CHEMICAL ENGINEERING TRANSACTIONS
VOL. 61, 2017
A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216
DOI: 10.3303/CET1761150

Economy-Wide Carbon Emissions Pinch Analysis

Raymond R. Tan[a,*], Kathleen B. Aviso[a], Dominic C. Y. Foo[b]

[a]Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
[b]Department of Chemical and Environmental Engineering, University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Dahrul Ehsan, Malaysia
raymond.tan@dlsu.edu.ph

Carbon Emissions Pinch Analysis (CEPA) was first introduced for carbon-constrained energy planning purposes. Since its inception, CEPA has been modified to apply to various systems at different scales, utilized in different geographic contexts, and extended through the use of alternative sustainability metrics or footprints. In this paper, CEPA is further extended to economy-wide systems where the segments of composite curves are comprised of sectors in a national or regional economy. This approach uses input-output analysis (IOA) to calculate carbon footprints of major sectors per unit of economic value; these are then subjected to pinch analysis using established CEPA methodology. The methodology is shown to yield important insights for carbon management by means of a case study using Philippine statistical data.

1. Introduction

Climatic impacts induced by human activity are believed to have already exceeded safe limits (Rockström et al., 2009). As a result, significant scientific research efforts have focused on developing metrics based on life cycle concepts to enable planetary-scale sustainability issues to be considered in decision-making at the practical level of individual firms or industrial plants (De Benedetto and Klemeš, 2009). The development of many such footprint-based metrics is described in a review paper by Čuček et al al. (2012). Process Integration (PI) methodology, which was originally developed to optimize heat recovery in industrial plants (Linnhoff et al., 1982) has proven to be an important engineering strategy for reducing carbon emissions due to the reduction in fuel use (Dhole and Linnhoff, 1993). Diversification of PI methodology and applications to a wide range of domains is documented in a handbook dedicated to this subject matter (Klemeš, 2013); furthermore, prospects for further extensions have been discussed in a recent paper (Tan et al., 2015a).

Carbon Emissions Pinch Analysis (CEPA) was first proposed by Tan and Foo (2007) for macro-scale energy planning problems. CEPA methodology has been applied to the analysis of energy systems in the Philippines (Foo et al., 2008), Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010), India (Krishna Priya and Bandyopadhyay, 2015), USA (Walmsley et al., 2015a) and China (Jia et al., 2016), among others. The methodology itself has also been extended towards other sustainability metrics, such as land footprint (Foo et al., 2008) or water footprint (Tan et al., 2009). In addition, methodological variations such as algebraic instead of graphical implementation have been proposed (Shenoy, 2010). The underlying foundations of different equivalent graphical and algebraic techniques were discussed by Bandyopadhyay (2015). Francisco et al. (2014) developed a method for simultaneous targeting and network synthesis in carbon-constrained energy planning problems. An attempt to extend CEPA to planning problems with multiple sustainability indicators was recently published (Jia et al., 2016); the use of an aggregate weighted sustainability indicator was then developed by Patole et al. (2016). Segregated targeting was proposed by Lee et al. (2009), with rigorous proof of optimality being given in a subsequent paper (Bandyopadhyay et al., 2010). Furthermore, the methodology has been applied to energy systems at different scales, such as process plant level (Tjan et al., 2010), industrial park level (Jia et al., 2009) and economic sector level (Walmsley et al., 2015b). Integration of CEPA with economic aspects has been considered by Tan et al. (2015b), while temporal aspects were first considered in an approach developed by Atkins et al. (2010), which was later applied to long-term analysis of

Please cite this article as: Tan R.R., Aviso K.B., Foo D.C.Y., 2017, Economy-wide carbon emissions pinch analysis, Chemical Engineering Transactions, 61, 913-918 DOI:10.3303/CET1761150

New Zealand’s emissions by Walmsley et al. (2014). A comprehensive review of literature related to CEPA is given by Foo and Tan (2016).

