CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545182

Pinch Analysis Techniques for Carbon Emissions Reduction in the New Zealand Industrial Process Heat Sector

Michael Walmsley*, Timothy Walmsley, Linda Matthews, Martin Atkins, James Neale, Peter Kamp

Energy Research Group, School of Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand
walmsley@waikato.ac.nz

Options for reducing industrial process heat greenhouse gas (GHG) emissions in New Zealand are investigated using the Carbon Emissions Pinch Analysis (CEPA) and Energy Return on Energy Invested (EROI) analysis methods. Renewable sources like geothermal, biomass, biogas from animal waste and heat pumps from renewable electricity are investigated. Results indicate that some regions of New Zealand are well placed to make significant reductions to process heat GHG emissions through shifting from fossil fuel heating to renewable heating without a large increase in energy expended or cost. Reducing GHG emissions below 1990 levels can be achieved by using wood waste and biomass in place of coal (33.3 PJ) and biogas from animal waste in place of natural gas (12.1 PJ) where high temperature heating is required (>90 °C), and renewable electricity driven heat pumps for low temperature heating (<90 °C) in dairy and meat processing industries (7.0 PJ). The expected increase in expended energy is 20 %. Over all the Central North Island of New Zealand has a significant degree of renewable and natural resource convergence and hence is a prime region for creating low carbon emission industries requiring process heat based on renewable energy and agricultural and forestry waste.

1. Introduction

Under the United Nations Framework for Convention of Climate Change, the New Zealand (NZ) Government has set a target of reducing carbon emissions to 5 % below 1990 levels by 2020 (Ministry for the Environment, 2014). According to the national Greenhouse Gas Inventory, NZ emissions reached an estimate of 76 Mt/y of CO_2-e in 2014, which is a 24 % increase from 1990 levels. Over the same period NZ's population has risen by about 32 % (Walmsley et al., 2014b). Industrial process heat includes process steam, hot water and direct heat systems and accounts for 7.4 Mt/y of NZ's CO_2-e emissions, which is 9.7 % of NZ's total emissions. Since 1990 process heat emissions have grown by 102 %, which is about triple the percentage population growth over the same period. The emissions increase can be chiefly attributed to the dramatic growth in dairy processing. NZ milk production has increased four-fold from 4.5 billion-L in 1990 to over 18 billion L in 2014 and 95 % of this increase is processed into milk powder, which consumes 4 – 10 GJ/t_{powder} of process heat. Reducing industrial process heat emissions through improvements in industrial energy efficiency (i.e. heat recovery) and through using renewable energy sources of heat generation is consequently an important part of the NZ strategy for achieving the 2020 emissions target.

Renewable energy resources found in NZ that can be used for the generation of process heat include: wood and biomass via combustion, geothermal and solar via direct and indirect heating systems, and renewable electricity from wind, hydro, geothermal and wave via heat pumps or direct use. NZ electricity production in 2011 consisted of 77 % from renewable resources (Walmsley et al., 2014a), which has since increased to 81 % due to generation increases of 17 % from geothermal and 6 % from wind (MBIE, 2015), whereas transport is almost exclusively dependent on imported oil.

This paper reports a strategy for reducing carbon emissions for the NZ process heat sector to below 1990 levels using renewable resources and opportunities for process heat generation. In the near term, growth

Please cite this article as: Walmsley M.R.W., Walmsley T.G., Matthews L., Atkins M.J., Neale J.R., Kamp P., 2015, Pinch analysis techniques for carbon emissions reduction in the new zealand industrial process heat sector, Chemical Engineering Transactions, 45, 1087-1092 DOI:10.3303/CET1545182

in process heat demand in NZ is assumed in this study to be similar in magnitude to industrial energy efficiency improvements. Hence the total fuel supply for 2014 and 2020 are the same. The formulated strategy is guided by the principles of Carbon Emissions Pinch Analysis (CEPA) (Tan and Foo, 2007) and Energy Return of Energy Invested (EROI) analysis (Walmsley et al., 2014b). Like the transport sector, options for reducing CO_2-e emissions in the industrial process heat sector are strongly influenced by the price of fossil fuels. Location of the heat demand relative to potentially competitive renewable resources like waste wood, biomass, geothermal and stranded renewable electricity is also important. The geography of NZ and the spread of the natural resources and of heat demand dictates there is a strong regional element to selecting the alternate options.

