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Dynamic Evaluation of the Economic and Environmental Impact of Resource Depletion for a New Chemical Project

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The availability of abiotic resources is still critical to the rapidly growing human population, and rising living standards. Standard methodologies are needed to account for the depletion of resources. Some of the methods for resource depletion evaluation consider replacement of a scarce resource with an alternative resource but do not consider a time frame for the same. However, resource substitution is decided by several factors such as resource costs and price elasticity of demand, which are dynamic. Moreover, the existing methods do not consider a driving force for the replacement to occur and do not analyse the long-term consequences of resource scarcity. In this paper, a dynamic resource depletion methodology is proposed, and it has been applied to a case study of natural gas scarcity in New Zealand. A system dynamics model predicts the gas price and the rates of gas consumption over an extended period. The potential impacts are quantified using life cycle assessment (LCA) and are further aggregated into a resource depletion indicator that is based on environmental economics and decision-making perspectives for the environment. The wider economic and environmental impacts that are a result of a new chemical plant during a period of gas shortage are evaluated. With the functioning of the new plant, it was found that the rate of potential gas scarcity accelerated, leading to an increase in wider economic and environmental impacts. The discounted greenhouse gas (GHG) emissions increased by 21 %, 30 % and 36 % for the individualist, hierarchist and egalitarian perspectives.

1. Introduction

The survival of humankind depends on the resources provided by nature. However, increased consumption of such resources will lead to their faster depletion, rendering such resources unavailable for future generations. The most commonly used methods for evaluation of abiotic resource depletion are within the framework of life cycle assessment (LCA) (Steen, 2006). The existing indicators for resource depletion evaluation, within the framework of LCA, can be classified as (a) based on simple summation of resources based on mass or energy (Steen, 2006), (b) based on remaining reserves or annual resource extraction rates (Adibi et al., 2017), (c) based on resource characteristics such as exergy consumption (Guinee and Heijungs, 1995) and (d) based on damage to the future resource extractions (Klinglmair et al., 2014). However, these methods do not evaluate the consequences of resource depletion. Most of these evaluation methods quantify the damage in terms of extra energy or extra cost of future resource extractions, beyond the fact that, there would be reduced availability of resources (Klinglmair et al., 2014). An alternative measure of resource depletion, which is based on impact analysis, was developed by Rimos et al. (2014). According to this approach, in case of resource scarcity, the best available resource is substituted, and the resulting impacts are quantified. However, Rimos et al. (2014) does not consider the specific driving force for resource substitution to occur; nor the timeframe over which it develops.

The aim of this study is to address the above research gaps by developing a dynamic resource depletion indicator. In this paper, the consequence analysis methodology that is proposed by Rimos et al. (2014) is extended by using a dynamic assessment framework that is coupled with market dynamics. In addition, the potential economic and environmental consequences of an accelerated rate of resource consumption are also evaluated.

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2. Research methodology

An outline of the proposed methodology is shown in Figure 1. In this paper, the applicability of the dynamic resource depletion methodology is assessed by using natural gas as a case study. A gas supply model forecasts the decline rates for different gas fields. A system dynamics model predicts the gas demand resulting from a gas shortage, for which the gas supply is given as an input. The predicted gas demand is used to estimate the environmental impacts using LCA, along with scenario studies. LCA has been widely used in the literature for evaluating the environmental impacts of chemical processes (Castaño et al., 2015). The impacts are further aggregated into a resource depletion indicator based on discounting and decision-making perspectives, namely the individualist, hierarchist and egalitarian approaches, for the environment.

