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Effect of ash on coal direct chemical looping combustion

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Abstract: Although major coal deposits are of high ash content, chemical loop combustion (CLC) technology for these coals are yet to be perfected. Thus, to evaluate the effect of ash on CLC process, a CFD model which incorporates both fuel and air reactors and their inter-connecting parts of a given pilot plant has been developed. The model results for sub-bituminous coal and metallurgical coke for CLC process have been validated against the published data within an error band of ±7–14%. The validated model is then used for two high ash content coals designated as A and B. Simulated results show that fuel conversions for A and B, are 93.8% and 87.79% respectively and that purity of CO_2 in fuel reactor exhaust are 89.12% and 90.73%. It is further observed that, ash components such as CaO, Fe_2O_3 exhibit significant reactivity at the operating conditions, whereas, it is negligible for SiO_2.

Keywords: high ash content coal; chemical looping combustion; CFD simulation.

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1 Introduction

The rising trend of energy usage and amount of CO_2 in atmosphere exceeding 400 ppm mark has created an alarming situation and thus provides required impetus for the development of clean energy processes. Power generation through renewable energy sources like solar, wind and geothermal appears to be promising; however, it is still a distant dream that these resources can meet the present energy demand. Further, nuclear energy, due to its constraints related to safety and spent fuel management, also creates impediment in its development and full use. The challenges offered by above energy resources are shifting the pressure towards the use of fossil fuel to meet the recent energy demands though, its depleting quality is a matter of concern and offering increased challenges in terms of its pre- and post-treatment (BP, 2013; U.S. Department of Energy, 2006).

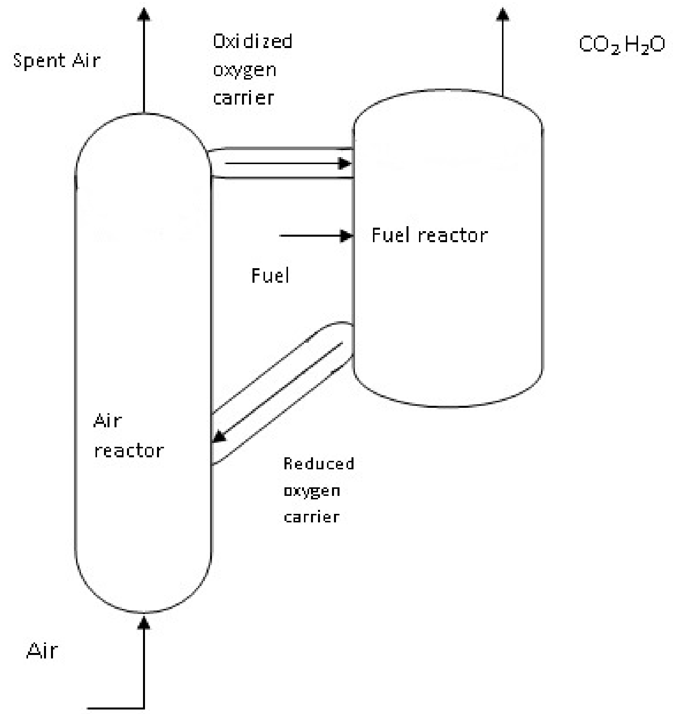
Further, secured availability of coal for around 200 years and its cost being marginally increasing with time unlike other fossil fuels, it appears to be a suitable fuel material for meeting present and future energy demands. However, as observed by Mauna Loa Observatory, the recent atmospheric CO_2 level has touched an alarming level of 400 ppm mark making it mandatory to develop clean, sustainable energy technologies for coal which can reduce CO_2 emission by capturing it in-situ. As chemical looping combustion is one such technology, a considerable amount of effort has been directed towards the development of this technology. Chemical looping process produces sequestration ready exhaust gases which mainly comprises of water and carbon dioxide from which water can be easily separated by the process of condensation.

Various simulation based investigations have been carried out on individual segments of the above process such as riser, fuel reactor, air reactor, etc. One such CFD based study is examined by Deng et al. (2008) on reaction kinetics of chemical looping combustion for fuel reactor only using FLUENT. They studied the effect of particle diameter, gas flow rate and bed temperature on fuel conversion. Further, a three-dimensional CFD model for circulating fluidised bed fuel reactor has been developed by Wang et al. (2013) using solid coal as a fuel and ilmenite ($FeTiO_3$) as an oxygen carrier. However, they have only evaluated the effect of operating variables on the fuel conversion of the fuel reactor. Furthermore, Wang et al. (2011) developed a three dimensional numerical model for reactions between coal gas as fuel and cuprous oxide on alumina as an oxygen carrier for fuel reactor only considering kinetic theory of granular flow and analysed the effects of the operating conditions such as bed height, bed temperature and operating pressure on fuel conversion. Though, Kruggel-Emden et al. (2010) conducted an interconnected multiphase CFD simulation study of chemical looping combustion using methane as fuel and Mn_3O_4 supported on $Mg\text{-}ZrO_2$ as oxygen carrier for two separate systems, where bubbling fluidised bed is used for fuel reactor and riser as air reactor, their study did not included the interaction between the two reactors. In the absence of actual interaction study, they considered a time dependent mass exchange between these two reactors through inlet and outlet boundary conditions only.

Though, a considerable work has been carried out in the field of chemical looping, there appears to be substantive gap related to CFD based study of the complete process which incorporates the flow of material through fuel reactor, air reactor and their inter-connecting parts simultaneously to incorporate interaction between various parts of the process. To bridge the above gap, the present CFD simulation is carried out for a 25 kW_{th} complete pilot plant developed at Ohio State University, USA and discussed by

Kim et al. (2013). They have discussed and reported the design criteria and operating conditions of the pilot plant wherein, two fuels namely sub-bituminous coal (SBC) and metallurgical coke (MC) have been used, one at a time, with iron (III) oxide supported on alumina as an oxygen carrier. They have considered eleven reactions that are taking place inside the fuel reactor and air reactor and their inter-connecting parts. A search in this regard, however shows that, they did not consider a few significant reactions for this purpose and neglected the effect of ash in the reactions. In the present work the CFD model is first verified against the reported results of the pilot plant data for the fuels SBC and MC. The model predicted values of fuel conversions for SBC and MC are 95.39% and 87.07% respectively while; the literature reported values are 97% and 81%. Furthermore, the predicted purities of CO_2 in fuel reactor exhaust streams are 90.19% and 92.57% while; the reported values are 99.8% and 99.6% respectively for SBC and MC. After the validation of the present model, it is applied on two coals found in the region of Asia-Pacific and Australia having high ash content designated as A and B respectively.

Figure 1 Process overview



In the chemical looping process, as proposed by Lewis and Gilliland (Fan, 2010), a carbonaceous fuel like natural gas, methane, coal, biomass, etc. first reacts in a fuel reactor with a metal oxide oxygen carrier such as iron oxide, nickel oxide, copper oxide, etc.. After reaction, this metal oxide gets reduced to metal and subsequently oxidises the carbon present in the carbonaceous fuel. The above reaction yields carbon dioxide and steam as products from which carbon dioxide can readily be separated by removing steam through the process of condensation. The reduced metal received from the fuel reactor is oxidised in the air reactor for its regeneration to metal oxide, which is then recycled back to the fuel reactor for reuse. The above discussed cyclic process is shown in Figure 1.

2 Problem description

Geometrical parameters of a 25 kW_{th} pilot plant developed by Ohio State University, USA and described by Kim et al. (2013) have been considered for the present CFD simulation. The pilot plant geometry, taken from the dissertation (Wadhwani, 2014), is shown in Figure 2 with dimension of different section in Table 1. Two different types of coal namely A and B having high ash contents are used one at a time in the pilot plant with iron (III) oxide as an oxygen carrier (Kim et al., 2013). Both coal samples have been selected in such a way that these depict average composition in the range of compositions for coal and ash shown in Figures 3 and 4. These figures cover overall variation in the components of coal found in the reserves of Asia-Pacific and Australia regions.

Figure 2 Pilot plant of present problem

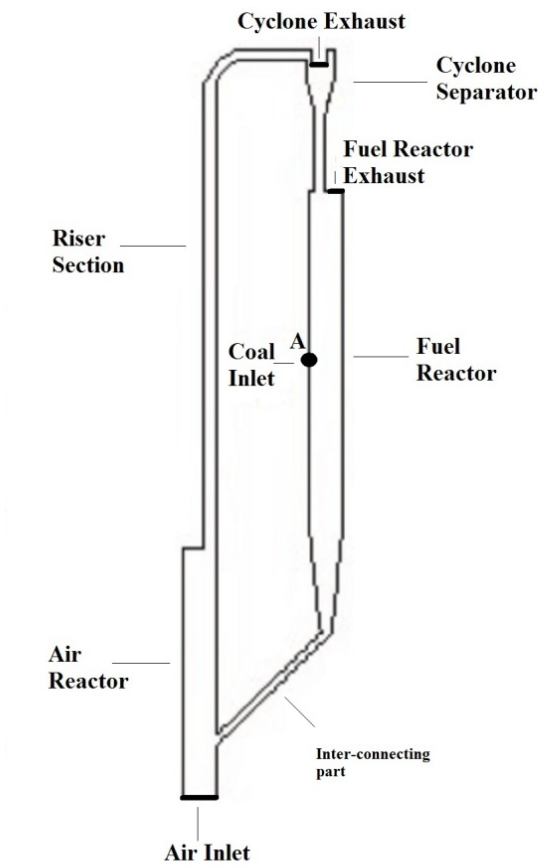


Figure 3 Variation in coal compositions found in regions of Asia-Pacific and Australia

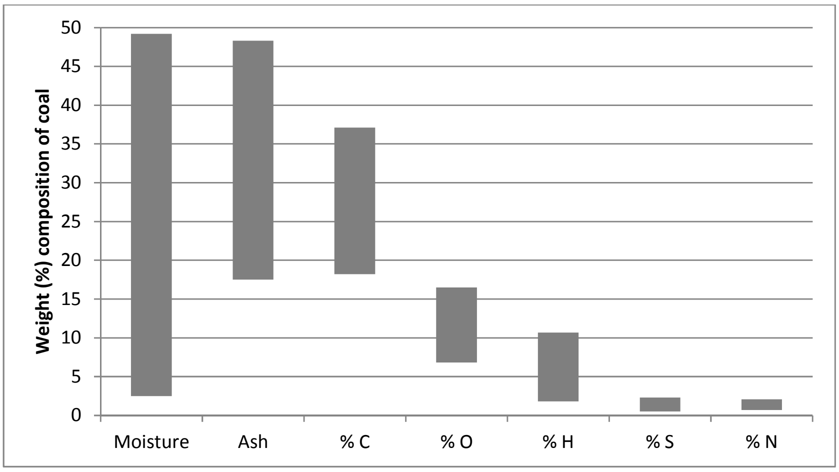


Figure 4 Variation in ash composition of coals found in regions of Asia-Pacific and Australia

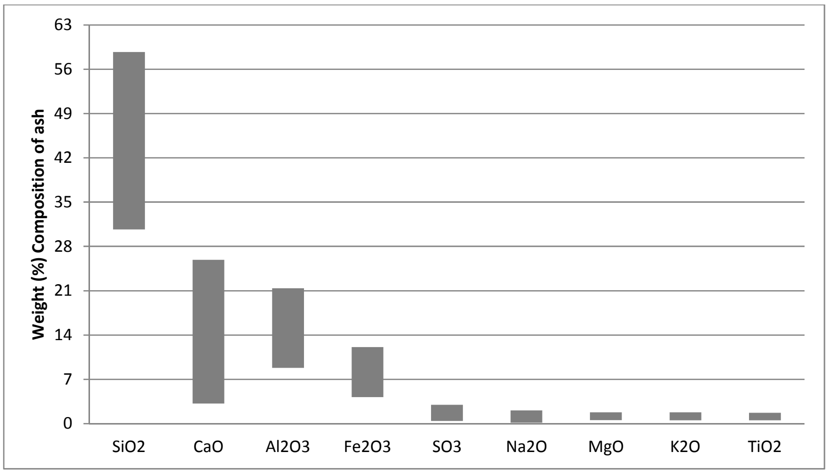


Table 1 Geometry parameters

Fuel reactor height	3.37 m
Fuel reactor diameter	0.34 m
Air reactor height	1.88 m
Air reactor diameter	0.33 m
Tube diameter	0.11 m
Riser height	4.68 m
Cyclone separator total height	0.62 m
Cyclone separator diameter	0.28 m

Tables 2 and 3 show the proximate analysis and ultimate analysis (on dry basis) for two coals i.e. A and B respectively that are used as fuels in the pilot plant described by Kim et al. (2013). Table 4 describes the composition of ash found in the coals used for simulation. Table 5 details properties of oxygen carrier that has been used for simulation.

Table 2 Proximate analysis of fuels

	Proximate analysis (dry basis)	
	A	*B*
Ash	25.87%	31.5%
Volatile matter	29.87%	7.5%
Fixed carbon	42.86%	59.9%
Energy value	26,120	23,398
Energy value*	30,729	27,527
Average particle size	125 μm	100 μm
Moisture	1.4%	1%

Note: *Moisture and ash free.

Table 3 Ultimate analysis of fuels

	Ultimate analysis (dry basis)	
	A	*B*
Carbon	61.76%	56.7%
Hydrogen	4.16%	3.2%
Nitrogen	0.76%	0.9%
Sulphur	0.91%	0.6%
Oxygen	5.14%	6.1%

Table 4 Ash compositions of fuels

Components	*Fuels composition*	
	A	*B*
SiO_2	54.18%	48.34%
Al_2O_3	32.84%	28.12%
Fe_2O_3	5.35%	11.88%
TiO_2	2.27%	1.6%
CaO	1.57%	7.17%
SO_3	1.47%	0.68%
MgO	0.53%	1.13%
Na_2O	0.41%	0.6%
K_2O	1.39%	0.48%

Further, the ash has been classified into two types: reactive ash component and non-reactive ash component for simulation purpose; the reactive ash component includes SiO_2, Fe_2O_3, CaO while non-reactive ash components consist of the rest of ash components. Aluminium oxide being fairly inert is considered as a non-reactive component; while Magnesium oxide and Titanium dioxide are considered as non-reactive components as well because their presence (wt. %) in ash is very less (< 3 wt. %). On the other hand, Silica (SiO_2) being fairly inert (mass weighted rate of reaction in the order of 10^{-22}) is taken as a reactive component due to its reasonable presence in the ash composition.