2. Data Sources and Analysis Methods

A nationwide survey of industrial boilers was used to determine indirect heat demand, fuel use, and emission levels for each industry and fuel type (EECA, 2011). Direct use heat demands for industries like steel making, methanol production and oil refining have been estimated based on typical production efficiencies. Energy use confidentially for these industries is maintained in the NZ Government energy use database because each industry consists of only one major company.
Carbon Emissions Pinch Analysis (CEPA) was originally developed by Tan and Foo (2007) as a graphical method for emissions reduction in energy planning. Energy Return of Energy Invested (EROI) analysis is applied to understand how a change in energy source (i.e. fuel) affects the quantum of expended energy needed to harvest and process the energy into its useful form. EROI is defined as the ratio of useful generated energy divided expended energy, i.e. E_{gen}/E_{ex}.

2.1 Emissions factors and EROI values for New Zealand in 2014

Net emission factors (NEF) and EROI ratios applied in this study are presented in Table 1. Renewable resources, like biogas, wood waste, black liquor and geothermal exhibits the lowest net emission factors, slightly below electricity, whose emission factor is based on the NZ electricity grid emissions factor in 2011 (Walmsley et al., 2014a). At present, biogas production is very limited in NZ, but has been included as an option for the future. Renewable resource emissions are regional and site dependent and for wood waste very dependent on average transport distances. Net emissions factors are taken from the NZ Ministry for the Environment (2007) and EROI values are from Hall et al. (Hall et al., 2014). The low emissions factor for electricity given its high energy quality is due to the high percentage of hydro, geothermal and wind generation in NZ. Fossil fuel resources all have emission factors above 50 kt CO2-e with natural gas being the lowest and lignite the highest.

Table 1: Net Emissions factor and EROI values applied in the NZ case study.

Resource	Net Emissions Factor (kt CO_2-e/PJ)	EROI ($E_{therm.}/E_{ex}$)	Resource	Net Emissions Factor (kt CO_2-e/PJ)	EROI ($E_{therm.}/E_{ex}$)
Biogas	1.0	10.0	Natural Gas	50.3	63.0
Wood	1.3	28.6	CNG	50.3	63.0
Black Liquor	1.3	28.6	LPG	55.9	56.7
Geothermal	12.0	76.5	Diesel	66.3	20.0
Electricity	13.9	34.0	LFO	69.4	20.0
			Coal	92.6	45.0

EROI ratios for industrial process heat generation for different resources vary from 20 for diesel to 74.5 for geothermal, with gas and coal also being high. Electricity EROI depends on whether it is direct use (EROI = 34) or via a heat pump (EROI = 102) with a coefficient of performance (COP) of 3 based on generating 80 – 90 °C hot water for process heating for low temperature processes, e.g. meat slaughter houses, food processing and dairy processing, which is may be combined with chilled water needs. Heat pump systems by EROI comparisons are highly competitive, but are the down side is they are much more temperature constrained compared to combustion heat derived processes, like burning coal, wood or black liquor. Clean geothermal derived steam is similarly temperature constrained to below 200 °C.

3. Results and Discussion

3.1 Process Heat Demand in New Zealand for 1990 and 2014

The process heat fuel mix in NZ in 1990 and 2014 are illustrated in Figure 1 using the CEPA and EROI composite curve methods. The fuel or resource with the lowest NEF is plotted first followed by the next highest and so forth (Figure 1A). For expended energy, composite curves the fuel or resource with the highest EROI is plotted first followed by the next highest and so forth (Figure 1B). Since 1990 the process heat sector has experienced significant growth.

Carbon emissions from process heat have doubled since 1990 from 4.5 Mt CO_2-e to 9.0 Mt CO_2-e in 2014, while process heat demand has increased from 100 PJ to 190 PJ. The slight difference in growth rate has resulted in the overall Process Heat Emissions Factor (PHEF) increasing by 10 % from 42.1 to 46.3 kt CO_2-e/PJ.