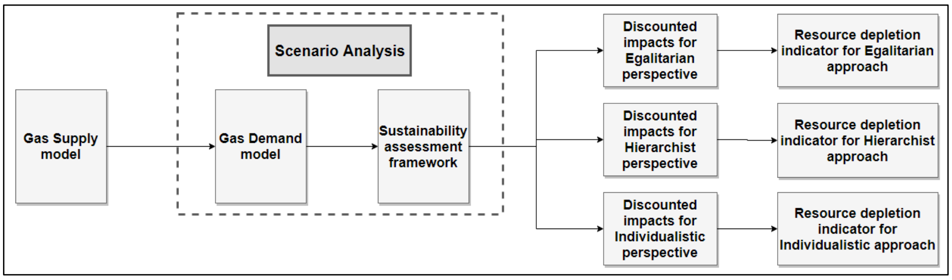

Figure 1: Block diagram showing the proposed research methodology

2.1 Case study of resource depletion

To study a realistic example of resource depletion, the case of New Zealand is selected, because it had already experienced gas scarcity. New Zealand is largely dependent on natural gas in several sectors such as power generation, petrochemicals production and space heating (MBIE, 2016). In New Zealand, natural gas was first commercially discovered at the Kapuni field in 1959, and the largest offshore gas field was discovered at Maui in 1969 (Gas Industry Company, 2016). However, the production at the Maui gas field reached its peak in the year 2001 following which the field started declining (MBIE, 2016). This led to short-term gas scarcity in the country for a period of five years. However, the gas scarcity was met by the development of new gas fields at Pohokura and Kupe (Levin and Duncan, 2011).
The New Zealand case study considers five different gas consuming sectors, such as electricity, commercial, residential, petrochemicals and other industry sectors. The gas that is consumed by the transportation, fishing and forestry sectors is not included in this study.

2.2 Gas supply model

The objective of this model is to forecast the occurrence of gas scarcity, by capturing the gas production decline trend. The concept of decline curve analysis has been widely used in the literature to predict the depletion behaviour of oil and gas fields (Hook, 2014). Based on the nature of production decline in different gas fields, the fields are modelled either by using the Hubbert decline model or the hyperbolic model. For new gas fields that are yet to reach the peak, the gas has been assumed to peak in the year 2016. The model is formulated based on regression analysis using historic gas production for different fields. The general form of the Hubbert's model and the hyperbolic decline model is shown in Eq(1) and Eq(2).

$$y(t) = 2y_P /(1+\cosh(m.(t-t_P))) \quad (1)$$

$$y(t) = k_0.[1+ab.(t-t_0)]^{-1/b} \quad (2)$$

In presented equations y(t) is the gas production rate at time t and y_P is the gas production at the peak year. k_0 stands for the initial gas production rate. The peak year is denoted by t_P. The parameters a and b represents gas production decline rate and model fitting coefficient, respectively.

2.3 Gas demand model

The aim of this model is to determine the gas consumption rates for different users in New Zealand. This model is defined based on the nature of causality between net rate of gas production, wholesale gas price and rates of sector gas consumption. Balanced production and consumption of gas is set as a constraint. Gas consumption is a function of gas price for the elastic sectors (electricity and petrochemicals), while it is a function of gas price and the market size for the inelastic sectors (residential, commercial, and other industries). The market size of the other industries sector is a function of the production growth rate for the dairy industry, while the market size for the residential and commercial sectors is a function of the population growth rate. Since there is no gas supply in the South Island, only the population growth for the North Island has been considered (Gas Industry Company, 2016). The resulting gas demand model is represented by Eq(3) to Eq(9).

$$dP/dt = k_1.(C_E + C_P + C_R + C_I + C_C - Q) \quad (3)$$

$$dC_E/dt = - k_2.dP/dt \quad (4)$$

$$dC_P/dt = - k_3.dP/dt \quad (5)$$

$$dC_R/dt = - k_4.dP/dt + k_5.\dot{M}_R \quad (6)$$

$$dC_I/dt = - k_6.dP/dt + k_7.\dot{M}_I \quad (7)$$

$$dC_C/dt = - k_8.dP/dt + k_9.\dot{M}_C \quad (8)$$

$$C_E + C_P + C_R + C_I + C_C = Q \quad (9)$$

Here, Q is the gas produced from all the fields and P is the wholesale gas price. The gas consumed by the electricity, residential, commercial, petrochemicals, and other industry sectors is denoted by C_E, C_R, C_C, C_P and C_I, respectively, while $\dot{M}_R$, $\dot{M}_I$ and $\dot{M}_C$ stand for the rate of market growth for residential, commercial and other industry sectors. The sensitivity coefficients of the model are represented by k.