Table 5 Properties of oxygen carrier

Reactive oxygen carrier	Fe_2O_3
Weight content of reactive oxygen carrier	40–60%
Average particle size of oxygen carrier	1.5 mm
Supporting oxygen carrier	Al_2O_3
Density of oxygen carrier	4724 kg/m^3

3 Model development

A 2-D CFD model for the inter-connected fuel and air reactor is developed using commercial computational software Fluent 6.3.26 and mesh for above process layout has been developed using GAMBIT 2.3.16. The amount of gases injected in the system as well as generated from the reaction amounts to about 90% by volume. Thus, the gas and the mixture of solids are assumed to flow as a fluid inside both the reactors and their inter-connecting parts. This assumption has been used for the development of an approximate CFD model. Eleven reactions discussed by Kim et al. (2013) along with seven other significant reactions plus six reactions related to ash (not incorporated by Kim et al., 2013), as given in Table 6, 7 and 8, respectively are considered for the present CFD simulation. Before a complicated two phase CFD model is selected for the analysis for the present problem, it is thought logical to use the least complicated model, the Species-Transport model with volumetric reaction for the present study to check whether it validates the pilot plant data under acceptable error limits or not. Following governing equations are solved on commercially available software Fluent 6.3.26 for the present model:

Table 6 Reactions proposed by Kim et al. (2013) for coal direct chemical looping process

Reaction no.	*Reaction*	*E_R (J/kmol)*
1.	$\text{Coal} \rightarrow C + CH_4 + NO_2 + SO_2 + CO_2 + H_2O$	
	For A:	
1.1	$C_{7.07}H_{5.67}N_{0.07}S_{0.04}O_{0.44} \rightarrow 5.6425C + 0.06CO_2 + 0.07NO_2 + 0.04SO_2 + 0.1H_2O + 1.3675CH_4$	8.5×10^7
	For B:	
1.2	$C_{6.99}H_{4.71}N_{0.095}S_{0.027}O_{0.565} \rightarrow 5.773C + 0.121H_2O + 0.095NO_2 + 0.027SO_2 + 1.117CH_4 + 0.1CO_2$	9.7×10^7
2.	$2Fe_2O_3 + C \rightarrow 4FeO + CO_2$	3.0124×10^8
3.	$4Fe_2O_3 + CH_4 \rightarrow 8FeO + 2H_2O + CO_2$	1.352×10^8
4.	$Fe_2O_3 + CO \rightarrow 2FeO + CO_2$	8.07×10^7

Table 6 Reactions proposed by Kim et al. (2013) for coal direct chemical looping process (continued)

Reaction no.	*Reaction*	*E_R (J/kmol)*
5.	$Fe_2O_3 + H_2 \rightarrow 2FeO + H_2O$	6.5×10^7
6.	$FeO + CO \rightarrow Fe + CO_2$	1.205×10^7
7.	$FeO + H_2 \rightarrow Fe + H_2O$	2.151×10^7
8.	$C + CO_2 \rightarrow 2CO$	2.11×10^8
9.	$C + H_2O \rightarrow CO + H_2$	2.31×10^8
10.	$2Fe + 1.5O_2 \rightarrow Fe_2O_3$	2.025×10^7
11.	$2FeO + 0.5\ O_2 \rightarrow Fe_2O_3$	2.55×10^7

Table 7 Other significant reactions for coal direct chemical looping process

Reaction no.	*Reaction*	*E_R (J/kmol)*
12.	$C + 2H_2 \rightarrow CH_4$	1.5×10^8
13.	$CO + H_2O \rightleftharpoons CO_2 + H_2$	1.26×10^7
14.	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	3×10^7
15.	$C + O_2 \rightarrow CO_2$	1.794×10^8
16.	$CO + 0.5O_2 \rightarrow CO_2$	1.674×10^8
17.	$2FeO + H_2O \rightarrow Fe_2O_3 + H_2$	7.79×10^7
18.	$2H_2 + O_2 \rightarrow 2H_2O$	2.852×10^7

Table 8 Reaction kinetics of reactive ash component

Reaction no.	*Reaction*	*E_R (J/kmol)*
19.	$CaO + CO_2 \rightarrow CaCO_3$	1.59×10^8
20.	$CaO + H_2O \rightarrow Ca(OH)_2$	1.744×10^7
21.	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$	9.92×10^6
22.	$SiO_2 + C \rightleftharpoons SiO + CO$	3.28×10^8
23.	$SiO + 2C \rightleftharpoons SiC + CO$	3.82×10^8
24.	$SiO + 3CO \rightleftharpoons SiC + CO_2$	2.741×10^8

Mass conservation equation:

The equation for mass conservation/continuity equation valid for compressible and incompressible flows can be written as:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = S_m \tag{1}$$

Momentum conservation equations:

In an inertial frame, the momentum conservation equation is described as below equation (2):

$$\frac{\partial(\rho\vec{v})}{\partial t}+\nabla.(\rho\vec{v}\vec{v})=-\nabla p+\nabla.\left(\overline{\overline{\tau}}\right)+\rho\vec{g}+\vec{F} \tag{2}$$

The stress tensor $\overline{\overline{\tau}}$ is given by equation (3)

$$\overline{\overline{\tau}}=\mu\left[\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)-\frac{2}{3}\nabla.\vec{v}I\right] \tag{3}$$

The second term on the right hand side of equation (3) is the effect of volume dilation.

Energy conservation equation:

The conservation of Energy is defined by the following equation (4):

$$\frac{\partial(\rho E)}{\partial t}+\nabla.\left(\vec{v}\left(\rho E+p\right)\right)=\nabla.\left(k_{eff}\nabla T-\sum_{j}h_j\vec{J}_j+\left(\overline{\overline{\tau}}_{eff}.\vec{v}\right)\right)+S_h \tag{4}$$

$$E=h-\frac{p}{\rho}+\frac{v^2}{2} \tag{5}$$

Species transport equations:

The local mass fraction of each species (Y_i) through the solution of a convection-diffusion equation for the *i*-th species is solved. It takes the following general form:

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla.(\rho\vec{v}Y_i)=-\nabla.\vec{J_i}+R_i+S_i \tag{6}$$

Mass diffusion in laminar flows:

In the above equation (6), this arises due to concentration gradients. In the present model, dilute approximation is assumed, under which it is defined as follows:

$$\vec{J_i}=-\rho D_{i,m}\nabla Y_i \tag{7}$$

The laminar finite-rate model:

The net source of chemical species *i*-th due to reaction is computed as the sum of the Arrhenius reaction sources over the N_R reactions that the species participate in:

$$R_i=M_{w,i}\sum_{r=1}^{N_R}\widehat{R_{i,r}} \tag{8}$$

Consider the *r*-th reaction written in general form as follows in equation (9) which is valid for both reversible and non-reversible reactions. For non-reversible reactions the backward rate constant is omitted.

$$\sum_{i=1}^{N}v'_{i,r}M_i \underset{k_{b,r}}{\overset{k_{f,r}}{\rightleftharpoons}} \sum_{i=1}^{N}v''_{i,r}M_i \tag{9}$$

For a non-reversible reaction, the molar rate of creation/destruction of species i in reaction r ($\widehat{R_{i,r}}$ in equation 8) is given by,

$$\widehat{R_{i,r}} = \Gamma\left(v_{i,r}^{"} - v_{i,r}^{'}\right)\left(k_{f,r}\prod_{j=1}^{N}\left[C_{j,r}\right]^{\left(\eta_{j,r}^{'}+\eta_{j,r}^{"}\right)}\right) \tag{10}$$

For a reversible reaction, the molar rate of creation/destruction of species i in reaction r, is given by,

$$\widehat{R_{i,r}} = \Gamma\left(v_{i,r}^{"} - v_{i,r}^{'}\right)\left(k_{f,r}\prod_{j=1}^{N}\left[C_{j,r}\right]^{\eta_{j,r}^{'}} - k_{b,r}\prod_{j=1}^{N}\left[C_{j,r}\right]^{v_{j,r}^{"}}\right) \tag{11}$$

The forward rate constant $k_{f,r}$ for reaction r, is computed using the Arrhenius expression

$$k_{f,r} = A_r T^{\beta_r} e^{-E_R/RT} \tag{12}$$

Values of $v'_{i,r}$, $v''_{i,r}$, $\eta'_{j,r}$, $\eta''_{j,r}$, β_r, A_r and E_R are provided to solve equation (10).

For reversible reactions, the backward rate constant $k_{b,r}$ for reaction r, is computed from the forward rate constant using the following relation:

$$k_{b,r} = \frac{k_{f,r}}{K_r} \tag{13}$$

The value of K_r is computed from the following equation (14):

$$K_r = e^{\left(\frac{\Delta S_r^0}{R} - \frac{\Delta H_r^0}{RT}\right)}\left(\frac{p_{atm}}{RT}\right)^{\sum_{i=1}^{N}\left(v_{i,r}^{"} - v_{i,r}^{'}\right)} \tag{14}$$

where, the term within the exponential function represents the change in Gibbs free energy, and its components are computed as follows:

$$\frac{\Delta S_r^0}{R} = \sum_{i=1}^{N}\left(v_{i,r}^{"} - v_{i,r}^{'}\right)\frac{S_i^0}{R} \tag{15}$$

$$\frac{\Delta H_r^0}{RT} = \sum_{i=1}^{N}\left(v_{i,r}^{"} - v_{i,r}^{'}\right)\frac{h_i^0}{RT} \tag{16}$$

3.1 Reactions kinetics

The present study is carried out for two types of coal A, and B; it utilises 24 reactions for the process which are taking place inside two reactors and their inter-connecting parts. In Table 6, 11 reactions proposed by Kim et al. (2013) are described while, in Tables 7 and 8, other seven significant reactions and six reactions pertaining to reactive ash components with their kinetics are tabulated.

Standard k-ε turbulence model:

The standard k-ε turbulence model described by Launder and Spalding in 1974 is used for the present study.

Equation (17) is described for turbulent kinetic energy k

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\epsilon-Y_M+S_k \tag{17}$$

And equation (18) is described for the rate of dissipation ε

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\delta x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \tag{18}$$

where, G_k is calculated by equation (19), G_b is calculated by equation (20), Y_M is calculated by equation (21).

$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ are the constants ($C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$)

$\sigma_k = 1$, $\sigma_\varepsilon = 1.3$

$$G_k=-\rho\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_i} \tag{19}$$

$$G_b=\beta g_i\frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \tag{20}$$

where, $Pr_t = 0.85$.

$$Y_M=2\rho\varepsilon M_t^2 \tag{21}$$

$$M_t=\sqrt{\frac{k}{a^2}}\ \text{and}\ a=\sqrt{\gamma RT}$$

Mass-weighted average of rate of reaction:

The mass-weighted average of rate of reaction in different sections are computed by dividing, the summation of the values of the rate of reaction multiplied by the absolute value of the dot product of the facet area and momentum vectors, by the summation of the absolute value of the dot product of the facet area and momentum vectors as given in equation (22):

$$\frac{\int\widehat{R_r}\,\rho\left|\vec{v}.d\vec{A}\right|}{\int\rho\left|\vec{v}.d\vec{A}\right|}=\frac{\sum_{i=1}^{n}\widehat{R_{i,r}}\rho_i\left|\vec{v_i}.\vec{A_i}\right|}{\sum_{i=1}^{n}\rho_i\left|\vec{v_i}.\vec{A_i}\right|} \tag{22}$$

4 Solution technique

In this section, solution technique adopted for the present study is described. The pilot plant dimensions are taken from the mechanical drawing of the pilot plant described by Kim et al. (2013). The boundary condition for air and coal inlets are defined as velocity inlet and mass flow inlet, while, fuel reactor and cyclone exhausts are defined as pressure outlets. Unsteady state simulations are carried out for present study and a time step of 0.001 s is chosen for mesh grid size of 0.01 m obtained from grid independence test for MC during model verification. The computational parameters used in present study are discussed in Table 9.

Table 9 Computational and simulation parameters for the present study

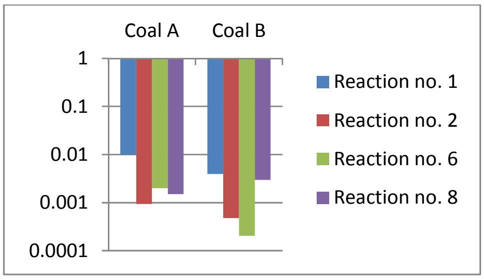
Operating pressure		10 atm	
Air inlet velocity		0.001 m/s	
Fuel flow rate for A		2 kg/h	
Fuel flow rate for B		2.25 kg/h	
Air and fuel inlet temperature		320 K	
Carrier CO_2 gas flow rate		10 LPM	
Under relaxation factors			
Pressure	0.1	Density	0.1
Momentum	0.1	Body Forces	0.1
Turbulent kinetic energy	0.1	Species	0.1
Turbulent dissipation rate	0.1	Energy	0.1
Model parameters			
Solver		Unsteady state, second order implicit	
Discretisation scheme		Second order upwind	
Pressure velocity coupling		SIMPLE	
Time step		0.001 s	
Iteration per time step		30	
Convergence criterion		10^{-5}	

5 Result and discussion

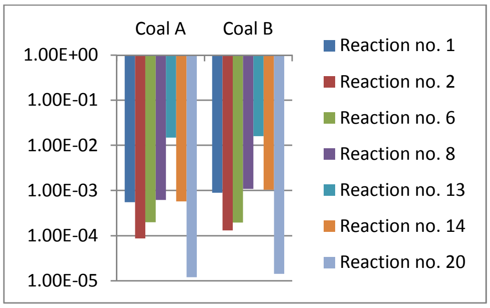
In this section, the results obtained from the study of the effect of ash components present in coal during coal direct chemical looping combustion using the validated 2-D CFD model developed in present study is discussed. The previously developed model incorporating eighteen reactions for MC and SBC showed a better agreement with the pilot plant data. In present study only reaction kinetic aspect of ash is studied, the melting of ash and its associated effects, oxygen carrier activity deactivation due to presence of ash, etc. are not incorporated. In the present CFD model, for both the fuels ‘A’, and ‘B’, six more reactions of reactive ash components are incorporated over and above eighteen reactions. While extending the present model to incorporate different types of ash bearing coals, the original dimensions of the pilot plant has not been specifically modified to suite the type of coal. Further, during the present simulation study, the limiting operating parameters like pressure drop, reactor bed temperature of the pilot plant have been kept within the limits fixed for the pilot plant.

In Figure 5, a comparison between mass weighted averages rate of reactions (computed using equation 22) in four different sections of the process i.e. fuel reactor section, inter-connecting section, air reactor and riser section has been carried out. From Figure 5(a) and 5(c), it is clear that, coal devolatilisation reaction (Reaction 1 [1.1, 1.2]) is the most dominating reaction in fuel reactor section, oxidation of iron to iron (III) oxide & combustion of left over carbon play a leading role in the air reactor. Further, water gas shift reaction is the most dominant in the inter-connecting pipe between fuel and air reactors as can be observed from Figure 5(b). In addition to above, in this section calcium hydroxide which is a product of reaction between CaO (present in reactive component of ash) with water forms plays a prominent role.

