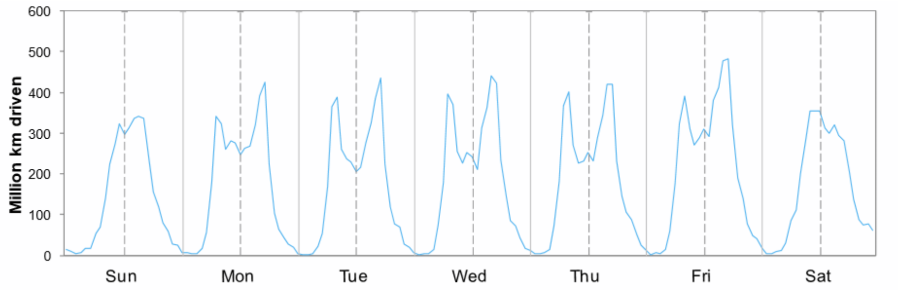
[63] Note that both north and south bound data is shown (this graph is sourced from NZ Transport Blog)

[64] Some people may plug their EVEV in to charge when they arrive at work, which may contribute to the morning electricity demand peak if they start work earlier than average.

Figure 95: Diurnal travel pattern for New Zealand[65]



Source: Ministry of Transport data

Solar photovoltaics

Solar panels turn sunlight into electricity. The panels are made up of photovoltaic (PV) cells, which convert sunlight into low voltage direct-current (DC) electricity.

PV panels cannot generate electricity for home use on their own. They require either an inverter (to turn the DC electricity into AC electricity), or batteries (DC stand-alone system), or both, to be able to produce useful electricity in the home. These additional 'balance of system' components are a significant part of the overall system cost for a consumer.

PV panels can use a variety of technologies, but by far the majority of panels today are either monocrystalline or polycrystalline silicon based panels. These technologies have been around for decades, but have been incrementally improving in efficiency, and reducing in cost.

Solar photovoltaic technology has very low maintenance costs due to no moving parts, and long system lifetimes. PV panels often have a 20-year, or longer, warranty period, albeit with reduced output down to about 85% of installed capacity as the panel ages. Other system components such as inverters have shorter expected lifetimes, and typically require replacement over the PV panel life.

The output of a PV panel is affected by the intensity of sunlight shining on to its surface.

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[65] This graph is sourced from the Ministry of Transport http://www.transport.govt.nz/assets/Uploads/Research/Documents/Drivers-2014-y911-Final-v3.pdf