2.4 Impact assessment

The predicted gas consumption rates from the gas demand model are used to calculate the environmental impacts using the LCA-based methodology. The system boundary for LCA includes gas extraction, processing and pipeline transportation for the upstream section. The downstream section considers the use phase of gas for electricity generation, residential heating and petrochemicals production. The inventory data is taken from the EcoInvent database (version 3.3) for the RoW (Rest-of-the-World) category. The impacts are calculated by using the ReCiPe 2008 method (Goedkoop et al., 2008). A key benefit of the ReCiPe method when compared with the other methods is the availability of wide range of midpoint impact categories (Cespi et al., 2014).

2.5 Scenario analysis

The proposed methodology is used to analyse different scenarios within New Zealand. These scenarios are briefly discussed here.

Scenario 0: Base case scenario

In this scenario, the users would continue gas consumption up to a situation of shortage. During the gas scarcity period, the sectors would adjust the consumptions based on their needs.

Scenario 1: New fertiliser plant scenario

This scenario investigates the potential impacts of a new urea plant on the wider New Zealand economy and the wider environmental performance. New Zealand is a net importer of urea largely from China and the Middle East (MPI, 2012) to support its agricultural economy. This scenario aids in the understanding of the competition among the different gas sectors.

At present, there is only a single urea manufacturing facility, owned by Balance Agri-Nutrients Limited, in New Zealand with a production capacity of 265 kt/y (MPI, 2012). In this study, a large urea plant is considered to meet the growing demand for urea in New Zealand. The proposed facility would have a urea production capacity of 2,200 kt/y and would operate for at least ten years.

2.6 Proposed dynamic indicator

In this paper, a dynamic resource depletion indicator is proposed based on the principle of environmental discounting. Discounting allows for the comparing of possible future damages with the current ones by rating them differently (Hellweg et al., 2003). The concept of discounting has been coupled with decision-making perspectives. According to the cultural perspective theory, there are three major ways of valuing the environment: the individualist, hierarchist and egalitarian approaches. These approaches have their own views for the environment. The individualist believes that nature is robust; the hierarchist believes that nature is tolerant up to a certain extent, while the egalitarian believes that nature is vulnerable.

In this study, the year 2016 is taken as the base year for discounting. The discount rates are decided based on the literature (Hellweg et al., 2003). A discount rate of +5 %, 0 % and -5 % is considered for the individualist, hierarchist and egalitarian perspectives, respectively. The environmental impact indicator is the ratio of the summation of discounted annual environmental impacts to the summation of discounted annual gas consumed (in terms of energy or mass), while, the economic impact indicator is the ratio of the summation of discounted annual wholesale gas price to the summation of discounted annual gas consumed.

3. Results and discussion

The formulated gas demand model was simulated in MATLAB® software, for which the forecasted gas supply was given as an input. The model results were further used as an input for LCA and scenario analysis.

3.1 Results of the gas supply model

The model-predicted gas production decline trend for the New Zealand system is shown in Figure 2. According to the forecast, the gas would be almost depleted by the year 2040.

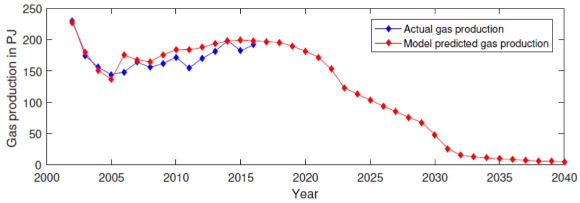

Figure 2: Comparison of historical and forecasted gas production for the New Zealand system

3.2 Model-forecasted results for the future

The competition among the different gas users starts increasing when the new fertiliser plant comes into operation. In the base case scenario, the gas price increases after 2030 due to the declining gas fields. However, in the scenario that involves a new fertiliser plant shown in Figure 3, a sudden increase in gas price from 7.1 to 9.4 NZ$ per GJ occurs in the year 2021, which occurs much earlier than it does in the base case scenario. The commencement of the new urea plant, shown in Figure 4(b), forces the different gas consuming sectors to reduce their gas consumption.