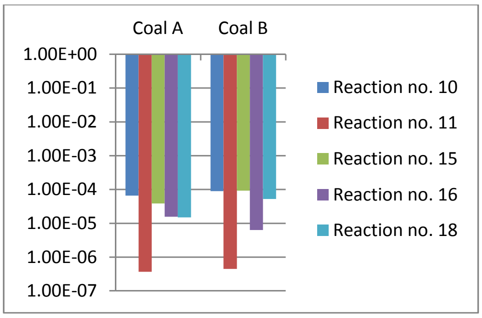
Figure 5 Mass weighted average rate of most dominating reactions in four sections of the process (see online version for colours)



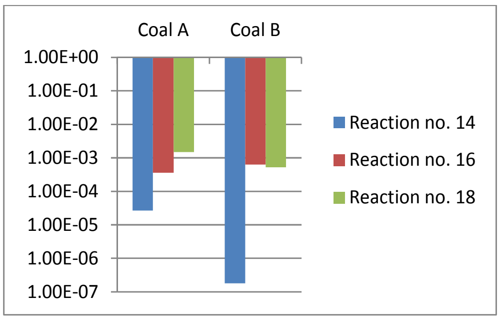
(a) Fuel Reactor section



(b) Inter-connecting section



(c) Air reactor section



(d) Riser section

From Figure 6 it can be seen that, whereas, fuel conversion for ‘A’ and ‘B’ are 93.8% and 87.89% respectively on coal basis, it is 89.12% and 90.73% for CO_2 purity in fuel reactor exhaust. Further, the normalised value of fuel flow rate, fuel reactor temperature and air reactor temperature for ‘A’ and ‘B’ fuel, when compared with the similar values of parameters for metallurgical coke, shows that the fuel reactor temperature remains slightly less than the metallurgical coke due to presence of high ash component and presence of reactive ash component which works as an oxygen carrier by transporting of oxygen from air reactor to fuel reactor. However, the fuel requirement for feasible operation is about 1.5–2 times (for both A and B fuels) when compared to the amount of metallurgical coke that is required to sustain operation, and air reactor temperature increases due to combustion of left over carbon in that section.

Figure 6 Comparative results for coal ‘A’ and ‘B’ (see online version for colours)

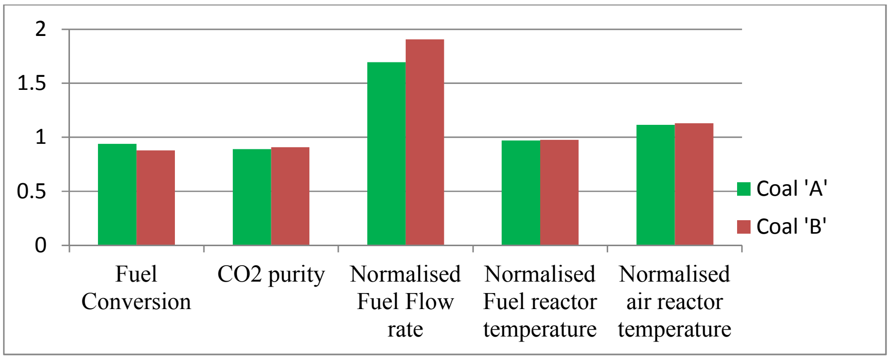


Table 10 Sensitivity analysis of operating pressure and fuel and air inlet temperature

Variable	*CO_2 purity*	*Fuel conversion*	*Fuel reactor temperature (K)*	*Air reactor temperature (K)*
Operating pressure				
			Coal A	
10 atm	89.12%	93.8%	1208	1076
15 atm	89.46%	93.5%	1200	1072
			Coal B	
10 atm	90.73%	87.89%	1214	1090
15 atm	90.46%	87.53%	1209	1083
Fuel and air inlet temperature				
			Coal A	
320 K	89.12%	93.8%	1208	1076
330 K	89.11%	93.81%	1209	1077
			Coal B	
320 K	90.73%	87.89%	1214	1090
330 K	90.72%	87.91%	1214	1092

In Table 10, the results of sensitivity analysis of the present CFD model are reported. The analysis is in respect to operating pressure of the system as well as air and fuel inlet temperatures on key output parameters such as CO_2 purity in fuel reactor exhaust, fuel conversion, and fuel and air reactor temperature. It can be seen that the sensitivity of system for change in operating pressure is significant while, sensitivity for fuel and air inlet temperature is almost negligible.

6 Conclusion

In present study, following salient features are observed:

1. Fuel conversion on dry ash free basis for fuel coals 'A' and 'B' are 93.8% and 90.73% respectively.
2. CaO and Fe_2O_3 as a part of reactive ash component shows reactivity under the process condition while SiO_2 exhibits a mass weighted average rate of reactions which is less than 10^{-20} kmol/m^3-s indicating that it works almost as an inert material.
3. The amount of ash present in fuel coal increases its fuel flow rate proportionately to maintain required feasible process conditions for chemical looping combustion. The carbon capturing efficiency decreases as fuel flow rate is increased. This observation is in conformity to Abad et al. (2013). Further, it can be seen that overall fuel conversion decreases as amount of non-carbonaceous species increases such as moisture and ash in the fuel coal as also been identified by Azis et al. (2013).
4. The carbon dioxide purity in fuel reactor exhaust increases with the rise in fuel reactor temperature for the two fuels used in the present study. This fact is in tune with the observations of Abad et al. (2013) carried out for El Cerrejón coal with less than 10% ash content.

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Nomenclature

A_r	Pre-exponential factor
β	Coefficient of thermal expansion
β_r	Temperature exponent
$C_{j,r}$	Molar concentration of species *j* in reaction *r*
$D_{i,m}$	Diffusion coefficient for the *i*-th species in the mixture
ε	The rate of dissipation
E_R	Activation energy for the reaction
$\vec{F}$	External body forces and also contains user-defined terms
$\gamma_{j,r}$	Third-body efficiency of the *j*-th species in the *r*-th reaction
g_i	Gravitational vector in the *i*-th direction
G_b	The generation of turbulence kinetic energy due to buoyancy
G_k	Generation of turbulence kinetic energy due to mean velocity gradients
$h^0{}_i$	Standard-state enthalpy (heat of formation) which are specified as properties for every species
I	Unit tensor
$\overrightarrow{J_i}$	Diffusion flux of the *i*-th species
$\vec{J}_j$	Diffusion flux of species *j*
K	Turbulent kinetic energy
$k_{b,r}$	Backward rate constant for reaction *r*
k_{eff}	Effective conductive (= $k + k_t$)
$k_{f,r}$	Forward rate constant for reaction *r*
k_t	Turbulent thermal conductivity
K_r	Equilibrium constant for the *r*-th reaction
M	Molecular viscosity
μ_t	Turbulent viscosity
M_i	Symbol denoting species *i*
M_t	Turbulent Mach number
$M_{w,i}$	Molecular weight of *i*-th species
$\eta'_{j,r}$	Rate exponent for reactant species *j* in reaction *r*
$\eta''_{j,r}$	Rate exponent for product species *j* in reaction *r*
N	Number of chemical species in the system
P	Static pressure
p_{atm}	Atmospheric pressure (101.325 kPa)
Pr_t	Turbulent Prandtl number for energy
$\rho\vec{g}$	Gravitational body force
R	Universal gas constant

R_i	Net rate of production of species *i* by chemical reaction
$\widehat{R_{i,r}}$	Arrhenius molar rate of creation/destruction of species *i*-th in reaction *r*
σ_ε	Turbulent Prandtl number for ε
σ_k	Turbulent Prandtl number for *k*
S_ε	User defined source term
S_h	The heat of chemical reaction and any other volumetric source by user defined function
S_i	Rate of creation by addition from dispersed phase plus any user defined sources
S^0_i	Standard-state entropy which are specified as properties for every species
S_k	User defined source term
S_m	Mass added to continuous phase from second phase or any user-defined sources
$\overline{\overline{\tau}}$	Stress tensor
Γ	The net effect of third bodies on the reaction rate
$v'_{i,r}$	Stoichiometric coefficient for reactant *i* in reaction *r*
$v''_{i,r}$	Stoichiometric coefficient for product *i* in reaction *r*
Y_j	The mass fraction of species *j*
Y_M	The contribution of the fluctuating dilation in compressible turbulence to the overall dissipation rate

Full circle: electricity, development and welfare

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Abstract: Electricity is presumed to be an essential contributor to economic growth in emerging economies. Whereas earlier research efforts employ traditional measures of growth, namely GDP per capita, to map the impact of electricity, this study chooses to measure the impact of aggregate electricity provision on all-round socioeconomic development as measured by the Human Development Index (HDI). Granger causality tests are run to establish the relationship between electricity and development for a sample of 21 countries chosen on the basis of average annual HDI scores of 4.00 and above cumulated over the periods 1981–1990, 1990–2000 and 2000–2012. For four countries, namely China, Egypt, Morocco and Nepal, unidirectional causality running from electricity consumption to human development was observed, while for Algeria, Egypt, Myanmar, Sudan and Yemen, the reverse was observed. It was found that reducing aggregate technical and commercial losses could improve development outcomes in varying degrees.

Keywords: HDI; human development index; HPI; happy planet index; electricity consumption; experienced well-being; causality testing; degrowth.

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1 Introduction

Traditional notions of comparative advantage have been drilled down to define individual tasks that are performed in different parts of a vast and complex global economy and trade network. Advances in communication technology have enabled hitherto marginal players to try and carve specialised niches for themselves in this milieu of 'trade in tasks' (The Economist, 2007). The vertical disintegration of the production and service delivery processes has provided individual nation states with the means of earning their sustenance, and of generating large-scale employment opportunity. Notwithstanding the magnitude of the tasks carried out, either in whole or in part, for this economic model to be sustainable, however, the economic machine would have to be operated continuously, 'like a top which to maintain its equilibrium must spin ever faster and faster' (Keynes, 1920).

Despite staggering improvements in energy efficiency of production processes as well as of end-user appliances, growth in emerging economies is as energy-intensive as witnessed among the industrialised nations four decades past (van Benthem, 2014). Increasing the supply of energy therefore becomes a precondition for continued economic growth, and other parameters held constant. In other words, besides human and material resources, abundant and affordable energy availability in general and rising electricity generation in particular are presumed to remain crucial inputs, whose historical role and contribution have been intensely studied and vigorously debated for several decades (Temin, 2014).

Arguably, the availability and pricing of electric power are vital in helping choose the underlying tasks that a nation state or region chooses to specialise in. Electricity is an acknowledged 'explicit factor of production' and a confirmed 'development enabler', and electrification-related interventions are known to be correlated with 'positive development outcomes' in the shape of 'economic growth and poverty alleviation' (Welle-Strand et al., 2012). Numerous studies have analysed the relationships between energy consumption and increased production as measured by the Gross Domestic Product (GDP). Menegaki (2014), for instance, presents a meta-analysis of 51 published studies relating *energy* consumption to GDP growth, with the caveat that findings from single-country studies are found to be less reliable relative to multi-country studies.

2 Background

2.1 Electricity consumption and economic growth

Analyses of the function of *electricity* as a vital input are less frequently undertaken and GDP-related figures are often employed as surrogates for income, development and welfare measures. Additionally, studies tend to employ *averages* such as GDP per capita and electricity consumption per capita to try and establish causality and feedback-loop relationships (Ahamad and Nazrul Islam, 2011; Ghosh, 2002; Burney, 1995). While employing cross-country or time-series data, or both, researchers fail to conclusively establish a causal relationship from electrification projects through economic growth and eventually to poverty alleviation and human welfare. For instance, Altinay and Karagol (2005) study 50 years worth of data and find evidence relating increased electricity consumption to economic growth in Turkey. Conversely, Mozumder and Marathe (2007) have found that rising GDP per capita causes a rise in electricity consumption per capita in Bangladesh, but not *vice versa*. Yoo (2005, 2006), on the other hand, has observed bidirectional causality between the parameters for Korea, Malaysia and Singapore over a 30-year horizon. The conundrum is further compounded by conflicting results from alternative statistical tests on an underlying data set. The ECM-based *F*-test applied by Tang (2008) on a data set for Malaysia largely overlapping with the time horizon as Yoo (2006) revealed that the underlying parameters were not cointegrated, while standard Granger causality tests revealed bidirectional causality, confirming earlier findings. Chandran et al. (2010) confirm the results concluding that the GDP elasticity of electricity consumption in Malaysia was 0.7.

Wolde-Rufael (2006) has studied 17 African countries for a 30-year period and has observed a unidirectional Granger causality from per capita real GDP to per capita electricity consumption for a mere six countries, a reverse Granger causality for three others and bidirectional Granger causality for an additional three. The author could not confirm a relationship between the parameters for the remaining five countries in the sample. In a relatively recent study, Apergis and Payne (2011) have classified 88 countries based on income levels and have observed: (i) bidirectional causality between electricity consumption and economic growth in the high-income and upper middle-income countries, (ii) unidirectional causality from electricity consumption to growth in low-income countries and (iii) short-run unidirectional causality with electricity consumption as a driver of growth, and a bidirectional long-run causality among the lower middle-income countries. The sample of 21 countries selected for the present study largely fall within the low-income and middle-income groups as defined in Apergis and Payne (2011).

Ferguson et al. (2000) have analysed 100 countries, then constituting 99% of the global economy, and have concluded that *electricity* usage, rather than *energy* usage, especially among high-income countries, was better correlated with wealth creation and hence should be made a 'development indicator'. Squalli (2007), however, cautions that economies with some common traits, as with being oil exporters, but dissimilar in other respects, could exhibit vastly differing causality results and such outcomes need to be interpreted bearing such diversity in mind.

2.2 Electricity consumption and intermediate variables

The relationships between electricity consumption and economic growth have also been established by employing intermediate macroeconomic and demographic variables. Narayan and Smyth (2005) find that employment and real-income Granger caused electricity consumption in Australia. Likewise, Narayan and Smyth (2009) find that a 1% increase in exports by a panel of Middle-Eastern nations led to a 0.17% increase in GDP, and a 1% increase in the GDP itself resulted in a 0.95% increase in electricity consumption. Similarly, Lean and Smyth (2010) find support for the hypothesis that electricity consumption led to an increase in exports and eventually to higher aggregate output in Malaysia.

On the other hand, Odhiambo (2009) concludes that increasing employment Granger caused economic growth in South Africa. Abosedra et al. (2009) have employed changes in temperature and relative humidity as exogenous variables to study the progression in electricity demand and economic growth. The present paper investigates this question of causality in greater depth, while making the often ignored, but significant, distinction among economic growth, industrialisation and ultimately to 'transforming peoples' lives' (Hydroworld, 2014).

2.3 'Degrowth' as a solution to 'unhappy growth'

Given the environmental impact of electricity generation, transmission, distribution, storage and consumption, the relationship between electricity usage and economic growth, and more importantly, the potential trade-offs between the two, intended to achieve beneficial environmental outcomes, have taken centre stage in international climate negotiations. The progressive expansion of the GDP, as traditionally defined, requires electricity inputs into construction, manufacturing and transportation. Similarly, higher disposable incomes consequent to the employment so generated could give rise to increased utilisation of electronic gadgets for entertainment and personal communication and for added comfort in households. Chen et al. (2007) have assembled a summary of causality tests that have attempted to establish a relationship between electricity consumption and GDP. Their own analysis of ten Asian countries helps them arrive at the conclusion that, notwithstanding short-run inconsistencies in causality across countries, real GDP and electricity consumption move together in the long run. The relationship between the two – the power intensity of GDP, for instance – is further conditioned by the efficiencies at each stage of production, distribution and consumption (Javid and Qayyum, 2014). Ayres and Voudouris (2014) observe that 'useful' energy is consistently underpriced, encouraging firms and governments to use too much rather than too little, often neglecting potential investments into energy conservation. Consequently, the GDP elasticity with respect to energy is reported to be higher than that of the electricity (Menegaki, 2014) and hence the current analysis of electricity – GDP – development – welfare assumes greater significance.