One limitation of current CEPA methodology is the inability to link emissions reduction to demand-side considerations. Thus, in this work, an improved methodology for economy-wide carbon emissions analysis and planning is developed by linking CEPA with Input-Output Analysis (IOA). The latter is a modelling framework developed by Leontief (1936) that uses linear algebra to describe supply chain linkages in economic networks. Such linkages are essential for computing life-cycle based metrics such as carbon footprint (Heijungs and Suh, 2002). This combined CEPA and IOA methodology allows PI principles to be applied to the analysis of economic networks at urban, regional or national scales. The rest of this paper is organized as follows. Section 2 gives a brief overview of the IOA framework. Section 3 then describes the proposed methodology, which is illustrated with a case study based on the Philippines in Section 4. Finally, conclusions and prospects for future work are given.

2. Input-Output Analysis (IOA) Framework

Input-Output Analysis (IOA) is a modelling framework that was first developed by Leontief (1936) to describe interactions of components of an economic system using a system of linear equations. Although the conventional application of the framework is for economic analysis at the national or regional scale, the IOA framework can potentially be used at different scales provided fundamental assumptions are satisfied. For example, Jia et al. (2014) developed an approach using an enterprise-scale IOA model in conjunction with Pinch Analysis (PA) to identify pollution prevention measures. IOA methodology is also closely related to the mathematical structure of Life Cycle Assessment (LCA) as described by Heijungs and Suh (2002). A comprehensive tutorial discussion of IOA principles can be found in the textbook by Miller and Blair (2009). The general IOA model is given by Eq(1):

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{1}$$

where **A** is the technical coefficient matrix, **x** is the total output vector and **y** is the final output (i.e., consumer demand) vector. The rows and columns of **A** are homogeneous economic sectors (e.g., power generation), each of which corresponds to a unique product (e.g., electricity). The coefficients of **A** give relevant input-output ratios that characterize production technologies (e.g., fuel requirement per unit of electricity produced). In conventional IOA models, these coefficients are usually reflected in terms of ratios of monetary values, but in principle the modelling framework can also use physical ratios. It is assumed that such coefficients are fixed because they reflect a given state of technology, which in turn can reflect underlying thermodynamic or stoichiometric principles. Each element of **x** gives the total output produced by its corresponding sector (e.g., total electricity generated), while each element of **y** gives the net output consumed to satisfy final demand (e.g., electricity used by households). Note that the sum of the elements of **y** is the Gross Domestic Product (GDP) of the economic system. The difference between corresponding elements of **x** and **y** give the intermediate demand (e.g., electricity used as an industrial input for manufacturing). Eq(1) can be rewritten as:

$$(\mathbf{I} - \mathbf{A})\,\mathbf{x} = \mathbf{y} \tag{2}$$

where **I** is the identity matrix. Furthermore, Eq(2) may be solved by matrix inversion:

$$(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{x} \tag{3}$$

where $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief inverse. This basic form of the IOA model describes supply chain linkages in an economic system or network via a relatively simple set of equations. This basic model can be extended to reflect environmental flows such as CO_2 by including a linear equation for material balances corresponding to emissions:

$$\mathbf{b}^{T}\mathbf{x} = z \tag{4}$$

where **b** is the vector of direct sector emissions, T signified a transposition operation, and *z* is a scalar quantity giving the total CO_2 emissions of the economic system. Combining Eq(3) and Eq(4) then gives:

$$\mathbf{b}^{T}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = z \tag{5}$$

Eq(5) provides no further information on the contributors to total CO_2 emissions. Hence, the carbon footprint corresponding to final demand or net output of each sector can be determined separately from other sectors using:

$$\mathbf{b}^{T}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y} = \mathbf{z}^{T} \tag{6}$$

where **Y** is the square matrix whose diagonal elements are the elements of **y**, and whose non-diagonal elements have values of zero, and **z** is the carbon footprint vector. The model corresponding to Eq(6) allows emissions arising from upstream supply chain linkages to be accounted for using LCA principles. For example, the carbon footprint of electricity should be accounted for when calculating the carbon footprint of any product that requires electricity inputs in its production.