Figure 96: Sunlight variation over days and seasons

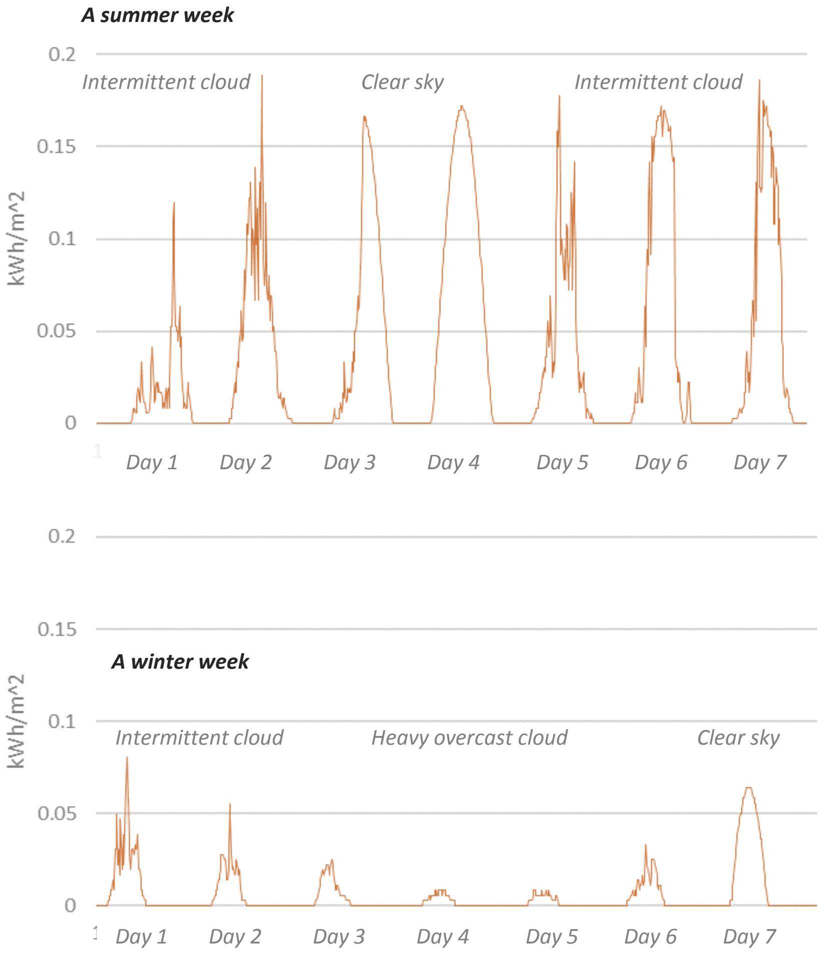

Figure 96 shows how sunlight energy falling onto a surface varies in intensity, as measured in kWh per square metre. It shows the distinct daytime/night-time pattern each day, caused by the position of the sun. There is also shorter term variability caused by cloud cover on some days. The summer and winter charts have the same scale, and it shows how the insolation is much lower in winter.

The electricity output of PVs is highly correlated with the intensity of sunlight on the panel. This means that PV electricity output will vary considerably over a year. In New Zealand, PV systems (depending on panel tilt angle) generally have about half the daily electricity generation in winter compared to summer[66] (for similarly clear days).

The intensity of sunlight also changes quickly within a day if clouds cause shading of the panels. It is not unusual for PV system output to halve within a few seconds for smaller rooftop systems (or about 10-20 seconds for large megawatt-scale PV systems).

This seasonal and intra-day variability of PV output can cause challenges when integrating PV into the total electricity system. While the challenges are all manageable, there are generally costs.

Grid-tie PV systems

The main components of a ‘grid-tie’ PV system are the PV panels and an inverter. These components are electrically connected or ‘tied’ to the grid (as the name implies). This is the most common form of residential and commercial PV system in New Zealand.

Grid-tie systems have the benefit of not needing batteries. While electricity generation and demand do still need to be balanced

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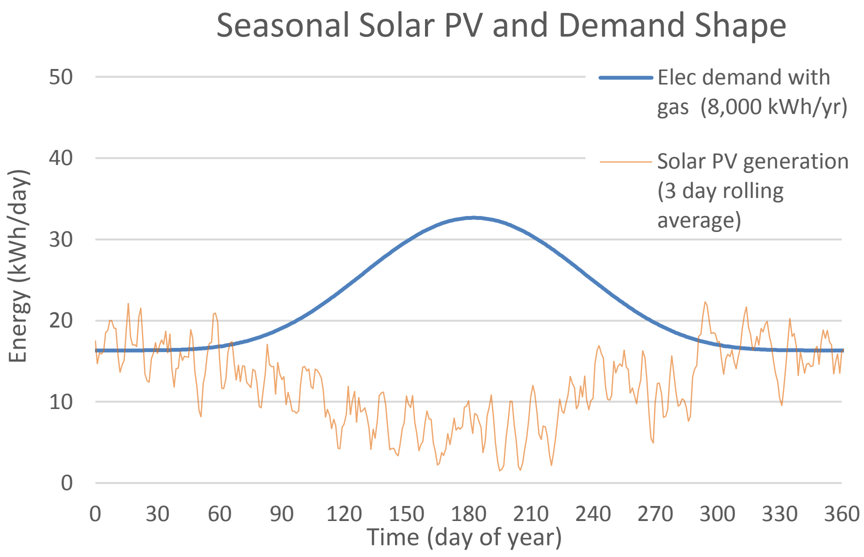
[66] PV panel output reduces as the panel temperature rises above ambient, thus summer output is attenuated because the sun is more intense and the average air temperature is higher.

from second to second, this job is left to the electricity grid with 'grid-tie' systems. The grid is used for stability and balancing services to make up for the inherent variability of PV generation. However, if there is a grid outage, grid-tie PV systems automatically stop generating (even if it's sunny). A grid-tie PV system cannot operate independently of the grid, and therefore does not provide back-up during grid outages.

In New Zealand, residential grid-tie PV systems typically export a significant portion of their generation to the grid. This happens whenever the PV output is higher than the electrical load of the household. For example, if no one is at home during the day, a 3kW system may export about 70% of its generation over a year.