The apparently insatiable demand for electricity and material inputs to feed the 'growth engine' is said to have far exceeded the bearing capacity of the planet. In a drastic departure from the accepted wisdom of the past, scaling back on production and consumption are recommended to enhance human well-being and to defend ecosystems. 'Degrowth', therefore, is a suggested 'redirection of the economy' to encourage people to live in 'frugal sustainability', working less, consuming less and living on less. The philosophy involves reusing materials, foregoing unsustainable practices and communities living together in harmony (Luttrell, 2013). While continuing to live with the GDP as an indicator of achievement – or lack of it – researchers point out that societies are not necessarily better-off simply because individuals, businesses or governments spend more, and have urged that analysts shall distinguish between the quantity and quality of growth, and between short-run and long-run objectives (Assadourian, 2013). Degrowth, as an economic philosophy, therefore, is an effort to delink material prosperity from individual and social well-being. Kallis (2011) recommends policies for minimum income levels, reduction in working hours, environmental and consumption taxes and controls on advertising in order to conserve on resource use, to minimise carbon emissions, and to build a society that lives better with less. Such economic *contraction* might prove to be a macro-pathway to a socially and ecologically sustainable future, according to Videira et al. (2014), and when combined with increased leisure – possibly from shorter working hours – could be termed 'happy degrowth' (Bilancini and D'Alessandro, 2012).

Recognising that contemporary financial and economic institutions and processes are built on ever-increasing consumption, Tokic (2012), however, believes that an economic contraction in the name of degrowth would lead to an economic implosion, a collapse in stock market valuations and to deflation. Policy-makers would then impulsively press for expansionary fiscal and monetary policy measures that trigger rapid growth, reversing the original premise. This reverts to exerting pressures on an already strained biophysical system. Further, Klitgaard and Krall argue that short-term degrowth or a planned 'steady state' could impose formidable challenges of unemployment, debt and poverty. James and Cato (2014) strongly condemn such inappropriate stimulation of aggregate demand that invariably leads to exploitative land use and to climate change and resource depletion, which, they believe, could never be redressed within the paradigms of contemporary capitalism.

'Degrowth', others believe, might be inevitable, and no longer a matter of policy choice, since the growth engine was rapidly drawing down upon finite fossil fuel resources, and that incomes were bound to shrink in tandem with lower energy availability (Douthwaite, 2012). Researchers also opine that 'dematerialisation' and 'detoxification' of the economy through various material efficiency options reveal that consumption side resource efficiency strategies could deliver larger savings than changes to production (Barrett and Scott, 2012). Macroeconomic measures to monitor and manage currency valuations and debt in such a situation would need to be designed sooner rather than later. Cuba, for instance, is said to have survived the collapse of the 1990s on the back of 'a consistent commitment to social services, a shift in agricultural methods and a high level of social capital' (Borowy, 2013). Despite suggestions to the contrary, degrowth, therefore, might not be a goal in itself but a transition to a steady state economy which operated within the bounds imposed by the biophysical ecosystem (Kerschner, 2010).

2.4 Restorative growth

Hauge (2014) argues that combating climate change and resulting food and water scarcity would entail restorative use of resources: a cyclical approach that would mimic biological systems and create beneficial synergies, where the waste product from one technology is absorbed as an input resource by another. Put differently, financial and social capital depends massively on natural capital, and, consequently, policy-makers cannot ignore the possibility of an 'ecosystem malfunction risk' and investments are required to safeguard and restore the health of all forms of capital (Waage, 2014). Continuing population growth and consumption beyond the physical limits of macro-ecological resource renewal implies that the post-industrial generations have been borrowing from the future. Elaborating the complexity of human – ecological systems, Golub et al. (2013) discuss the ethical concept of 'restorative justice', as means to remedy past and present injustices stemming from violence, conquest, asymmetries of power and information, leading to improved resource management, social cohesion and ultimately to preserving the life-support systems of the planet. James and Cato (2014) assert that solutions to global problems might ultimately be found in the local establishment of an 'ecological – economy' that produces just enough to meet society's needs. Mainstream economic analysis needs to discover middle ground between ecological pessimism on the one extreme and technological optimism at the other. Statistics reported and analysed need to be more meaningful than averages or aggregates, as with the numbers of people living in extreme poverty, the disparities in wealth and income, depletion and recovery rates of ecosystems and species and biodiversity extinction rates from overexploitation (Mace, 2012).

3 Human development

Development is the enlargement of people's choices. It is more than mere production, economic growth or accumulation of wealth, and includes qualitative features including longevity, health, education and a decent standard of living. Such choices, in the true sense, include political freedom, civil liberties, guaranteed human rights and dignity and personal self-respect. Above all, the process of development is slated to create a favourable environment for people to make choices, to explore their capabilities and to mould their own lives in accordance with their needs and interests, with a view to ultimately maximising happiness (HDR, 1990).

The United Nations Development Program (UNDP) created the Human Development Index (HDI), a single statistic between 0 and 1, encompassing various dimensions, which served as a frame of reference across countries and across time. The index is built by weighting, aggregating and normalising three dimensions – health, education and income – using their geometric means of (i) education component comprising the mean years of schooling for adults aged 25, and expected years of schooling for children of school entering age, (ii) life expectancy at birth on a scale of 20–83.57 years, (iii) the wealth component on a scale of \$100–\$87,478 (PPP, estimated for Qatar in 2012), and (iv) decent standard of living measured by logarithm of GNI per capita (PPP\$). The HDI is also disaggregated by social group or region to enable specific policy actions to eliminate disparities and gaps. Above all, the index is a measure of socio-economic progress and stresses the importance of the manner in which material wealth is spent, and helps individual countries and regions retain focus on the ultimate objective of enriching human lives (HDI, 2014).

Niu et al. (2013) observe that higher income countries consume higher quantities of electricity and show higher levels of human development. Yet, the outcomes vary considerably across countries falling within various income groups. Ouedraogo (2013) reports that among 15 'developing countries', in the short run, electricity consumption does not impact HDI, while a long-term positive cointegration relationship is found to exist with a 1% increase in electricity consumption increasing a country's position on the HDI by 0.22%. The transition from low to medium development of an economy appears to be achieved at about 500 kWh of electricity per capita (Leung and Meisen, 2005).

4 Methodology, sample and results

For the present study, a representative sample of 21 countries was selected based on average annual HDI scores for three time periods, 1980–1990, 1990–2000 and 2000–2012, that added up to 4.0 or more. The sample consists of several countries from lower middle-income and upper middle-income group, as classified by Apergis and Payne (2011).

As discussed above, the HDI is computed using three variables, i.e. Gross National Income (GNI), Education Index (mean and expected schooling years) and Life Expectancy Index. The unique feature of this index is that it evolves over time, based on new available data and emerging needs. Hence, this index is dynamic in nature and helps in tracking development in a much better way. To make the results comparable over time, the index is recalculated for the previous years as well, using latest available flag posts (highest over time) for each of the three variables.

4.1 Electricity consumption and human development

The Granger causality test was run for each country in the sample with lags of two, three, and four years, approximating four years to one business cycle, in order to test for causality between electricity consumption and development, the latter as measured by the HDI. The results are displayed in Table 1. It was observed that for four countries, China, Morocco and Nepal, unidirectional causality ran from electricity consumption to development with a lag of two years, with the results being statistically significant at 90%. Interestingly, in the case of Egypt, causality was also observed running from development to electricity consumption with a lag of four years. This would imply that enhancing reliable electricity supplies could deliver improved developmental outcomes, while, simultaneously, higher education and health achievements could augment demand for electricity. In the case of China, the unidirectional Granger causality from electricity to development for three and four year lags was statistically significant at 99%. Overall, the direction of causality from incremental supply of electricity to human development, or vice versa, is influenced by the proportion of the population with access to electricity and the initial state of human development in the economy.

Table 1 Granger causality relationships between electricity consumption and HDI scores

Country	*Lag length 2 yr*	*Lag length 3 yr*	*Lag length 4 yr*	*Causality*
Bangladesh	1.00196 (0.39045)	1.52242 (0.25911)	1.02865 (0.44314)	
	0.32878 (0.72486)	0.65515 (0.59501)	0.65703 (0.63682)	
Algeria	0.3818 (0.68908)	0.15444 (0.92481)	1.16807 (0.3866)	
	1.66481 (0.22235)	3.22987 (0.06087)*	2.43099 (0.1235)	Dev → Elec
China	5.70282 (0.01439)**	10.6562 (0.00106)***	9.48063 (0.00275)***	Elec → Dev
	0.57898 (0.57251)	0.788 (0.52345)	0.5227 (0.722)	
Egypt	6.15665 (0.01117)**	2.49745 (0.10939)	1.61632 (0.25209)	Elec → Dev
	2.06173 (0.16178)	1.39092 (0.29314)	2.98096 (0.08002)*	Dev → Elec
India	0.36299 (0.70154)	1.55156 (0.25218)	1.02062 (0.44665)	
	0.1749 (0.84123)	0.09193 (0.96308)	0.01507 (0.99946)	
Iran	0.48519 (0.62491)	0.87556 (0.48086)	0.44545 (0.77347)	
	0.17548 (0.84075)	0.28838 (0.83294)	1.11913 (0.40553)	
Morocco	0.37123 (0.69605)	2.98789 (0.07346)*	1.78911 (0.21512)	Elec → Dev
	1.34194 (0.29097)	1.08051 (0.39431)	1.83896 (0.20565)	
Myanmar	0.34353 (0.7147)	0.70521 (0.56705)	2.00057 (0.17811)	
	3.59126 (0.05316)*	3.78976 (0.04017)**	4.66023 (0.02588)**	Dev → Elec
Nepal	3.0814 (0.07566)*	2.28562 (0.13086)	1.43425 (0.29914)	Elec → Dev
	1.9427 (0.17772)	0.76544 (0.53501)	0.82554 (0.54095)	
Sudan	0.70409 (0.51019)	1.27469 (0.3273)	1.63581 (0.24758)	
	1.98843 (0.1714)	3.31903 (0.05687)*	3.22547 (0.06673)*	Dev → Elec

Table 1 Granger causality relationships between electricity consumption and HDI scores (continued)

Country	*Lag length 2 yr*	*Lag length 3 yr*	*Lag length 4 yr*	*Causality*
Tunisia	0.45266 (0.64434)	0.10483 (0.95567)	0.22612 (0.91697)	
	0.61752 (0.55244)	0.4495 (0.72226)	0.25067 (0.90211)	
Turkey	0.79813 (0.46839)	1.08338 (0.39322)	0.3699 (0.82443)	
	1.35736 (0.2872)	0.09216 (0.96295)	0.08034 (0.98644)	
Yemen	0.23435 (0.79393)	0.41137 (0.74783)	0.50683 (0.73247)	
	5.6046 (0.01522)**	3.39231 (0.0538)*	3.25981 (0.06508)*	Dev → Elec

Note: ‘t’ probability shown in parentheses.

* Significant at 90%; ** significant at 95%; *** significant at 99%; → indicates causality.

On the other hand, for Myanmar, Algeria, Sudan and Yemen, a unidirectional causality was observed running from development, as measured by the HDI, to electricity consumption, confirming that development in these countries had led to an increase in electricity consumption. Only in the case of China, the present results confirm findings from earlier research including Shiu and Lam (2004) and Yan et al. (2008).

In certain instances, the present findings contradict the conclusions from earlier research, since the present research studies development outcomes rather than GNI alone, even as the latter forms part of the HDI computation. For Algeria, Benin and Malawi, Wolde-Rufael (2006) and Jumbe (2004) had observed causality running from electricity consumption to income, while the present findings for these countries showed no causal relationship between electricity consumption and development. In the case of Sudan, Wolde-Rufael (2006) had analysed the causal relationship between per capita electricity consumption and per capita income, and had found no causality in either direction, while the present results indicate a unidirectional causality running from development to increased gross electricity consumption.

4.2 Technical and commercial losses

For the subset of countries where causality was observed to be running from electricity consumption to HDI, with a view to further establishing a firm relationship between electricity and human development, a regression analysis was undertaken with ΔHDI as the dependent variable and HDI and incremental electricity consumption as independent variables to provide for the lower marginal impact of increasing electricity consumption on HDI. It was observed that for China and Nepal, if the quantum of electricity making the difference between production and consumption had been made available, the HDI would have been higher by 1.25–2.04%. The year 2011 HDI scores for China and Nepal, respectively, would have been 0.72 and 0.544 in place of 0.71 and 0.53.

For individual countries where a unidirectional causality running from electricity consumption to development is established, the present study further investigates the impact of electricity consumption as an input on individual components constituting the HDI, namely the level of educational attainment measured by the number of years of formal instruction, income measured by the GNI, and life expectancy in years. The results are discussed further herein below.

4.3 Electricity consumption and educational attainment

The present study finds a unidirectional causality running from electricity consumption to education for Bangladesh, Iran and Morocco indicating that the increased supply of electricity in these countries could result in longer years of schooling in these countries. Conversely, a unidirectional causality running from education to electricity consumption is observed for Algeria and Yemen: results are displayed in Table 2.

Table 2 Granger causality relationships between electricity consumption and educational attainment

Country	*Education index*	*Causality*
Bangladesh	3.52039 (0.15727)	
	6.14555 (0.08935)*	Elec → Edu
Algeria	9.92371 (0.05126)*	Edu → Elec
	0.32888 (0.60649)	
China	0.63247 (0.48456)	
	0.05335 (0.83218)	
Egypt	0.61078 (0.4915)	
	4.1736 (0.13367)	
India	0.14147 (0.73185)	
	0.00676 (0.93967)	
Iran	2.31918 (0.22516)	
	7.315 (0.0735)	
Morocco	0.42168 (0.56238)	
	5.45237 (0.10168)	
Myanmar	1.32463 (0.33317)	
	0.19493 (0.68873)	
Nepal	3.76777 (0.14756)	
	0.66894 (0.47334)	
Sudan	4.35116 (0.12827)	
	0.00157 (0.97093)	
Tunisia	1.65186 (0.28894)	
	0.70137 (0.46379)	
Turkey	4.0925 (0.13626)	
	0.6434 (0.48114)	
Yemen	10.8999 (0.04568)**	Edu → Elec
	0.02876 (0.87613)	

Note: * Significant at 90%; ** significant at 95%; → indicates causality.

4.4 Electricity consumption and GNI

Electricity consumption in Nepal was found to drive increases in income. Likewise, a unidirectional causality running from electricity consumption to GNI is observed for Myanmar and Sudan. In other words, for Myanmar and Sudan, development as measured by the HDI is presumed to drive gross electricity consumption which in turn leads to increased income, as indicated by the results displayed in Table 3.

Table 3 Granger causality relationships between electricity consumption and Income

Country	*GNI*	*Causality*
Bangladesh	0.94193 (0.40337)	
	0.01573 (0.90812)	
Algeria	0.80714 (0.43518)	
	0.76874 (0.44515)	
China	0.59622 (0.49627)	
	1.23859 (0.34689)	
Egypt	0.3279 (0.607)	
	1.75109 (0.27755)	
India	0.99631 (0.39177)	
	3.72486 (0.14917)	
Iran	0.01353 (0.91475)	
	1.49104 (0.30927)	
Morocco	0.65919 (0.47629)	
	0.02574 (0.88273)	
Myanmar	3.75489 (0.14804)	
	11.9793 (0.04061)**	Elec → GNI
Nepal	18.395 (0.0233)**	GNI → Elec
	0.24135 (0.65693)	
Sudan	1.09743 (0.37179)	
	7.59717 (0.07037)*	Elec → GNI
Tunisia	3.27338 (0.16812)	
	5.08581 (0.10941)	
Turkey	0.34671 (0.59738)	
	0.44148 (0.55392)	
Yemen	0.07381 (0.80349)	
	0.00221 (0.96549)	

Notes: * Significant at 90%; ** significant at 95%; →indicates causality.