3. Methodology

There has been limited application of IOA methodology and graphical visualization methods for carbon emissions reduction. Tahara et al. (2005) proposed a methodology with which firms can benchmark their own emissions intensity performance with industry average values derived from national-scale IOA data. An important contribution of their methodology is the identification of internal (i.e., on-site) and external (i.e., upstream via supply chain) components of carbon footprint. This methodology was later extended and linked to PI and PA by Tjan et al. (2010), who applied the methodology specifically to process plants. In this work, the proposed framework essentially involves using the IOA model described in the previous section as input into established CEPA methodology. The main steps can be summarized as follows:

- Acquire relevant economic (**A** and **y**) and environmental data (**b**).
- Calculate carbon footprint of sectors (**z**) using Eq(6).
- Use the corresponding elements of **y** and **z** as data for CEPA.
- Arrange the sectors in order of increasing carbon intensity, determined by the ratio of corresponding elements of vectors **z** and **y**.
- Plot each segment in sequence of the source composite curve on rectangular coordinates, with economic value as the horizontal axis and CO_2 emissions as the vertical axis; this step results in a composite curve that summarizes and aids in the visualization of the emissions profile of the economic system.
- The previously generated source composite curve can then be compared with an exogenously determined reference sink composite curve; for example, the latter can be deduced from nationally determined commitments to reduce CO_2 emissions intensity as part of an international agreement.

This methodology is illustrated in the next section with a case study.

4. Illustrative Case Study

This case study is based on an analysis of national CO_2 emissions in the Philippines. Official economic data from the Philippine Statistics Authority (2017) and emissions data from the Philippine Department of Energy (2017) for the year of 2006 are used here. The original data for IOA are disaggregated to the level of 70 sectors, but these are aggregated using the computational procedure described by Miller and Blair (2009) into five major sectors (i.e., Industry, Transportation, Others, Electricity and Other Energy) both for brevity and for consistency with the available emissions data. The consolidated sector labelled as “Others” includes agriculture and commercial activities. The resulting matrix **A** is given in Table 1, whose columns may be interpreted as input components into any given sector. For example, for the column corresponding to “Industry,” the entries indicate that every Philippine Peso (PhP) of industrial output on average requires PhP0.403 of industry inputs, PhP0.008 of transportation inputs, etc. (PhP60 is approximately equivalent to €1). As previously stated, these costs imply physical proportions which are in turn characteristics of the technology in use.

Table 1: Coefficients of technical coefficient matrix

	Industry	Transportation	Others	Electricity	Other Energy
Industry	0.403	0.114	0.094	0.077	0.555
Transportation	0.008	0.030	0.013	0.002	0.002
Others	0.223	0.169	0.202	0.029	0.044
Electricity	0.016	0.006	0.011	0.125	0.001
Other Energy	0.034	0.208	0.010	0.087	0.129

Table 2 shows the data used to compute the sector carbon footprints. The total output and final demand columns correspond to vectors **x** and **y**. The direct CO_2 intensity column corresponds to vector **b**, and is determined by dividing sector direct emissions statistics by the corresponding total economic output value. For example, total electrical power generation is valued at PhP0.29 trillion, and the total CO_2 emission from all power plants is 26.30 Mt, which results in an intensity of 91.21 kg/PhP. However, these values do not account for supply chain dependencies, and thus do not reflect life cycle CO_2 emissions, or the true carbon footprint. The latter value can be determined using Eq(6), which gives the resulting data in the last two columns of Table 2 (note that the sectors here have been ranked in order of ascending CO_2 intensity on a life cycle basis). It can be seen, for example, that even if total power plant emissions amount to 26.30 Mt, only 9.70 Mt is accounted for as the footprint associated with final demand of electricity by end users. The remaining 16.60 Mt are accounted for as part of the CO_2 footprint of other goods or products that consume electricity.