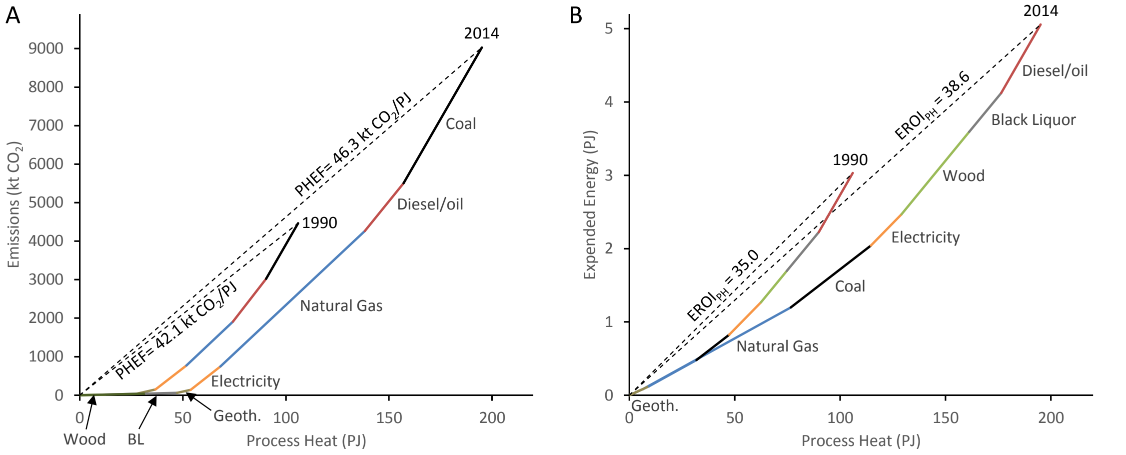

Figure 1: New Zealand-wide Industrial process heat demand in 1990 and 2014 with their associated carbon emissions (A) and expended energy (B).

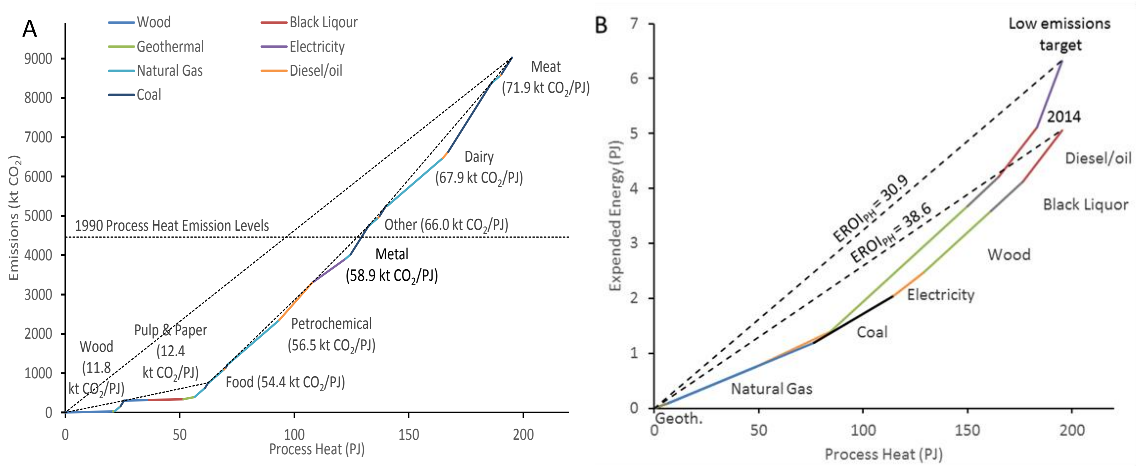

Figure 2: Process heat use by industry and fuel type in New Zealand in 1990 and 2014, with their associated emissions (A) and expended energy (B).

Over the same period, expended energy has increased 67 % from 3.0 PJ to 5.1 PJ, and the average national process heat EROI has increased from 35.0 in 1990 to 38.6 in 2014. Growth in natural gas use stands out as the most common heating fuel, followed by coal, wood, diesel/oil, black liquor in pulp and paper processing, electricity and geothermal. Increased process heat demand has been driven by a 440 % increase in milk powder production for exporting in the dairy sector between 1990 and 2014 and, to a lesser extent, population growth of 32 %, which drives more local food and materials production for domestic consumption. Meanwhile, the pulp and paper industry has seen a rapid decline in demand for and subsequent production of newsprint from a peak of 377 Mt in 2005 to less than 155 Mt in 2014 resulting in less process heat demand for the Central North Island mill at Kawerau.