4.5 Electricity consumption and life expectancy

The present study finds unidirectional causality running from life expectancy to electricity consumption in Iran, Morocco, Myanmar, Tunisia and Yemen, suggesting that longevity drives higher electricity consumption in these countries. In case of Sudan, electricity consumption leads to greater life expectancy, while the feedback from electricity consumption to longevity is significant at 90% for Yemen, as summarised in Table 4.

Table 4 Granger causality relationships between electricity consumption and longevity

Country	*Life expectancy*	*Causality*
Bangladesh	0.53996 (0.51568)	
	2.56143 (0.20781)	
Algeria	3.9254 (0.14188)	
	0.94815 (0.40201)	
China	0.08242 (0.79273)	
	1.99877 (0.25233)	
Egypt	0.10657 (0.76553)	
	0.01369 (0.91425)	
India	4.83968 (0.11518)	
	3.427 (0.16123)	
Iran	17.3004 (0.02527)**	Life → Elec
	4.14942 (0.13443)	
Morocco	5.58552 (0.0991)*	Life → Elec
	1.18515 (0.35595)	
Myanmar	11.624 (0.04217)**	Life → Elec
	1.64209 (0.29011)	
Nepal	2.31418 (0.22555)	
	1.01855 (0.3872)	
Sudan	1.93274 (0.25865)	
	10.5756 (0.04742)**	Elec → Life
Tunisia	9.50722 (0.05399)*	Life → Elec
	0.62926 (0.48557)	
Turkey	1.10536 (0.37031)	
	3.74177 (0.14853)	
Yemen	19.3627 (0.02176)**	Life → Elec
	6.20895 (0.08835)*	

Note: * Significant at 90%; ** significant at 95%; → indicates causality.

5 Electricity consumption, development and contentment

Traditional measures of aggregate production and consumption ignore the impacts of such economic activity on the lives of common people, in whose name the macroeconomy is said to be managed. The Happy Planet Index (HPI) computed and published by the New Economics Foundation (www.happyplanetindex.org) seeks to remedy this anomaly by assessing the ability of an economy to achieve long and satisfied lives for its people, within the constraints imposed by natural ecosystems. Among the variables considered for HPI computation is a self-reported 'experienced well-being' score from surveys of random samples of common citizens. As the 'life-satisfaction' data are available for years 2006, 2009 and 2012, and not for intervening years, the rigour of this test and the strength of the conclusions are limited by the granularity of data. The present study extends the causality tests as depicted herein below and the results are presented in Tables 5 and 6.

Table 5 Causality relationship between electricity consumption and experienced well-being scores

Country	*Intercept*	*Electricity consumption*	*HPI (t-1)*	*HPI (t-2)*
Algeria	17.3682	0.0000	0.0	0.5776
p-value	0.7139	0.9009	N/A	0.7188
Egypt	13.8109	0.0000	–0.2	0.0000
p-value	0.9144	0.8120	0.9	N/A
Myanmar	44.8925	0.0000	0.0	0.0000
p-value	0.0000	0.5212	N/A	N/A
Sudan	86.0926	0.0000	0.0	–2.6614
p-value	0.7943	0.4494	N/A	0.8309
Yemen	–17.6598	0.0000	1.1	0.0000
p-value	0.7274	0.7102	0.2	N/A

Table 6 Causality relationship between HDI numbers and experienced well-being scores

Country	*Intercept*	*HDI*	*HPI (t-1)*	*HPI (t-2)*
China	254.7746	–154.9263	–1.6566	0
p-value	0.5209	0.7055	0.8708	N/A
Egypt	–709.5055	1179.1020	–0.6724	0
p-value	0.5037	0.4813	0.6061	N/A
Morocco	153.5360	–230.1208	0.6797	0
p-value	0.2933	0.6298	0.8729	N/A
Nepal	40.2259	–181.6952	2.0202	0
p-value	0.6889	0.4575	0.5924	N/A

Group 1 nations: China, Egypt, Morocco, Nepal

Aggregate electricity consumption → HDI score → Life satisfaction

Group 2 nations: Algeria, Egypt, Myanmar, Sudan, Yemen

HDI score → Aggregate electricity consumption → Life satisfaction

6 Discussion, conclusions and recommendations

It is widely acknowledged that traditional methods of measuring economic growth, namely the GDP, GNI, per capita income, etc., do not take intangible outcomes and non-market externalities, namely healthier lives, depleting environmental stock, etc., into account, thus confirming the need for well-rounded measures of development such as the UNDP's HDI. Further, given the diminishment in the environmental stock, observers have spontaneously advocated sustainable means of development, and have proffered ideologies such as 'degrowth', which amounted to a calibrated slowing down of the economy, and 'restorative growth' with a view to restoring the damage already unleashed.

Research has hitherto presumed that electricity was an input to enhance production in an economy and that such enhanced output would automatically result in greater well-being and happiness. This in itself is not substantiated by sound statistical analyses. The present study observes that the availability of electricity plays a significant role in achieving development outcomes in a few instances, while developmental outcomes such as higher incomes, themselves drive higher electricity consumption in others. The present findings corroborate select findings of the past while contradicting others, owing to the use of the HDI scores, as opposed to gross measures such as incomes or averages such as per capita incomes, per capita electricity consumption, etc., or relative measures such as ranks.

Electricity consumption causes human development, but this causality is not true for all the countries and hence cannot be generalised across the sample. Further, given that the HDI itself is composed of three different indices (life expectancy, income and education), if unidirectional causality were found running from electricity consumption to HDI, it cannot automatically be concluded that electricity consumption caused the growth in each of, or collectively in all of, the three variables; it could well be the case that only one, or two, of these variables was driven by the increase in electricity consumption. Additionally, the results from the present analyses indicate that in countries where unidirectional causality ran from electricity consumption to development outcomes, if the production-consumption gap were to be narrowed by managing technical and commercial losses in transmission and distribution more effectively, the human development outcomes could be influenced positively. At the present moment, data on installed renewable energy capacity might be available but actual power generation from such capacity is less easy to come by. Future research could evaluate the developmental outcomes from replacing traditional centralised generation with cleaner alternatives and distributed generation.

The study was further extended to study the causality from the first-stage outcome – HDI scores or electricity consumption to 'life satisfaction' (within the HPI), as reported by a survey audience in the respective countries. Owing to limited frequency of the HPI data available, a causality relationship was not established from either electricity consumption or HDI to stated well-being. While it is acknowledged that the absence of evidence is certainly not the evidence of absence, the present study explores the oft-made arguments relating to electricity consumption and welfare.

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Should rising oil prices or monetary policy bear more responsibility for the economic recession? Empirical evidence from China

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Abstract: Based on Chinese macroeconomic monthly data from January 2001 to December 2010, a structural vector autoregression (SVAR) model is used to assess the difference in the impact of the central bank's monetary policy on output, before and after eliminating responses to oil price volatility, and to separate the net impact of oil price volatility on output. Results for the response to an impulse show that when the interference of monetary policy responses with oil price volatility is removed, the short-term negative impact of oil price shocks on output disappears. Variance decomposition results show that the contributions of oil price volatility and monetary policy to output volatility are 5.7159% and 32.4796%, respectively, or 2.5695% and 4.5606% less than before eliminating the interference, which indicate that monetary policy and its tight response to oil price shocks bear greater responsibility than the oil price shocks for the economic recession in China.

Keywords: oil price shocks; monetary policy; output volatility; China.

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1 Introduction

According to BP Statistical Review of World Energy, oil accounts 33.6% of global primary energy consumption in 2010, and oil price shocks affect every aspect of modern life. Rising oil prices are regarded as a threat to global inflation and economic growth. Since the 1970s, the world has experienced three oil crises, and each crisis gave the global economy a huge shock. The first oil crisis started in October 1973, when the members of the OAPEC proclaimed an oil embargo. By the end of the embargo in March 1974, the price of oil had risen from \$3 per barrel to nearly \$12. This oil crisis caused American industrial production dropped by 14%, and Japanese by above 20%. The Second oil crisis occurred in the USA due to decreased oil output in the wake of the Iranian Revolution in 1979. The price of crude oil rose from \$13 to \$34 per barrel among 12 months. The rise in prices is widely believed to have been a significant factor in the western economic recession of the late 1970s.The Third oil crisis was caused by the Gulf War in 1990. Average monthly prices of oil rose from \$17 per barrel in July to \$36 per barrel in October. The first and second oil crises, especially, had a significant negative impact on Western countries and led to economic recession and double-digit inflation. Oil price shocks were accompanied usually by monetary policy changes; if the monetary authorities' tightened monetary policy to fight against inflation, further economic downturn would follow as a consequence. Although for many economies the empirical results support the conclusion that high oil prices have negative impacts on the macroeconomy, such as early studies of Hamilton (1983, 1988, 1996), Mork and Olsen (1994), Lee and Ni (1995) on developed countries and later studies of Cunado and Gracia (2005), Fan et al.(2007), Rafiq et al. (2009) on developing countries, there is still no unanimous conclusion about whether oil prices or monetary policy should bear more responsibility for the economic recession. Ferderer (1996) found that monetary policy tightens after oil price shocks, whereas oil price shocks have stronger, more prominent impacts on an economy than monetary policy. Darrat et al. (1996) finds that the impacts of oil prices on US output disappear when they control for the impact of interest rates. Bernanke et al. (1997) use the standard vector autoregression (VAR) model and the structural vector autoregression (SVAR) model to compare the two cases (whether or not monetary policy responds to oil price shocks), and they find that the impacts of oil price shocks on output are much smaller in the latter case. Moreover, its effects disappear rapidly. Leduc and Sill (2004) use a dynamic stochastic general equilibrium model to simulate the impacts of oil price on a real economy under two different policy environments, the fixed growth rate of currency (i.e., monetary policy does not react to oil price) and simple Taylor monetary policy rules (i.e., monetary policy responds to oil price). They find that output losses brought by the former are 37% smaller than losses that result from the latter. Hamilton (2008) notes that most empirical studies contend that the increase of oil prices bears more responsibility than monetary policy for the loss of output.

With China's accession to the WTO in 2001, its degree of economic openness is growing. The impact of oil price shocks on its macroeconomy is becoming a concern in Chinese society. Although China's energy consumption structure is still dominated by coal, oil consumption only accounts for 20% of China's primary energy consumption. However, China's economy has never before depended on oil like it does today, nor has it been so sensitive to oil prices. According to data disclosed by the Chinese Ministry of Industry, during the first five months of 2011, China's dependence on imported oil reached 55.2%, in comparison to the USA where dependence on imported oil was 53.5%. China surpassed the USA to become the largest importing country in the world; this percentage also exceeds 50%, which is recognised internationally as a "security warning line". China has become one of the nations in the world that is most vulnerable to oil price shocks. There are many studies on the impact of oil price shocks on China's macroeconomy, which mainly focus on certain aspects of the impact of oil price shocks on the macroeconomy, especially the GDP. For example, Du et al. (2010) apply VAR models to find that world oil prices significantly affect the economic growth and inflation in China. Fan et al. (2007) and Wei et al. (2010) systematically analyse the effects of oil prices on the macroeconomy by using the Computable General Equilibrium (CGE) model, and their results indicate that international crude oil prices have negative effects on the Chinese real GDP and positive effects on the overall price level. By developing a SVAR model, Tang et al. (2010) find that an oil price increase negatively affects output and investment but positively affects inflation and interest rates. Lin and Mou (2008) conduct an analysis under the framework of CGE and note that for China's economic structure, an energy price increase leads to a decline in real output, may result in inflationary pressures at the same time, and likely leads to economic stagflation. Liu and Jiang (2009) come to similar conclusions by using the SVAR model. Based on 1994–2009 quarterly data and the co-integrated vector error correlation model, Zhou and Li (2010) find that there is an equilibrium relationship between oil prices and GDP; a long-term rise in oil prices restrains the growth of GDP, while a short-term increase in oil prices has a positive (but insignificant) impact on GDP. However, the above-mentioned literature does not distinguish oil price shocks from monetary policy response in examining the impact of oil price shocks on the macroeconomy, and thus, these results cannot reflect the true impact of oil price shocks on output. There is not enough corresponding empirical evidence about whether rising oil prices or monetary policy should bear more responsibility for economic recession.

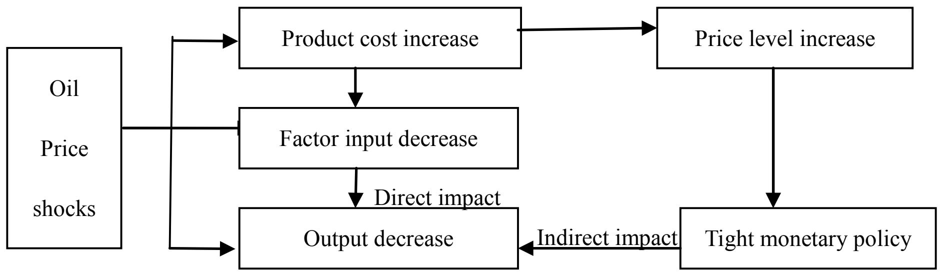
In this paper, we develop a SVAR model to empirically analyse the impact of crude oil price volatility on China's macroeconomy. We examine whether monetary policy variation is affected by oil price volatility and attempt to eliminate the disturbance of monetary policy affected by oil shocks in order to reveal the true impact of oil price volatility on output. The remainder of the article is organised as follows: Section 2 presents the transmission mechanism of oil price shocks to China's macroeconomy, Section 3 describes the empirical model and data analysis, Section 4 discusses the empirical results, and Section 5 summarises this article.

2 Transmission mechanisms of oil price shocks to China's macroeconomy

Representative theories of the mechanisms and channels of oil price shocks that affect the macroeconomy include the theories of supply shocks effect, income transfer effect, and monetary channel effect. The theory of supply shock effect explains the impact of oil price shocks on a macroeconomy from the aspect of aggregate supply. Bernanke (1983), Hamilton (1988), and Rotemberg and Woodford (1996), for example, believed that enterprises reduce inputs of energy, capital, and labour because of higher oil prices, which results in a decline in production capacity and an increase in unemployment in the economy. Economic entities will enter a new stable equilibrium growth path, and the output growth rate will slow down under the new stable equilibrium. Dohner (1981) and Brown and Yucel (2002) emphasised the income transfer effect of higher oil prices. They believed that oil price increases lead to the transfer of income from net oil importers to net oil exporters. Income decline leads the rational consumers in net oil importers to reduce their consumption expenditures, thereby reducing aggregate demand. The demand increase that results from the revenue increase in oil-exporting countries is less than the demand decrease of oil-importing countries, which gives rise to a global aggregate consumption demand reduction, output decline, and even economic recession. The theory of monetary channel effect advocates that oil price increases change a country's monetary policy and, therefore, have an impact on output and prices. Pierce and Enzler (1974) and Segal (2007) believe that oil price increases affect an economy through monetary channels from two sides. On one hand, higher oil prices increase general price levels, reduce real money balances, increase the real interest rates, and have an adverse impact on the economy. On the other hand, if an economy is not satisfied with the real income decline caused by an economic downturn, then easing monetary policy is adopted in light of stabilising short-term output and wages and prices will rise sharply. Monetary authorities will adopt a tight monetary policy in order to maintain the relative stability of output and inflation, and thus, the real economy will suffer a greater negative impact in the long run.