Since the residential users, shown in Figure 5(a), are one of the badly impacted sectors, they would reduce their gas dependency much earlier than they do in the base case scenario, as it becomes unaffordable.

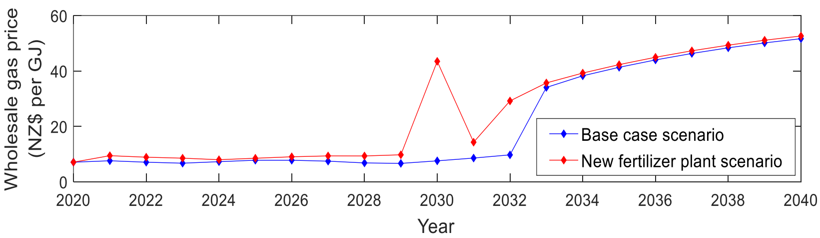

Figure 3: Comparison between model-predicted wholesale gas prices for the scenarios

The reduced availability of gas in 2030 causes the gas price to increase by almost five times to 43.47 NZ$ per GJ. However, once the new urea plant shuts down, the wholesale gas price decreases in 2031. This increases the affordability of gas and the different users continue consuming gas, as shown in Figure 5.

However, as the gas availability starts declining in the year 2031, the different sectors again have to readjust their consumptions accordingly.

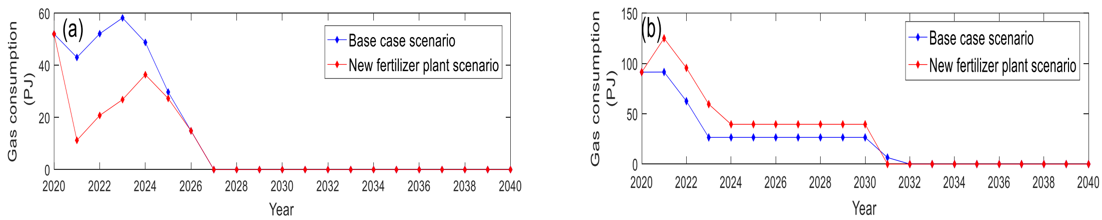

Figure 4: Comparison of model-predicted gas consumption rates for the (a) electricity sector and (b) petrochemical sector

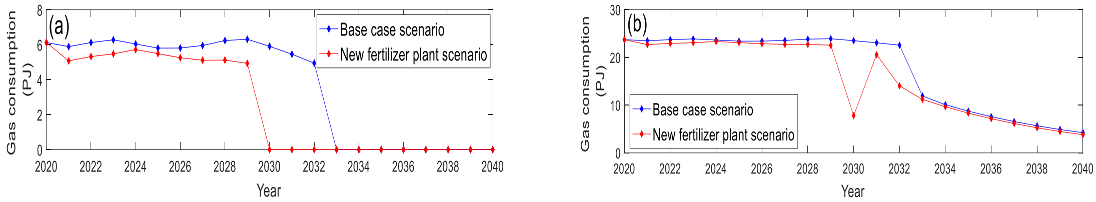

Figure 5: Comparison of model-predicted gas consumption rates for (a) the residential sector and (b) the other industry sectors

3.3 Results of the economic impact assessment

The discounted gas price, which is shown in Figure 6, increases in the scenario that involves a new fertiliser plant when compared with the base case scenario. The increase is 18 %, 21 % and 23 % for the individualist, hierarchist and egalitarian perspectives.

The operation of the new urea plant during the period of gas scarcity causes the wholesale gas price to increase. It was found that the economic impact is the highest under the egalitarian perspective for both the scenarios. This is because the individualist focuses only on the present, while the egalitarian stresses more on the future. As the prices are forecasted to increase only in the future during the period of gas shortage, the egalitarians, therefore, would be paying the highest price.