NZ wide CEPA emissions composite curves for each industry sector and fuel mix are presented in Figure 2. Sectors divide into two main groups according to their average net PHEF. The wood based sectors of wood processing and pulp and paper processing make up about 30 % of NZ process heat demand. A high level of renewable process heat from black liquor, wood left-overs and geothermal results in low PHEF's of

11.8 for wood processing and 12.4 kt CO_2-e/PJ for pulp and paper. The other industrial sectors of food, metals, dairy and meat account for most of the remaining process heat demand. In these sectors, fossil fuels of natural gas, diesel, coal and some electricity are used and PHEF's vary from 54.4 to 71.0 kt CO_2-e/PJ depending on the fuel mix. Dairy and petrochemical are the two biggest process heat users overall, followed by pulp and paper, metals and wood.

3.2 Regional analysis

A map of NZ showing the process heat demands of the top 30 sites and the locations of geothermal and wood resources is presented in Figure 3A. NZ is made up of two main islands that are long and slender and process heat demand is quite variable across the country. Opportunities to use renewable heat resources in industry are affected by geography, which determines the proximity of resources to heat demands. To highlight this, emissions composite curves for different fuel mixes by region are presented in Figure 3B corresponding to the five regions labelled in Figure 3A. The overall PHEF for NZ is 38.6 kt CO_2-e/PJ, but the regional PHEF's vary from 34.6 to 62.0 kt CO_2-e/PJ with the Central North Island having the lowest and the Auckland & Northland region having the highest.

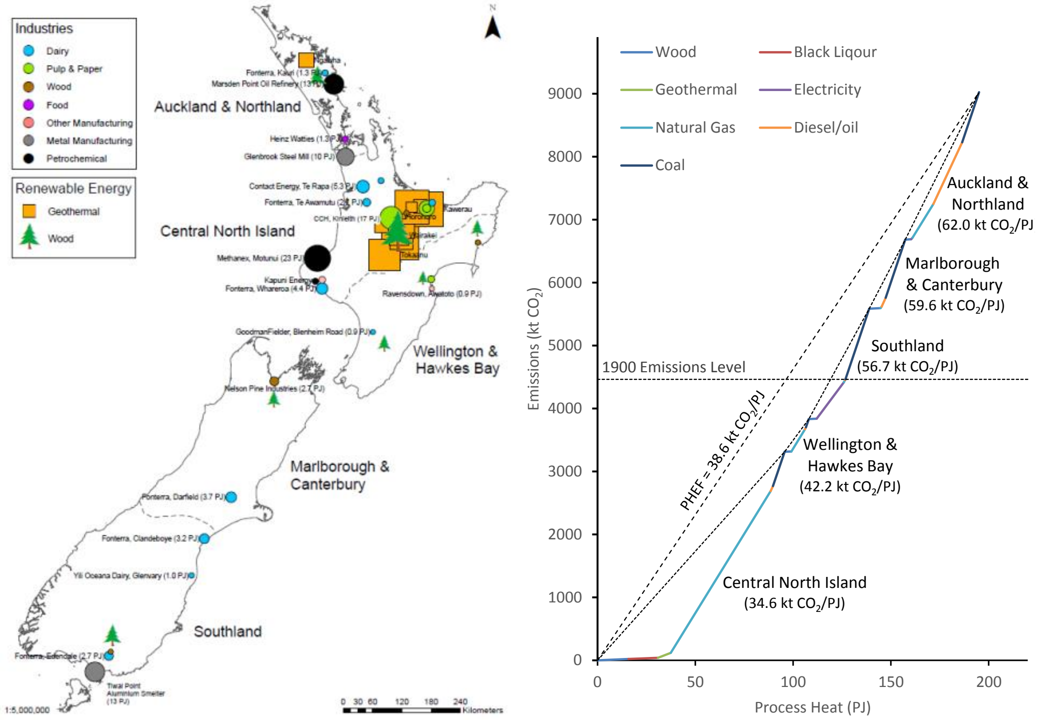

Figure 3: (A) Map of process heat demand by industry type and geothermal and wood process heat supply in New Zealand in 2014. (B) Process heat use in New Zealand in 2014, by region and fuel type, with their associated emissions.

The Central North Island stands out as the region with the largest process heat demand and the lowest PHEF due to the high use of renewable geothermal and wood resources and natural gas drawn from wells near the Motunui Methanol plant (see Figure 3A), which are all in plentiful supply within the region. The process heat demands are mainly associated with methanol and urea production in the west and wood and pulp and paper processing in the east, which are reflections of the large natural gas reserves in the west and large wood resources in the east. These are good examples of natural resource convergence contributing to rural and economic development of regions.