Synthesising mainstream studies, this paper considers that oil price shocks mainly affect China's macroeconomy from direct and indirect approaches according to the specific mechanism shown in Figure 1. On one hand, as an important means of production, oil price increases will lead to higher energy, capital, and labour prices, and the increase on general price levels has a direct impact on the macroeconomy. On the other hand, the general price level increase will urge the central bank to tighten its monetary policy in order to stabilise prices and, consequently, lead to a second round of variations of output and price levels, which is the indirect impact. Although the Chinese government regulates refined oil prices, higher crude oil prices will lead to the increase of the prices of coal and other oil alternatives, and enterprise production costs will go up. This will cause enterprises to reduce the factors of production inputs, diffuse their rising costs to downstream industries through the industry chain and, finally, to consumer goods, forming the hidden dangers of inflation. To keep the national macroeconomy stable and stabilise prices, tight monetary policy will be adopted, and the economy will further decline.

Figure 1 Transmission mechanism of oil price shocks to a macroeconomy.



3 An empirical model

Structural vector autoregression (SVAR) models have become a popular tool in recent years in the analysis of the monetary transmission mechanism and sources of business cycle fluctuations. It is an extension on the traditional VAR approach in that it combines economic theory with time-series analysis to determine the dynamic response of economic variables to various disturbances. The main advantage of SVAR analysis is that the necessary restrictions on the estimated reduced form model make the economic significance of a model much clearer. Prior researchers have successfully employed SVAR models, for instance, Ahmed et al. (2011), Yasunori et al. (2013) and Fardous et al. (2013) examined the impact of oil price shocks on macroeconomic activities of Asia and Pacific such as Australia, New Zealand, Singapore, Hong Kong, Malaysian etc. In this paper, we follow their example and adopt SVAR model to analyse the impact of oil price shocks on price levels and total output of China, and then, using the strategy of Bernanke et al. (1997) to separate the impact of interest rate variations from the comprehensive impacts of oil price shocks, we explore the independent actions of oil price and monetary policy behind these impacts.

3.1 Variable selection and measurement

Consistent with our research goal, this paper examines the impact of international crude oil price volatility on four different variables: producers' cost, price level, monetary policy, and output variations. Firstly, as mentioned above, oil price shocks are important reasons for the world economic fluctuations. We therefore introduce oil price as an independent variable into the SVAR as a leading indicator of commodities price. Secondly, although refined oil prices in China are regulated by government, higher crude oil prices may lead to the increase of the prices of coal and other oil alternatives, and enterprise productions costs will then go up. Therefore, the Industrial Producer Purchasing Price Index measuring the cost to producers is included in the SVAR, serving as a mediation variable of oil price fluctuation affecting economy and a leading indicator of inflation level. Thirdly and Fourthly, in order to investigate the impact of oil prices volatility on China's output and the responses of monetary policy, we bring output and monetary policy variables into the model. However, as a large independent economic system, Chinese macroeconomics are only weakly and remotely affected by foreign output, prices, and interest rate. Therefore we do not include these exogenous variables in our model. To draw conclusions as objectively as possible to reflect Chinese current economic realities, this paper uses the research sample interval from January 2001 to December 2010, a total of 120 months of data.

This paper chooses the WTI price volatility as the metric of international oil prices, and transforms the dollar price into the Renminbi (RMB) price by means of the exchange rate. Oil price data come from the website of the US Energy Information Administration (http://www.eia.doe.gov/), and data for the exchange rate come from the official website of the People's Bank of China (http://www.pbc.gov.cn/). We choose the Industrial Producer Purchasing Price Index to measure the cost to producers and the consumer price index (CPI) to measure the level of inflation. Both sets of price index data come from the official website of the National Bureau of Statistics. We choose M2 to measure monetary policy because the chain growth of the M2 money supply is recognised as the indicator that best reflects the monetary policy condition. In addition, because China only publishes quarterly GDP data, we choose the growth rate of industrial added value instead of GDP growth as the metric of output volatility. Data for M2 and the growth rate of industrial added value come from the official website of the People's Bank of China and the China Economic Information Network statistical database (http://db.cei.gov.cn/). We convert the industrial producer purchasing price index, consumer price index, M2, and the industrial added value to time series whose base period is January 2001. In addition, to avoid bias arising from seasonal factors, this paper also uses the X12 seasonal adjustment method to eliminate seasonal fluctuations in the above-mentioned variables. For details, see Table 1.

Table 1 Variable specification

Variable code	*Variable name*	*Variable meaning*	*Fixed base processing*	*Seasonal adjust*	*Processing specification*
OILP	West Texas Intermediate crude oil price	Oil prices expressed in local currency	×	×	Convert into RMB according to exchange rate
IPPI	Industrial product purchase price index	Price level variation of main raw material, fuel, power in industrial company	✓ (2001.01=100)	✓	Calculate depending on base year's raw material price and year-on-year growth data
CPI	consumer price index	Level of inflation	✓ (2001.01=100)	✓	Convert by month to month data
M2	Money supply	Monetary policy variation	✓ (2001.01=100)	✓	Convert by month to month data
OUTP	Industrial added value	Output variation	✓ (2001.01=100)	✓	Convert according to base year's industrial added value and year-on-year data

Notes: "✓" represents "Yes" , "×" represents "No".

3.2 SVAR model

The representation of p-order lag SVAR model that includes k variables is:

$$AY_t = A_0 + \sum_{i=1}^{p} A_i L^i Y_t + \varepsilon_t \tag{1}$$

where $Y_t = \left(y_{1t}, y_{2t}, \ldots, y_{kt}\right)'$ is a $(k+1)$ vector, $A_i, i = 1, \cdots, p$ are the $k \times k$ coefficient matrix, L is the lag operator, ε_t is a $(k+1)$ order white noise random error vector, $E\left(\varepsilon_t \varepsilon_t^{'}\right) = D = I$, and coefficient matrix A describes the relationships among variables over the same period.

Multiplying both sides of formula (1) by A^{-1} , we get:

$$Y_t = A^{-1}A_0 + \sum_{i=1}^{p} A^{-1}A_i L^i Y_t + A^{-1}\varepsilon_t = B_0 + \sum_{i=1}^{p} B_i L^i Y_t + u_t \tag{2}$$

where $B_0 = A^{-1}A_0,\ B_i = A^{-1}A_i$.

Further simplify formula (2) to get:

$$B(L)Y_t = B_0 + u_t \tag{3}$$

where $B(L) = I_k - \sum_{i=1}^{p} B_i L^i$ is a (k×k) parameter matrix of the lag operator L.

The covariance matrix of the error vector in formula (3) is as follows:

$$E\left(u_t u_t^{'}\right) = A^{-1}E\left(\varepsilon_t \varepsilon_t^{'}\right)(A^{-1})^{'} = A^{-1}D(A^{-1})^{'} = \Omega = I_k \tag{4}$$

To estimate the SVAR model, first use the least squares method to estimate formula (2), then calculate Ω, and, finally, estimate the parameters of the SVAR model according to the restriction. In the SVAR model, if no constraint is imposed on matrix A, there will likely be many solutions, leading to an unidentified model. To identify the structural impact of the SVAR model, matrix A needs k*(k–1)/2 constraints to be imposed. Based on economic theory, practical experience, and research purposes, researchers usually sort the variables of the SVAR model and restrict contemporaneous relationships among variables.

According to the analysis of mechanism of oil price shocks to China's macroeconomy in Section 2, we sort the endogenous variables in the SVAR model as follows: oil price volatility (OILP), Industrial Products Purchased Price Index (IPPI), Consumer Price Index (CPI), money supply (M2), and industrial added value (OUTP). The specific model is defined as follows:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ a_{21} & 1 & 0 & 0 & 0 \\ a_{31} & a_{32} & 1 & 0 & 0 \\ 0 & a_{42} & a_{43} & 1 & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & 1 \end{bmatrix} \begin{bmatrix} OILP \\ IPPI \\ CPI \\ M2 \\ OUTP \end{bmatrix} = A_0 + \sum_{i=1}^{p} A_i L^i \begin{bmatrix} OILP \\ IPPI \\ CPI \\ M2 \\ OUTP \end{bmatrix} + \begin{bmatrix} \varepsilon_t^{OILP} \\ \varepsilon_t^{IPPI} \\ \varepsilon_t^{CPI} \\ \varepsilon_t^{M2} \\ \varepsilon_t^{OUTP} \end{bmatrix} \tag{5}$$

and, $E\left(\varepsilon_t \varepsilon_t^{'}\right) = D = I$.

The first and second formulas in the model are the energy price volatility equation (5.1) and equation (5.2). As the shares of Chinese oil production and consumption in the world are not large enough to directly affect the world crude oil price, we assume that the OILP is not affected by other economic variables in the contemporaneous period. Although the refined oil price is regulated by the government, coal and other energy prices fluctuate in the same direction as crude oil price volatility. So, a_{21} is expected to be negative, and the IPPI is not affected by other variables in the short-term.

The third formula in the model is China's CPI equation (5.3), and the expression is:

$$CPI = -a_{31}OILP - a_{32}IPPI \tag{5.3}$$

The IPPI reflects the variation of the price level of main raw materials, fuel, power, and some daily necessities. The rise of oil prices and the IPPI will lead to an increase in inflation. Therefore, this paper assumes that the inflation rate is contemporaneously positively influenced by crude oil prices and the IPPI, and a_{31} and a_{32} are expected to be negative.

The fourth formula is the central bank's M2 equation (5.4):

$$M2 = -a_{42}IPPI - a_{43}CPI \tag{5.4}$$

To stabilise commodity prices, the central bank usually adjusts the money supply by adjusting the legal reserve requirement, the official rate of interest, and other means in accordance with the relevant price level. Due to price regulations for refined oil, crude oil price shock is of less reference value than the IPPI and CPI to the central bank's M2. Therefore, we assume that M2 is influenced by the IPPI and the impact of the CPI over the same period and not affected by the contemporaneous OILP. Thus, a_{42} and a_{43} are expected to be positive.

The fifth formula is the OUTP equation (5.5):

$$OUTP = -a_{51}OILP - a_{52}IPPI - a_{53}CPI - a_{54}M2 \tag{5.5}$$

Because energy is the source of the main raw materials and power for most industries, this paper assumes that the OUTP will be negatively affected by contemporaneous major energy price fluctuations, including the OILP and the IPPI, and a_{51} and a_{52} are expected to be positive. In addition, the central bank adopts the proper monetary policy tools at their discretion to adjust the M2 according to the CPI, and the OUTP will be affected. Thus, we assume that the CPI and the M2 will contemporaneously affect the OUTP, a_{53} will be positive, and a_{54} will be negative.

3.3 Method of eliminating the monetary policy reaction to oil price volatility

To remove the responses to oil price shocks from the monetary policy, we follow the strategy adopted by Bernanke et al. (1997) that separates the impact of variations in interest rates from the combined effects of oil price shocks and analyse the impact of oil shocks on the macroeconomy after eliminating monetary policy responses to oil shocks. If we do not consider other variables except oil price volatility, M2 can be represented (depending on oil price shocks) in a moving average form as follows:

$$M2_t = \lambda_0 e_t + \lambda_1 e_{t-1} + \cdots + \lambda_p e_{t-p} \tag{6}$$

where e_{t-i} denotes the innovation of OILP which have a unit variance and λ_i are moving average parameters. The moving average parameters in formula (6) are the lag impulse response of the M2 with respect to one standard deviation of innovation of OILP. For instance, a one standard deviation of OILP induces a contemporaneous response λ_0 of M2, 1 month delayed response λ_1, and etc.

Then, an adjusted monetary policy variable series, $M2A_t$, devoid of responses to oil price volatility, can be constructed as follows:

$$M2A_t = M2_t - \sum_{i=0}^{p} \frac{b_i \times \mathrm{Re}\,sid_{t-i,OILP}}{S.D._{OILP}}, \ p \le 120 \tag{7}$$

where Resid is the time (t-i) residual of the regression of OILP on other variables in the SVAR model. S.D. is the standard deviation of Resid, and $b_i = \lambda_i \times S.D$ is the magnitude of the *i*th period impulse response of M2 to a one-standard deviation shock in OLIP, *p* is the lag phase of the impact of OILP on M2. Taking into account the possibility that the impact of OILP on M2 may persist for a long time, we set *p* as the maximum value of the sample (*p* = 120).

Re-estimating the SVAR model with the $M2A$ series, we can obtain the coefficient matrix from the new variables and the new impulse response functions. The $M2A$ series no longer contains the effects of OILP. To re-estimate the coefficient matrix A in the SVAR model, we need to redefine equation (5.4). Assuming that M2 is negatively affected by the contemporaneous CPI and, no longer is subject to the impact of OILP and IPPI, then the monetary policy equation becomes:

$$M2 = -a_{43}CPI$$

where $a_{41}=a_{42}=0$, $a_{43} > 0$.

4 Empirical results and analysis

4.1 Data processing

Economic and financial time series usually are non-stationary and have strong trends. Setting up the SVAR model with non-stationary series may lead to spurious regression, so we applied the Augmented Dickey-Fuller (ADF) test to check whether all of the variables are stationary. If the series are non-stationary, then the usual approach is difference processing, which may lead to excessive differences and the loss of important information. This paper refers to the method of Toda and Yamamoto (1995), adopted with no difference processing, which takes $p + d_{\max}$ as the best lag phases of the VAR model to eliminate spurious regression among the variables. Where p is the VAR model lag term determined by general methods, $d_{\max}$ is the largest cointegration order that may exist in the variables. Table 2 presents the stationary test results with ADF test.

Table 2 ADF test for stationary

Variable	*Random walk model*	*Random walk model including intercept*	*Random walk model including tread term and intercept*
		Levels	
OILP	0.8320	0.4640	0.2531
IPPI	09862	0.9307	0.1559
CPI	0.9999	0.9998	0.4828
M2	0.9999	0.9971	0.9253
OUTP	1.0000	0.9552	0.3369

Table 2 ADF test for stationary (continued)

Variable	*Random walk model*	*Random walk model including intercept*	*Random walk model including tread term and intercept*
		First differences	
$\triangle$OILP	0.0000**	0.0000**	0.0000**
$\triangle$IPPI	0.0002**	0.0007**	0.0043**
$\triangle$CPI	0.0035**	0.0000**	0.0000**
$\triangle$M2	0.0973*	0.0004**	0.0014**
$\triangle$OUTP	0.0642*	0.0000**	0.0000**

Notes: ** and * represent rejection of the null hypothesis at the significance levels of 1% and 10%, respectively.

Test results show that the original series are non-stationary, but the first-order differences are all stationary. Thus, the modelling series are the $I(1)$ series and $d_{\max} = 1$. The VAR model lag orders determined by the criteria AIC, SC, LR, the FPE, and HQ are shown in Table 3. The determined lag phase is 2 by three types of criteria, so we choose it for the lag terms of the VAR model. Moreover, $d_{\max} = 1$, and then 3 is the best lag phase of the SVAR model in our study.