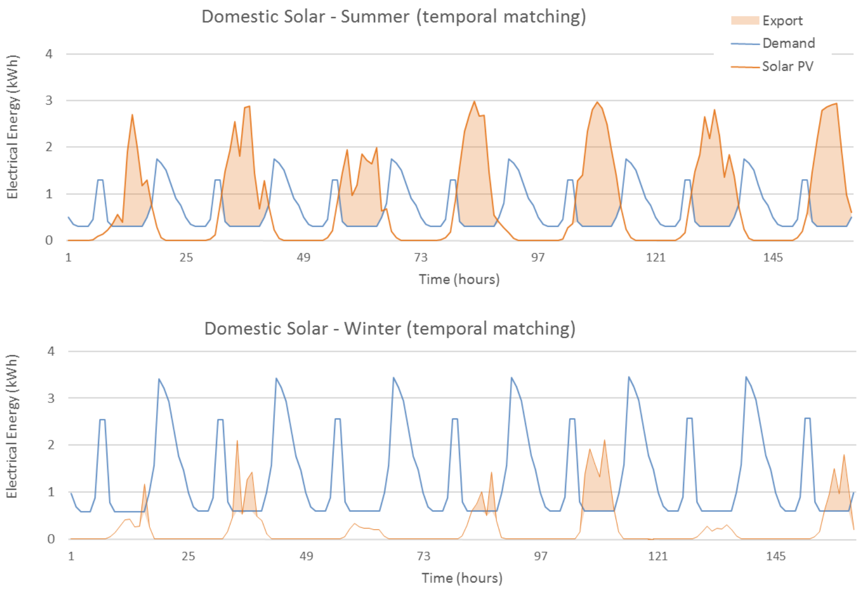
Figure 97: Profiles of electricity demand and PV generation.



This is because PV output is negatively correlated (i.e. out of phase) with the seasonal demand for a house that is not usually occupied during the day as shown in Figure 97.

Even in winter when household electricity demand is highest, a 3 kW PV system can export electricity around the middle of the day, even though the total *daily* demand is much higher than total *daily* generation.

Figure 98: Variation of demand and PV generation over days



This occurs because of the variations of household demand and PV generation within each day. This is illustrated by Figure 98 which shows demand and PV generation over six day periods during the summer and winter respectively.

Batteries

Batteries are a key enabling technology for EVs. Overall, battery prices are reducing, but technology is not yet convergent (just like EVs).

There are many competing battery chemistries, each with various attributes. The key measures of battery performance are:

- Battery useful life - often this is charge cycle dependant, and can depend on the typical level of charge[67] and how fast batteries are charged, but for some chemistries it is solely time and (ambient temperature) dependent and unrelated to state of charge
- Battery cost for a given storage capacity ($/kWh)
- Energy density (kWh/kg) which affects vehicle performance in terms of range and also due to battery weight.

At present, batteries are reducing in cost and increasing in energy density, but it is not yet clear which chemistries have the greatest potential for development. In 2014, battery cell costs were between US$300 per kilowatt-hour and US$500 per kilowatt-hour (with battery pack prices of the order of US$600/kWh).

Battery pack prices are expected by some commentators to fall to about US$200/kWh by 2020 (with cell prices of the order of US$100/kWh). By way of comparison, Tesla's 'Powerwall' domestic battery pack has been marketed at a retail price of about US$430/kWh in 2015.

The battery 'cell' prices differ from the 'battery pack' prices because the cells are the main, but not the sole, components of a battery pack.

A typical battery pack is made up of cells packaged into modules, and multiple battery modules packaged into a battery pack which also includes cooling, and physical protection to ensure safe operation. Given that some cell chemistries require a lot more thermal management than others, and may have different cell voltages, not all cell prices are comparable. While one battery's cell price may be comparatively lower, the resulting battery pack from this cell may be more expensive due to cooling and safety requirements.

One particular issue is battery pack safety - some chemistries are more prone to overheating, and in extreme cases, fire. This issue has been more apparent in smaller consumer products that don't have active thermal management (e.g. hover boards[68] and drones). In larger applications where cooling mechanisms have been provided (such as EVs), there have only been a few incidents of battery 'overheating' reported in the media.

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[67] The common lithium ion consumer batteries have a longer useful life if not kept fully charged – this is why modern laptops offer a 'battery life extending' charge mode that only charges the battery to 80%. Similarly, many lithium ion batteries can be 'fast charged' but this also reduces the batteries life.

[68] This is a significant issue for some brands of small consumer products using lithium ion batteries in soft polymer packing (i.e. LiPo – lithium polymer batteries). Some fire departments in the US and UK have taken the step of having warnings on their websites to raise public awareness of the issue. See also www.economist.com/blogs/economist-explains/2014/01/economist-explains-19

Table 3: Typical EV battery chemistries

Various battery chemistries
Lithium cobalt oxide
Lithium nickel manganese cobalt
Lithium nickel cobalt aluminium
Lithium iron phosphate
Lithium manganese spinel
Lithium titanate oxide