The Auckland and Northland region has the next largest process heat demand, but the highest regional PHEF. This occurs because the region contains NZ's only oil refinery and steel mill, which both use fossil fuels for process heating; oil for the refinery, and coal and natural gas for the steel mill. The oil refinery is located in Northland because of its proximity to NZ's largest city Auckland. The refinery uses 100 % imported oil, of which about 7 % is used for process heating. The steel mill is located in South Auckland near the black titanomagnetite iron sand resource, which is mined directly off North Island west coast beaches. Coal is supplied from nearby mines and natural gas is pumped to the mill by pipeline from the west coast of the Central north Island.

The Southland region has the next largest demand and the third highest emissions. Expansion of dairy farming and its associated milk powder production in the region is the main cause of the increase. Coal, electricity and very little wood are the primary process heating resources. Southland also has NZ's only Aluminium smelter at Tiwai Point, which uses about 15 % of NZ's electricity (Walmsley et al., 2014a) of which about 60 % is used as process heat. The Marlborough and Canterbury region similarly uses coal and wood, supplemented with some oil. The use of wood as a heating fuel is associated with the wood processing plant near Nelson. The Wellington and Hawkes Bay region has the smallest heating demand and uses a range of fuel from wood, natural gas, oil and coal.

3.3 Future Scenarios

To reduce NZ's emissions to below 1990 levels (4.5 Mt CO_2-e), the CEPA method suggests that fuels with the highest emissions factor should be replaced by fuels or resources with lower emissions factor. However such an approach does not adequately account for the difference in fuel costs in different regions and for different industries. Identifying the best low emissions options for a region, for an industry and for the country as a whole, requires the use of EROI analysis and multivariable optimisation of heating resource options for minimal expended energy at specified emissions levels. Preliminary investigation suggests good options for NZ are: using wood waste and biomass in place of coal and biogas for natural gas where high temperature heating is required (>90 ^oC), and renewable electricity driving heat pumps for low temperature heating (<90 ^oC).

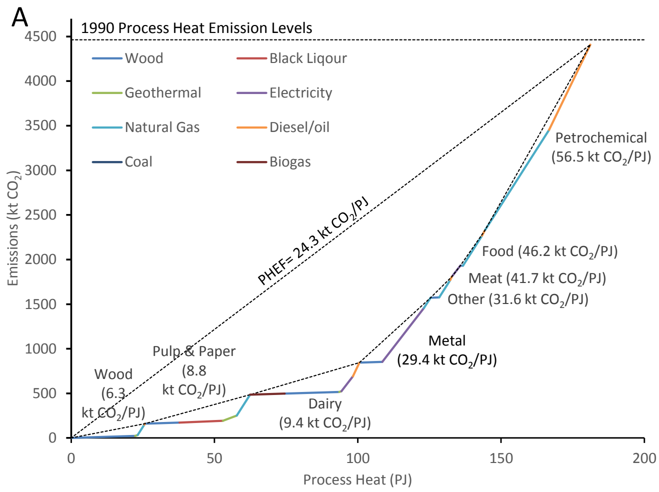

Figure 4: Reducing emissions (A) from process heat use in New Zealand below 1990 emissions level maintaining 2014 demand levels with its associated impact on expended energy (Figure 2(B)).

The employed strategy for lowering emissions from industrial process heat in this study (in order of priority):

(1) Use heat pumps for low temperature heating, <90 °C, in the dairy and meat processing industries - 7.0 PJ.

(2) Substitute wood and biomass for coal - 33.3 PJ, and

(3) Substitute biogas for natural gas in North Island dairy plants - 12.1 PJ.

About half of the process heat needs of dairy processing and nearly all of meat's process heat demand falls below 90 °C. Mechanical heat pumps are a good solution for these industries because they also require significant quantities of chilled water and often have low temperature waste heat streams. In total this strategy reduces process heat demand from fossil fuels by 7.0 PJ, while increasing electricity use by 0.64 TWh (2.3 PJ), which is 1.5 % of the national electricity grid.

The second strategic move, substitution of wood/biomass for coal, is a longer term objective and depends heavily on the coal price and transport cost. The calorific value of wood is less than half that of coal, and as a result transport costs, which is the main source of carbon emissions for wood, are approximately double for the same amount of process heat generation.