Table 2: Emissions intensity and carbon footprint data of key sectors

	Total Output (trillion PhP)	Final Demand (trillion PhP)	Direct CO_2 Emissions (Mt)	Direct CO_2 Intensity (g/PhP)	CO_2 Footprint (Mt)	CO_2 Intensity (g/PhP)
Others	5.9	3.34	5.08	0.86	15.52	4.65
Other Energy	0.43	0.01	0.53	1.22	0.06	6.00
Industry	5.67	2.51	9.33	1.65	21.81	8.69
Transportation	0.46	0.32	26.36	57.79	20.51	64.09
Electricity	0.29	0.09	26.3	91.21	9.7	107.78

The data in the final demand and CO_2 footprint columns of Table 2 can then be used to generate the economy-wide source composite curve for the Philippines, using the same steps described in CEPA literature (e.g., Tan and Foo, 2007). The resulting composite curve is shown in Figure 1. A diagonal line from the origin to the tip of the composite curve will have a slope that is equal to the total CO_2 intensity of the entire economy which is 10.8 g/PhP, based on a GDP of PhP6.27 trillion and CO_2 emissions amounting to 67.6 Mt. This line is shown in red in Figure 1, and acts as the sink composite curve of the system.

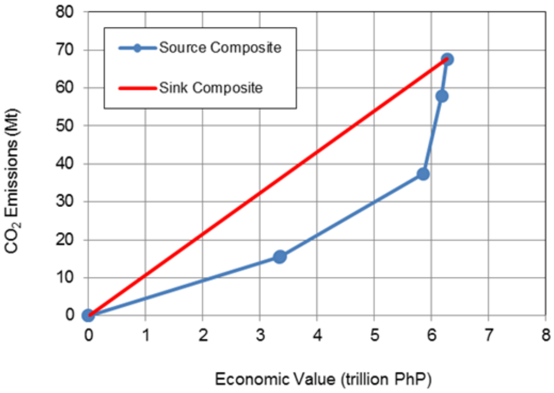

Figure 1: Composite curve of the Philippine economy

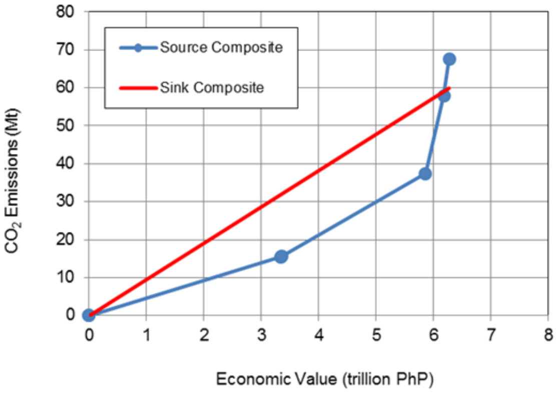

Figure 2: Composite curve of the Philippine economy with reduced CO_2 emissions

The graphical depiction of the economy-wide CO_2 emissions profile as a composite curve reveals insights that are useful for analysis and decision-making. For example, if a benchmark of 60 Mt of CO_2 emissions is assumed, corresponding to 11.2% reduction compared to the baseline level, an infeasible orientation results as shown in Figure 2. Note that the source and sink composite curves cross each other. Thus, the source composite curve can be shifted to the right until a feasible orientation is achieved, as shown in Figure 3. A magnification of the boxed region is shown on the right hand panel for clarity. It can be seen that the source composite curve needs to be shifted to the right, along a locus of slope 4.65 g/PhP (equivalent to the life cycle CO_2 intensity of the “Others” sector of the system), by PhP0.1 trillion. This shift corresponds to an increased contribution to GDP of economic activities that make up “Others” (i.e., agriculture and commercial services). At the same time, it can be seen that the segment of the source composite curve corresponding to final consumption of electricity by end users protrudes beyond the sink composite curve. This result indicates that reductions need to focus on end-use electricity conservation measures in households (e.g., through increased use of efficient electrical appliances). Similar analysis can be done using a different sink composite curve. For example, alternative benchmarks for analysis can include other countries, or regional clusters of countries.