Table 3 Decision for lag terms of the VAR model

Lag	*LR*	*FPE*	*AIC*	*SC*	*HQ*
0	NA	1.79e-12	–12.8568	–12.7355	–12.8076
1	1893.3570	4.91e-20	–30.2723	–29.5441	–29.9768
2	141.3655	1.90e-20	–31.2535*	–29.8905*	–30.6839*
3	45.5436	1.86e-20*	–31.2448	–29.3117	–30.4657
4	39.8330*	1.90e-20	–31.2255	–28.6962	–30.2108
5	19.3222	2.42e-20	–31.0230	–27.8676	–29.7428
6	19.4210	3.07e-20	–30.8164	–27.0542	–29.2899
7	23.2894	3.68e-20	–30.6764	–26.3074	–28.9037
8	28.9026	4.07e-20	–30.6370	–25.6612	–28.6182

Note: * represents the optimal lag term.

4.2 SVAR model estimation results and analysis

Estimated results for the coefficient matrix A are shown in Table 4. As we expected, a_{21} and a_{31} both are negative, which means that the IPPI and CPI increase along with the OILP, while a_{21} is not significant.

Contrary to our expectations, a_{32} is positive, which means that the CPI does not rise with the increase of the IPPI. The possible reason for the behavior of the CPI may be related to price regulation policy in China, like the study of Wu et al. (2012). China’s price regulation is focused mainly on basic industrial raw materials and consumer goods, and it takes direct price regulation on basic industrial raw materials while it guides the prices of consumer goods by increasing the supply or taking indirect regulation through monetary policy. When faced with wild shocks in the international oil price, the prices of basic industrial raw materials, such as refined oil and electricity, do not rise sharply due to direct regulation, but the CPI increases significantly because of general changes in relative prices caused by oil price shocks.

Table 4 Coefficient matrix A estimates

	OILP	*IPPI*	*CPI*	*M2*	*OUTP*
Equation (5.1)	1	0	0	0	0
Equation (5.2)	–0.0130	1	0	0	0
Equation (5.3)	–0.0052**	0.0218	1	0	0
Equation (5.4)	0	0.0362	0.0994**	1	0
Equation (5.5)	0.0030**	–0.0146	0.2406***	–0.1280**	1

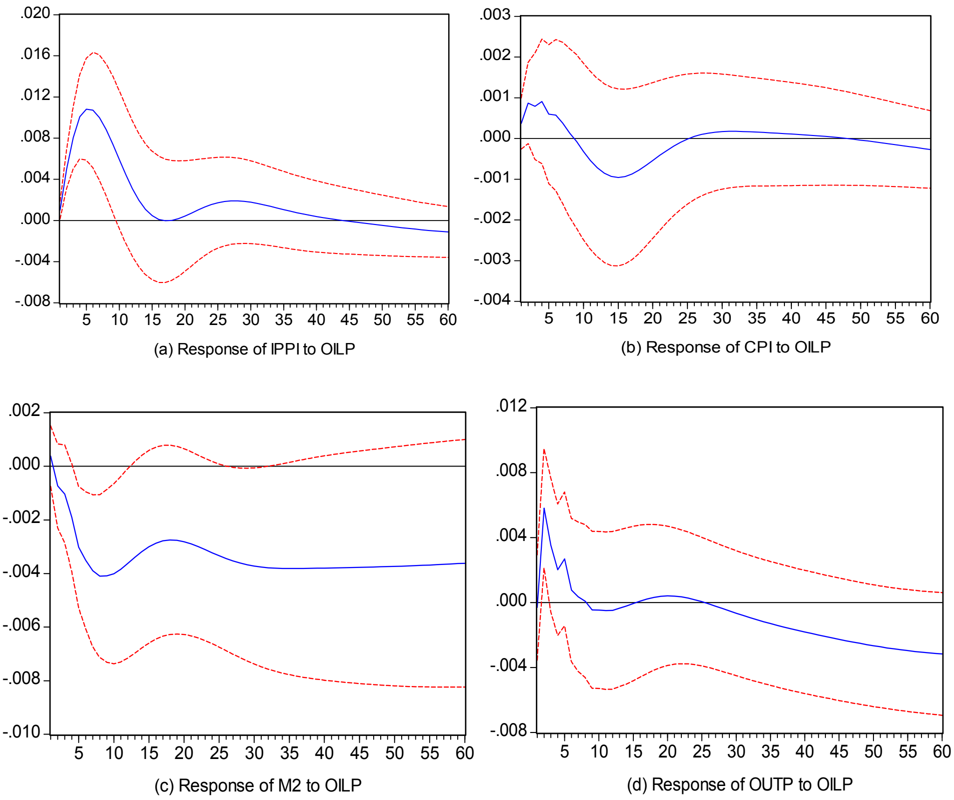
Notes: ***, **, and * represent significance at the 1%, 5% and 10% levels, respectively.

In equation (5.4) for the central bank's monetary policy, a_{42} and a_{43} are positive and consistent with our expectations, which means that the central bank timely reduces M2 according to the rise of the IPPI and CPI. In equation (5.5) for output variations, a_{51} is positive and consistent with our expectation, which demonstrates that a rise in the OILP will reduce the OUTP, which is significant at the level of 5%. Contrary to our expectation, a_{52} is negative; that is, the OUTP rises along with the increase of the IPPI. We speculate that faced with rising production costs, enterprises can raise prices to maintain profits and output levels based on the price elasticity of demand in the short run, which is why the OUTP does not decrease with the rise of the IPPI. a_{53} is positive, and it is significant at the level of 1%; the CPI will have a significantly negative impact on the OUTP, which is again consistent with our expectations. a_{54} is negative, which means that the OUTP and the M2 move in the same direction, which is also consistent with our expectations.

Figure 2 shows the impulse response of the SVAR model. From Figure 2, we can find the responses of variables to the OILP during 60 month lag terms. The impact of one standard deviation impulse of the OILP on the IPPI is positive from the second term, reaches a maximum in the fifth term, subsequently gradually weakens to close to zero in the 16th term, and, after that, the positive impacts slightly bounce up again and fade in the 44th term. The results show that faced with rising oil prices, despite the refined oil price regulation in China, the main production costs of industrial enterprises respond in a short time and the impacts persist for a long time.

One standard deviation impulse of the OILP has a positive effect on the CPI in the short term, which rises gradually and reaches a maximum in the 4th term. The effect begins to weaken rapidly from the 5th term and finally changes into a negative effect from the 9th term, which reaches a maximum in the 15th term and maintains a negative effect in the long term. This indicates that rising oil prices drive inflation to increase in the short term, while it will turn out to be a recession with the reversal of the economy over a little longer time frame, which will cause deflation.

Figure 2 Impulse responses and their two standard deviation error bounds from the SVAR model (see online version for colours)



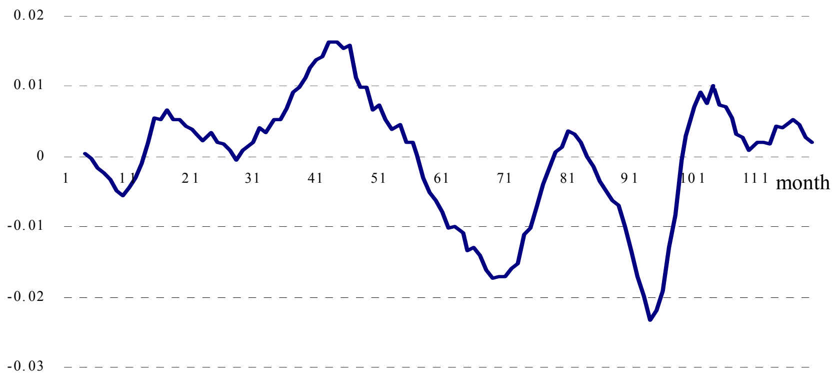
The M2 displays an obvious negative reaction from the 2nd term and reaches a maximum in the 8th term for one positive standard deviation impulse in oil prices. Although this negative effect subsequently slows down and repeats, it persists for a long time, which indicates that rising oil prices have a greater impact on monetary policy in China, where the central bank usually adopts a tight monetary policy in response to inflation expectations caused by rising oil prices, and continues during a longer cycle, which is very consistent with the actual situation in China.

The OUTP does not immediately turn out to be in a recession during the first eight terms following one positive standard deviation impulse in the OILP. On the contrary, rising oil prices will stimulate an increase in output. However, this positive impact decreases gradually from the 9th term and changes into a negative effect from the 16th term. After some slight fluctuations over a period of time, the oil price volatility begin to have a continuously negative impact on output.

4.3 The responsibility of the recession analysis

According to section 3.3, Figure 3 plots the fluctuations of M2 attributed to oil price volatility.

Figure 3 Fluctuations of money supply attributed to oil price volatility (see online version for colours)



According to formula (6), we obtain the adjusted money supply series M2A and re-estimate the SVAR model. Then, we get the new impulse response function, which is shown in Table 5 and Figure 4. Comparing Table 5 with Table 4, we find that, after eliminating monetary policy responses to oil price volatility, only a_{51} changes from negative to positive, which means that the negative impact of oil prices on contemporaneous output disappears after eliminating the monetary policy response. Thus, without taking into account the responses of the monetary policy, rising oil prices have little direct impact on output in the short term.

Table 5 Coefficient matrix A estimates after eliminating monetary policy responses to oil price volatility

	OILP	*IPPI*	*CPI*	*M2*	*OUTP*
Equation (5.1)	1	0	0	0	0
Equation (5.2)	–0.0131	1	0	0	0
Equation (5.3)	–0.0033*	0.0254	1	0	0
Equation (5.4)	0	0	0.1007**	1	0
Equation (5.5)	–0.0018	–0.0039	0.2367***	–0.0640*	1

Notes: ***, **, * represent significance at the 1%, 5% and 10% significance levels, respectively.

Figure 4 shows the impulse response of the SVAR model to the OILP after eliminating the monetary policy response to oil price volatility. Comparing Figure 4 with Figure 2, we found that after eliminating the monetary policy response to oil price volatility, for one standard deviation variation of oil prices, the impulse response functions of the IPPI and CPI are basically the same as those in Figure 2 and there is no essential difference except slight differences in lagged terms. Figure 4 (c) shows the impulse response of the M2 after the removal of the interference of monetary policy response to oil price volatility. From Figure 4(c), we can determine that for the first 10 terms, the response of the adjusted M2A series basically hovers around 0 for the impulse of oil prices, followed by a contractile response, and then remains below 0. The results suggest that the oil price volatility basically has no impact on the monetary policy in the short term, after excluding the interference of the monetary policy response to oil price volatility.

Moreover, they also demonstrate that the method of excluding the interference of oil price s volatility used in the paper is effective. However, oil price volatility still had a negative impact on monetary policy after a long period (10 months later). This suggests that, in the long term, rising oil prices will affect monetary policy due to variations in relative prices.

Figure 4 Impulse response to oil price volatility after removing the interference of monetary policy (see online version for colours)

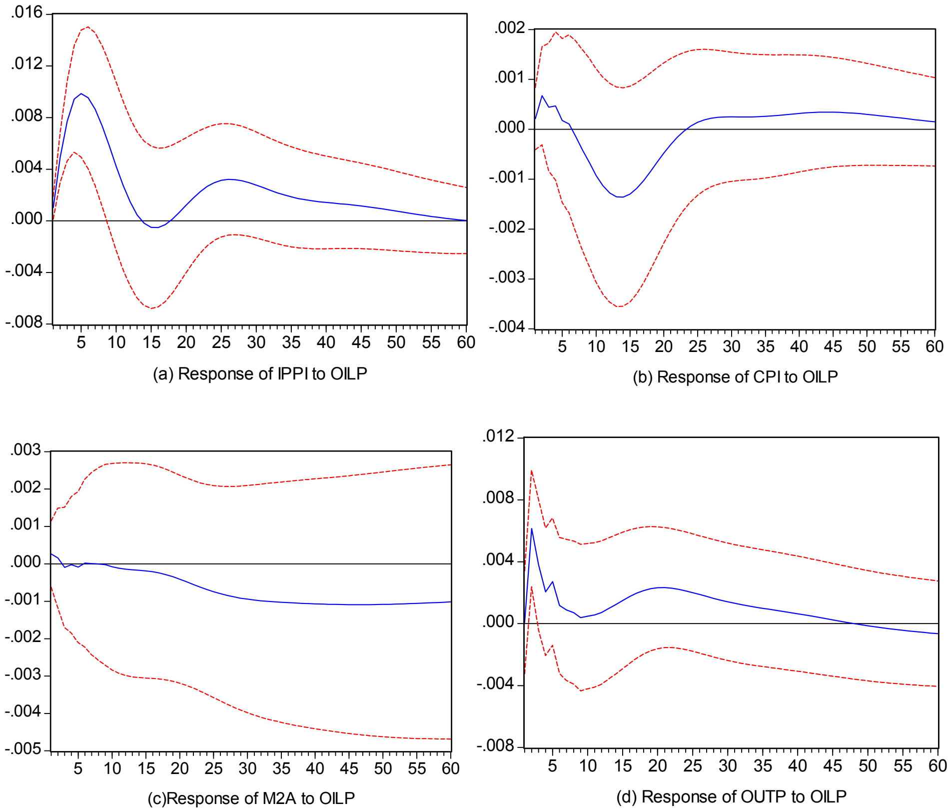


Figure 5 shows the impulse response of the OUTP to the OILP variation before and after eliminating the influence of oil price volatility on the monetary policy. From Figure 5, after eliminating the influence of oil price volatility on the central bank's monetary policy, the impulse response of the OUTP to the OILP become weaker, the onset of economic recession is delayed, and the depth of economic recession is greatly reduced.

To further analyse the role played by monetary policy in the process of an economic recession caused by oil price volatility, this paper compares the variance decompositions of the OUTP before and after eliminating the monetary policy responses to oil price volatility, From Tables 6 and 7, we find that in the 60th term (after removing the monetary policy responses to oil prices), the OUTP error decomposition proportions explained by the volatility of the OILP and M2 were 5.7159% and 32.4796%, respectively, which were 2.5381% and 4.5606% less than the results obtained without eliminating the interference (the response of monetary policy to oil prices). The proportions explained by the IPPI and CPI became a little larger. These results again indicate that the central bank's monetary policy and its tightening response to oil price rising should bear more responsibility for the economic recession caused by oil price volatility in China. In view of robustness, the output error decompositions in the 70th and 80th terms are also reported in Table 6 and Table 7, and the conclusion is basically the same as in the 60th term.