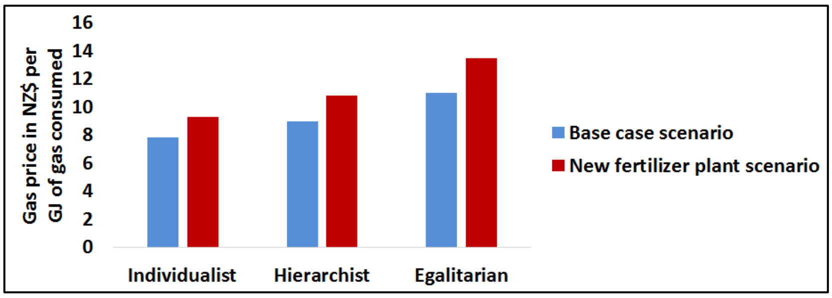

Figure 6: Comparison of economic impact indicators based on decision-making perspectives

3.4 Results of the environmental impact assessment

The environmental impacts, shown in Figure 7, are highest for the acidification potential and the ozone depletion potential under the egalitarian perspective. This is because egalitarians, based on the principle of discounting, give more importance to the future than the present. As the impacts are higher in the future due to the functioning of the new urea plant, the emissions would be accordingly highest for the egalitarian perspective. However, it is found that the trend gets reversed in the case of global warming potential, shown in Figure 8, with the highest impacts under the individualistic approach.

This is because of the significant amount of methane and nitrous oxide emissions during the upstream processing of gas and the related downstream uses. When compared with carbon dioxide, both methane and nitrous oxide have a short lifetime in the atmosphere and the related emissions occur during the first few years. As the individualists consider a time frame of 20 y for impact assessment, the related impacts are also the highest for individualists.

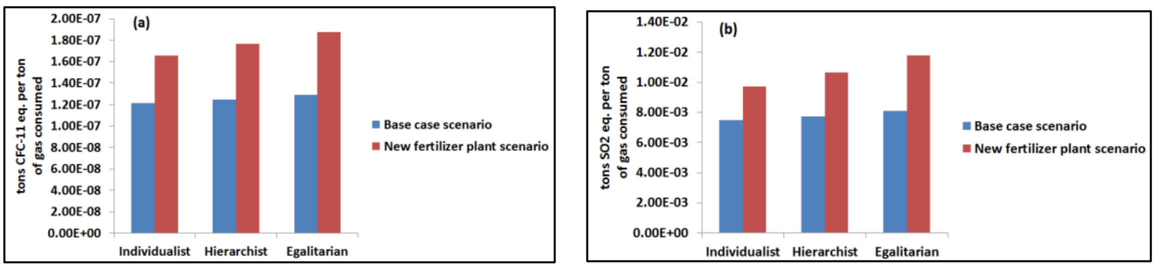

Figure 7: Comparison of discounted (a) ozone depletion potential and (b) acidification potential results based on different decision-making perspectives

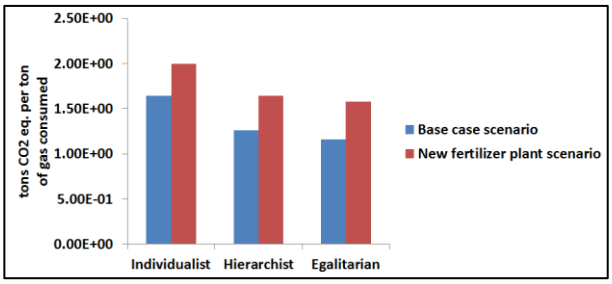

Figure 8: Comparison of discounted global warming potential results based on decision-making perspectives

4. Conclusions

In this paper, a dynamic resource depletion methodology is proposed and it has been applied to a case study of gas shortage in New Zealand. The wider economic and environmental impacts of the operation of a new chemical plant during the period of gas shortage have been quantified. With the functioning of the new urea plant, the discounted wholesale gas price increased by 18 %, 21 %, and 23 % for the individualist, hierarchist, and egalitarian perspectives, while, the discounted greenhouse gas (GHG) emissions increase by 21 %, 30 % and 36 % for the individualist, hierarchist and egalitarian perspectives. It can be concluded that, with the functioning of the fertiliser plant, the potential gas scarcity accelerates, and the related impacts become larger. The dynamic resource depletion methodology can be used by decision-makers to assess the way the consequences of resource shortage are likely to impact both the wider economy and the environment.

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