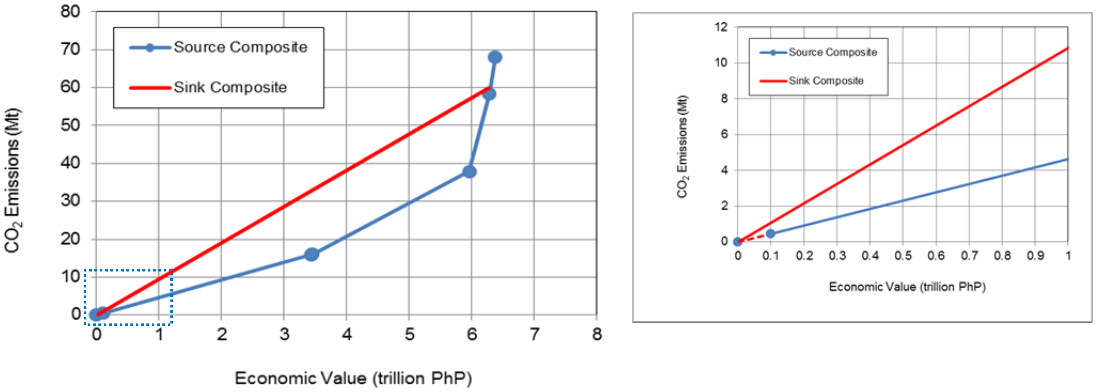

Figure 3: Adjusted composite curve of the Philippine economy based on emissions of 60 Mt, with magnified view shown on the right

5. Conclusions

In this paper, an approach to economy-wide CEPA has been developed. This methodology uses IOA to compute the carbon footprint of economic sectors (or their corresponding products), and this data is then used as an input into CEPA. Using a case study based on Philippine data, the methodology is shown to provide useful insights for determining how carbon emissions intensity can be reduced. The methodology itself is applicable at smaller (e.g., city or region level) or larger (e.g., content level) scales. In the future, such approaches can be further scaled down to process plant, enterprise or supply chain levels. Changes in sector carbon intensities (e.g., shift to more renewables for power generation) can also be reflected through changes in the shape of the composite curves. In addition, the methodology can also be linked to other methodologies such as mathematical programming.

References

Atkins, M. J., Morrison, A. S. and Walmsley, M. R. W., 2010, Carbon Emissions Pinch Analysis (CEPA) for emissions reduction in the New Zealand electricity sector, Applied Energy, 87, 982-987.

Bandyopadhyay, S., Sahu, G. C., Foo, D. C. Y., Tan, R. R., 2010, Segregated Targeting for Multiple Resource Networks Using Decomposition Algorithm, AIChE Journal, 56, 1235 – 1248.

Bandyopadhyay, S., 2015, Mathematical foundation of Pinch Analysis, Chemical Engineering Transactions 45, 1753-1758.

Crilly D., Zhelev T., 2008, Emissions targeting and planning: An application of CO2 emissions pinch analysis (CEPA) to the Irish electricity generation sector, Energy, 33, 1498-1507.

Čuček, L., Klemeš, J. J., Kravanja, Z., 2012, A Review of Footprint analysis tools for monitoring impacts on sustainability, Journal of Cleaner Production 34, 9-20.

De Benedetto, L., Klemeš, J. J., 2009, The Environmental Performance Strategy Map: an integrated LCA approach to support the strategic decision-making process, Journal of Cleaner Production, 17, 900-906.

Department of Energy. Key Energy Statistics 2009 (https://www.doe.gov.ph/key-energy-statistics-2009, accessed on January 31, 2017).

Dhole, V. R., Linnhoff, B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers & Chemical Engineering, 17, S101-S109.

Foo, D. C. Y., Tan, R. R., Ng, D. K. S., 2008, Carbon and Footprint-Constrained Energy Sector Planning Using Cascade Analysis Technique, Energy, 33, 1480-1488.

Foo, D. C. Y., Tan, R. R. 2016. A review on process integration techniques for carbon emissions and environmental footprint problems. Process Safety and Environmental Protection, 103, 291-307.

Franciso, F. D. S., Pessoa, F. L. P., Queiroz, E. M., 2014, Carbon sources diagram – A tool for carbon-constrained energy sector planning, Chemical Engineering Transactions, 39, 1495-1500.

Heijungs, R., Suh, S., 2002, The Computational Structure of Life Cycle Assessment, Springer, Dordrecht, Netherlands.

Jia X. P., Liu H. C., Qian Y., 2009, Carbon Emission Pinch Analysis for Energy Planning in Chemical Industrial Park, Modern Chemical Industry, 29, 81-85.