However, coal has the highest emissions factor and when an equitable price for carbon is instituted by the NZ Government, it is anticipated that the economics for conversion of coal boilers to duel fuel – coal and wood/biomass – boilers will become common in industry. The third and final strategy, substituting biogas for natural gas, requires a significant change in dairy farming practice in NZ. The greatest opportunity for industrial scale production of biogas is from cow manure.

At present, cows in NZ are pasture fed and this is regarded by the industry as a competitive advantage in terms of milk quality (McGilloway, 2005). Even so, centralised feeding systems, usually based on a grain diet, present the opportunity for efficient collection and processing of cow manure into biogas, which can feed directly into NZ's North Island gas network. In addition, the intensity of milk production in grain-based systems, i.e. milk solids output per cow per day, can increase two-fold compared to the pasture fed because of the increase in food uptake by the cows (McGilloway, 2005).
How best to sustainably operate dairy farms in NZ will be a point of hot debate in the future as emissions reductions from process heat is sought and farmlands become more constrained by urban growth. The effect of implementing these strategies lowers emissions from process heat to below 1990 levels (Figure 4A) with only a 25 % increase in expended energy (Figure 2B). Numerous other options with even lower emissions levels do exist and need further investigation, but achieving lower emissions comes at the expense of increasing expended energy and hence costs to society and the economy at large. Maximising use of biomass for energy production will be important (Čuček et al., 2014).
Expansion of the use of geothermal for process heat is limited because of geography. As a result most geothermal use is for electricity production. Large geothermal reserves are available in the Central North Island are enough for all process heating requirements less than 200 °C in the country, however expansion of processing capacity is needed within this region to take full advantage of the renewable resources available. Detailed energy system studies for Denmark (Lund, 2009) have concluded that wood waste and other carbon sources of heat should not be used for heating in a 100 % renewable system but should be saved for use in liquid fuels and biomaterials. Such a strategy makes sense for Denmark but for countries with large forest resources a combined liquid fuels and process heat use strategy could have merit.

4. Conclusions

NZ is well placed to reduce carbon emissions from industrial process heating through the substitution of fossil fuels with wood, biomass, renewable electricity via industrial heat pumps, and animal waste to biogas. Minimum expended energy options are strongly governed by regional demand and energy resources and the temperature range of the heating demand. NZ has large amounts of dairy, meat, and wood processing resulting in process heat demand temperatures that are low compared to countries with predominantly petrochemical and metals processing based industries.

References

EECA, 2011, Heat Plant New Zealand. <enduse.eeca.govt.nz> accessed 01.02.2013.

Čuček L., Varbanov P.S., Klemeš J.J., Kravanja Z., 2014, Multi-Objective Regional Total Site Integration. Chemical Engineering Transactions, 35, 97-102.

Hall C.A.S., Lambert J.G., Balogh S.B., 2014, EROI of different fuels and the implications for society. Energy Policy 64, 141–152.

Lund H., 2009. Renewable Energy Systems: The Choice and Modeling of 100% Renewable Solutions. Academic Press, San Diego, USA.

MBIE, 2015. Electricity. <med.govt.nz/sectors-industries/energy/energy-modelling/data/electricity> accessed 26.03.2015.

McGilloway, D.A. (Ed.), 2005. Grassland: A Global Resource. Wageningen Academic Publishers, The Netherlands.

Ministry for the Environment, 2014. Greenhouse Gas reports. Climate Change Information New Zealand <climatechange.govt.nz/carbon-reports> accessed 26.03.2015.

Ministry for the Environment, 2007. Emission factors and methods 2007. Minist. Environ. <mfe.govt.nz/publications/climate/guidance-greenhouse-gas-reporting-2008-09/html/page3.html> accessed 26.03.2015.

Tan R.R., Foo D.C.Y., 2007. Pinch analysis approach to carbon-constrained energy sector planning. Energy, 32, 1422–1429.

Walmsley M.R.W., Walmsley T.G., Atkins M.J., Kamp P.J.J., Neale J.R., 2014a. Minimising carbon emissions and energy expended for electricity generation in New Zealand through to 2050. Appl. Energy, 135, 656–665.

Walmsley M.R.W., Walmsley T.G., Atkins M.J., Kamp P.J.J., Neale J.R., Chand A., 2014b. Minimising carbon emissions and energy expended for the New Zealand transport sector through to 2050, Proceedings of the 9th Conference on Sustainable Development of Energy, Water and Environment Systems, SDEWES2014-0107.