Jia, X., Li, Z., Wang, F., Foo, D. C. Y., Tan, R. R., 2016, Multi-Dimensional Pinch Analysis for Power Generation Sector in China, Journal of Cleaner Production, 112, 2756-2771.

Jia, X. P., Li, Z., Wang, F., Foo, D. C. Y., Tan, R. R., 2015, Integrating input-output models with pinch technology for enterprise sustainability analysis, Clean Technologies and Environmental Policy, 17, 2255-2265

Klemeš, J. J., ed., 2013, Handbook of Process Integration (PI): Minimisation of Energy and Water Use, Waste and Emissions, Elsevier/Woodhead, Cambridge, UK.

Krishna Priya G.S., Bandyopadhyay S., 2013, Emission constrained power system planning: A pinch analysis based study of Indian electricity sector, Clean Technologies and Environmental Policy,15, 771-782.

Lee, S. C., Ng, D. K. S., Foo, D. C. Y., Tan, R. R. 2009, Extended Pinch Targeting Techniques for Carbon-Constrained Energy Sector Planning, Applied Energy, 86, 60-67.

Leontief, W., 1936, Quantitative input and output relations in the economic system of the United States. Review of Economics and Statistics, 18, 105-125.

Miller R. E., Blair P. D., 2009, Input-output Analysis: Foundations and Extensions, 2nd ed., University Press, Cambridge, UK.

Patole, M., Tan, R. R., Bandyopadhyay, S., Foo, D. C. Y., 2016, Pinch analysis approach to energy planning using weighted composite quality index, Chemical Engineering Transactions, 52, 961-966.

Philippine Statistics Authority, 2006, Input Output Tables of the Philippines (https://psa.gov.ph/content/2006-input-output-tables-philippines, accessed on January 31, 2017)

Rockström J., Steffen W., Noone K., Persson A., Chapin F. S., Lambin E. F., Lenton T. M., Scheffer M., Folke C., Schellnhuber H. J., Niykvist B., De Wit C. A., Hughes T., Van der Leeuw S., Rodhe H., Sorlin S., Snyder P. K., Constanza R., Svedin U., Falkenmark M., Karlberg L., Corell R. W., Fabry V. J., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J. A., 2009, A safe operating space for humanity, Nature, 461, 472-475.

Shenoy U. V., 2010, Targeting and design of energy allocation networks for carbon emission reduction. Chemical Engineering Science, 65, 6155-6168.

Tahara K., Sagisaka M., Ozawa T., Yamaguchi K., Inaba, A., 2005, Comparison of “CO2 Efficiency” Between Company and Industry, Journal of Cleaner Production, 13, 1301-1308.

Tan, R. R. and Foo, D. C. Y., 2007, Pinch Analysis Approach to Carbon-Constrained Energy Sector Planning. Energy, 32, 1422-1429.

Tan, R. R., Foo, D. C. Y., Aviso, K. B., Ng, D. K. S., 2009, The Use of Graphical Pinch Analysis for Visualizing Water Footprint Constraints in Biofuel Production, Applied Energy, 86, 605-609.

Tan, R. R., Bandyopadhyay, S., Foo, D. C. Y., Ng, D. K. S., 2015a, Prospects for novel Pinch Analysis application domains in the 21st Century, Chemical Engineering Transactions, 45, 1741-1746.

Tan, S. T., Ho, W. S., Hashim, H., Lim, J. S., Lee, C. T., 2015b, Waste Management Pinch Analysis (WAMPA) with Economic Assessment, Chemical Engineering Transactions, 45, 145-150.

Tjan, W., Tan, R. R., Foo, D. C. Y., 2010, A Graphical Representation of Carbon Footprint Reduction for Chemical Processes, Journal of Cleaner Production, 18, 848-856.

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

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J. 2015a. Achieving 33% renewable electricity generation by 2020 in California, Energy, 92, 260-269.

Walmsley, M. R. W., Walmsley, T. G., Atkins, M. J., Kamp, P. J. J. and Neale, J. R., and Chand, A., 2015b, Carbon Emissions Pinch Analysis for emissions reductions in the New Zealand transport sector through to 2050, Energy, 92, 569-576.