Figure 5 Impulse response of output to oil price volatility before and after eliminating the interference of monetary policy (see online version for colours)

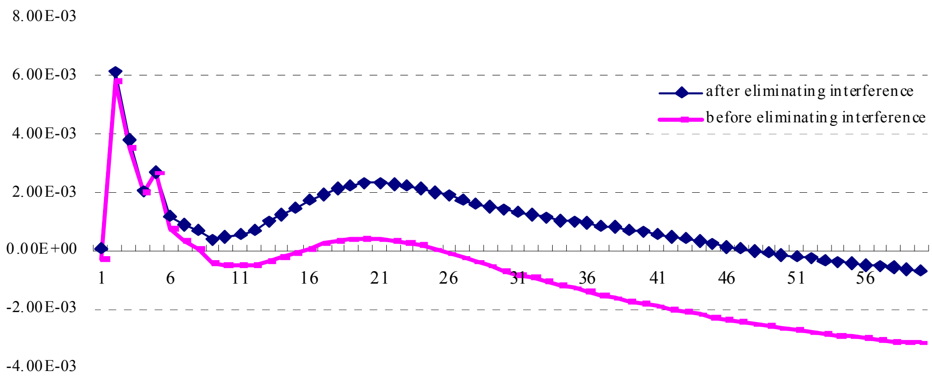


Table 6 Variance decomposition of the output before eliminating the monetary policy responses to oil price volatility

Period	*S.E.*	*OILP*	*IPPI*	*CPI*	*M2*	*OUTP*
1	0.0810	0.0286	0.4095	9.7013	2.1783	87.6824
2	0.1224	9.0287	5.5821	7.9675	2.5266	74.8951
3	0.1583	9.5032	6.7491	8.6451	4.9729	70.1297
4	0.1839	8.3286	7.4165	9.1356	4.9711	70.1482
5	0.2020	8.4929	7.8940	9.4720	5.8563	68.2848
6	0.2139	7.5507	7.5887	11.0470	6.5858	67.2278
7	0.2220	6.8758	7.3173	12.6062	7.1018	66.0989
8	0.2277	6.3503	7.0237	14.3363	7.8470	64.4427
9	0.2326	5.9063	6.7102	16.2680	8.5117	62.6038
10	0.2369	5.5632	6.4816	18.0660	9.2078	60.6814
20	0.2641	3.8669	5.8718	28.3811	17.4552	44.4250
30	0.2797	3.2549	5.1126	29.3760	25.3043	36.9523
40	0.2872	3.7279	4.6675	26.9629	31.3218	33.3200
50	0.2907	5.5627	4.8604	24.2177	35.1542	30.2049
60	0.2924	8.2854	5.3136	22.2555	37.0402	27.1053
70	0.2936	11.0392	5.6445	20.7970	37.7881	24.7312
80	0.2945	13.3084	5.7494	19.4410	38.1896	23.3117

Table 7 Variance decomposition of the output after eliminating the monetary policy responses to oil price volatility

Period	*S.E.*	*OILP*	*IPPI*	*CPI*	*NM2*	*OUTP*
1	0.0801	0.0024	0.4892	9.4710	1.9430	88.0944
2	0.1197	9.8031	5.7362	7.7201	1.8544	74.8863
3	0.1531	10.5638	6.8133	8.3464	3.1906	71.0860
4	0.1774	9.1639	7.5841	8.9015	3.4156	70.9350
5	0.1949	9.2473	8.1283	9.3973	3.8305	69.3965
6	0.2076	8.3272	7.7721	10.8267	4.2828	68.7913
7	0.2172	7.6826	7.4858	12.2500	4.6454	67.9361
8	0.2249	7.1774	7.1705	13.8630	5.0978	66.6913
9	0.2315	6.7123	6.8523	15.5969	5.5701	65.2684
10	0.2372	6.3637	6.6181	17.2496	6.0856	63.6830
20	0.2654	6.2936	5.3657	27.5356	12.9940	47.8112
30	0.2826	7.1220	4.5012	30.0414	19.5321	38.8034
40	0.2907	6.6785	4.9220	29.0146	24.9342	34.4508
50	0.2946	6.1011	6.2389	26.8673	29.2170	31.5757
60	0.2960	5.7159	7.8052	24.8288	32.4796	29.1706
70	0.2966	5.5489	9.1595	23.0828	34.9841	27.2247
80	0.2969	5.4806	10.1730	21.5370	37.0331	25.7764

5 Conclusions

In this paper, we empirically investigate the impact of oil price volatility on monetary policy and the impact of purging the monetary policy responses to oil price volatility on output, separate the impacts of oil price volatility and monetary policy on output, by constructing a five-variable SVAR model, select monthly data from January 2001 to December 2010 as the study sample, and come to the following conclusions:

1 Before eliminating the responses of monetary policy to oil price volatility, the short-term impact of rising oil prices on output is negative and significant at the level of 5%; after eliminating the responses, the short-term negative impact of rising oil prices on output disappears.

2 Before eliminating the monetary policy responses to oil price volatility, the impacts of one standard positive deviation impulse of oil prices on money supply are obviously negative from the 2nd term and reach a maximum in the 8th term, and the adverse impact persists for a long time. Oil price volatility basically has no impact on money supply in the short term, after eliminating the responses of monetary policy to oil price volatility. However, oil price volatility still has a negative impact on monetary policy after a long period (10 months later).

3 Facing short-term rising of oil prices, the CPI does not increase with the index of industrial product purchase price; output does not decrease significantly either.

4 Variance decomposition results show that before the response to oil price volatility is removed from the monetary policy, the contributions of oil price volatility and monetary policy to output variability are 8.2854% and 37.040 2%, respectively. After eliminating the monetary policy responses to oil price volatility, the contributions change to 5.7159% and 32.4796%, lower by 2.5381% and 4.5606%, respectively. However, the contributions of the index of industrial product purchase price and CPI to output volatility both increase.

The above empirical results show that, without considering the interference of monetary policy, international oil price increases have little direct impact on output in the short term. The central bank's monetary policy and its tightening response to rising oil price should bear more responsibility for the economic recession caused by oil price volatility in China. Faced with rising production costs, enterprises can raise prices based on the price elasticity of demand to maintain their previous profits in order to maintain their output levels in the short term, but in the long run, rising oil prices will affect the CPI and monetary policy because of the variations of relative prices, which will have a significant negative impact on output.

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From Copenhagen to Durban and the challenge for sustainable levels of GHG concentrations

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Abstract: The Durban Conference of Parties (COP17) has approved a deal to negotiate and arrange by 2015, a global commitment to reduce Greenhouse gases (GHGs) starting from 2020 onwards. COP17 confirmed the Cancún (COP16) agreement concluding that future global warming should be limited to below 2°C post-industrial. This report investigates scenarios of gradually stringent remaining emissions quotas (REQ) resulting to increased probabilities to limit temperature rise below 2°C. REQ are applied as cumulative bounds in the combined TIMES-MACRO model of the USA with the MERGE Integrated Assessment Model both able to analyse technological change. The study summarises the main findings and conclusions of this parametric analysis where all world regions accept a binding protocol or Accord starting in 2020 mitigating global warming. The mathematical description of the combined model that integrates in one set of equations and one objective function two hybrid top-down and bottom-up models with complementary regional representation is described in this paper.

Keywords: Kyoto extension; climate change; 2°C warming; integrated assessment; global commitments.

Reference to this paper should be made as follows: Kypreos, S. and Lehtilä, A. (2016) 'From Copenhagen to Durban and the challenge for sustainable levels of GHG concentrations', *Int. J. Global Energy Issues*, Vol. 39, No. 5, pp.323–339.

Biographical notes: Socrates Kypreos (MSC in Physics) served as Head of Energy Economics Group at the Paul Scherrer Institute (PSI) Switzerland until 2009. After retirement he remained active as honorary member of the Group. He was involved in studies of advanced nuclear power stations and in Energy Systems Analysis representing Switzerland in the IEA-ETSAP Program. He was Project Manager and Principal Investigator in different projects funded by the European Community and the Alliance for Global Sustainability, responsible for the development of Integrated Assessment Models at PSI. He also served as adviser and co-examiner for PhD studies related to energy, economy and environment at PSI/ETHZ.

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This paper is a revised and expanded version of a paper entitled 'From Copenhagen to Durban and the quest for sustainable levels of GHG concentrations' presented at the 'International Energy Workshop', Cape Town, South Africa, 19–21 June 2012.

1 Introduction

Perhaps the most significant decision taken until now by the numerous Conferences of the Parties (COPs) of the United Nations Framework Convention on Climate Change (UNFCCC) was the so-called Copenhagen Accord (CA). This Accord has been prepared by the Copenhagen Conference of Parties (COP15), and it has been endorsed by the COP16 in Cancún. The aim of the CA is to combat global warming with differentiated reduction targets of greenhouse gas emissions by country and by mobilising resources supporting adaptation and carbon-free technology in developing countries (DCs). Following this Accord, Annex I Parties (industrialised countries) and non-Annex I Parties (developing countries) have submitted reduction proposals (pledges) and mitigation actions to the UNFCCC secretariat. One hopes that the 21st Conference of the Parties that will take place in Paris in 2015 will institutionalise these pledges to a post-Kyoto extension by approving a form of commitments to combat global warming.

However, as the final outcome on mitigation depends on the modalities for the protocol extension after 2020, it is legitimate to question the levels of GHG reduction sufficient to serve as a Post-Kyoto policy framework aiming *to stabilise GHGs concentration at levels that would prevent dangerous anthropogenic interference with the climate system* (UNFCCC Art. 2) and the associated costs for the participants. The low progress in carbon emission control obtained until now questions the ability to sustain global warming below 2°C. This is especially the case in a period following the economic recession of 2008, but the signs of temperature change in the atmosphere and the oceans are increasing and decisions need to be taken.

These are the overarching questions of the study we are trying to answer applying an innovative model that integrates MERGE (Manne and Richels, 2004) with the TIMES-MACRO model of US (Loulou and Labriet, 2008), both being well known models. Special emphasis is given to model US – a key player for mitigation policy – as we need to analyse details of technological change including among others the end-use markets not available in MERGE.

A significant study that helps to quantify the probability to sustain global warming below 2°C as function of the remaining GHGs emissions quotas (REQ) has been published in Nature (Meinshausen, 2009). This study, based on comprehensive probabilistic analysis, claims that cumulative emissions up to 2050 are robust indicators of the probability that twenty-first century warming will not exceed 2° C relative to pre-industrial temperatures. The results of the study summarised in Table 1 are well accepted in the scientific community and may serve as a benchmark to define cumulative targets for our analysis.

Table 1 Probabilities of exceeding 2°C based on Meinshausen et al. (2009)

	Indicators	*Emissions*	*Probability of exceeding 2° C*
Scenario	*Cumulative CO_2/GHGs*		
50%	Cumulative CO_2 emissions 2000–50	1437 $GtCO_2$	50%
33%	Cumulative CO_2 emissions 2000–50	1158 $GtCO_2$	33%
25%	Cumulative CO_2 emissions 2000–50	1000 $GtCO_2$	25%
20%	Cumulative CO_2 emissions 2000–50	886 $GtCO_2$	20%
50%	Cumulative GHG emissions 2000–50	2000 $GtCO_2e$	50%
33%	Cumulative GHG emissions 2000–50	1687 $GtCO_2e$	33%
25%	Cumulative GHG emissions 2000–50	1500 $GtCO_2e$	26%
20%	Cumulative GHG emissions 2000–50	1356 $GtCO_2e$	20%

Based on the CA pledges and some extra assumptions for the TIMES regions compiled by Labriet (2010), the global CO_2 emissions for 2020 adopted in the study are 39 $GtCO_2$ (10.64 GtC) and are introduced as a lower bound. This level is lower than the ranges discussed in den Elzen et al. (2011). According to this study *if the current reduction offers of Annex I and non-Annex I countries are fully implemented, the global greenhouse gas emissions could amount to 48.6–49.7 $GtCO_2eq$ by 2020. Recent literature suggests that the emission level should be between 42 and 46 GtCO2eq (or 11.5 to 12.5 GtCeq) by 2020 to maintain a "medium" chance (50–66%) of meeting the 2 °C target. The emission gap is therefore 2.6–7.7 $GtCO_2eq$.*

Our study postulates different levels of carbon emissions quotas for the period 2020–2050, aiming to assess the feasibility to meet the 2 °C target. Simultaneously, the global target of CO_2 emissions in the period of 2020 in the constrained cases remains free to optimisation but above the level of 39 $GtCO_2$.

2 The baseline

The baseline development considered in MERGE is based on the assumptions made in the EU project ADAM, Edenhofer et al. (2010), fine-tuned with the baseline scenario development generated by the TIMER model (Van Vuuren et al., 2006; Magné et al., 2010) for that project. The baseline or business as usual (BAU) excludes any consideration of climate policies. The MERGE regions refer to the European Union (EU), Eastern Europe and former Soviet Union (EEFSU), China, India, Japan, CANZ (Canada, Australia and New Zeeland), MOPEC (Mexico and OPEC) and the rest of the world (ROW). USA which is the ninth world region is analysed based on the assumptions and database of the IEA-ETSAP TIAM project (Loulou and Labriet, 2008).

In the baseline, electricity production increases, as a consequence of population and economic growth from 19 PWh in 2010 to 70 PWh in 2060, while the annual primary energy use increases from 455 EJ in 2010 to 1072 EJ in 2060. Existing fossil fuel-based thermal plants are progressively phased out and replaced initially by a combination of pulverised coal and natural gas combined cycle (NGCC), followed by integrated gasification combined cycle (IGCC) coal plants due to their outstanding high efficiency and low fuel cost. Next to IGCC, wind turbines, nuclear reactors and wind power are the most competitive power generation systems.

Primary energy is supplied mainly by fossil fuels (oil, coal and gas) followed by renewable energy forms and biomass. As a consequence, energy related carbon emissions reach a level of 14 GtC and the atmospheric concentration of CO_2 becomes 545 ppmv. This moderate increase of GHGs in the atmosphere is the consequence of learning by doing (LbD) and learning by research (LbS) options of the model for renewable systems and advanced coal systems with carbon capture and sequestration (CCS). LbD reduces the specific investment cost (eventually to the level of their floor cost) as function of experience making for example wind energy a competitive baseline option. Learning is applied in all scenarios as a standard modelling option and favours the penetration of carbon-free options already in the baseline case.

Next to the baseline we perform a parametric analysis with different cumulative emission reduction targets aiming to restrict temperature change to below the 2°C target at different probabilities, a policy goal initially accepted by the European Parliament (European Commission 2007) and confirmed in Cancun. The MERGE model describes the emissions of other GHGs based on a baseline development and their marginal abatement supply curves while TIMES defines an explicit treatment of mitigation technologies for CH_4 and N_2O. We have introduced cumulative bounds for CO_2 emissions as this is the significant component in the cumulative integral of GHGs but the balances of other Kyoto gases are also presented and compared to the REQ given in Table 1.

3 Global emission budgets and marginal costs

We present and discuss in the following some key results as for example the level of emission reduction and the associated probabilities to exceed the 2°C of post-industrial warming, the implied global carbon taxes, and finally the economic implications and the technological changes for the world regions in respect to the baseline developments. All scenarios are estimated with a discount rate of 3 percent.

3.1 Global emission budgets

Figure 1 illustrates the annual emission levels for different cumulative budgets imposed for the period 2020–2060 guided by the emission budgets of Table 1. Simultaneously a lower bound takes care that at least the global level of CO_2 emissions in 2020 remains above the level of 39 $GtCO_2$/yr. Without this bound the model would have been free to select eventually emission levels for the period of 2020 below the Copenhagen pledges.

Examining the column of cumulative emissions 2000–2050 of Table 2 (estimated by applying the trapezoidal rule for the annual emission level 2000–2050 and comparing these values to the values listed in Table 1, we obtain via interpolation the corresponding probabilities to exceed the 2°C warming. We confirm that the obtained exceedance probability for the imposed cumulative bounds is below 50%, i.e., we have three cases with an exceedance probability of 50%, 37% and 30%.

Figure 1 Annual GHG equivalent carbon emissions estimated for the baseline (BAU) and under different cumulative budgets from 2020–2060 with 50%, 38% and 30% probability of exceeding 2°C

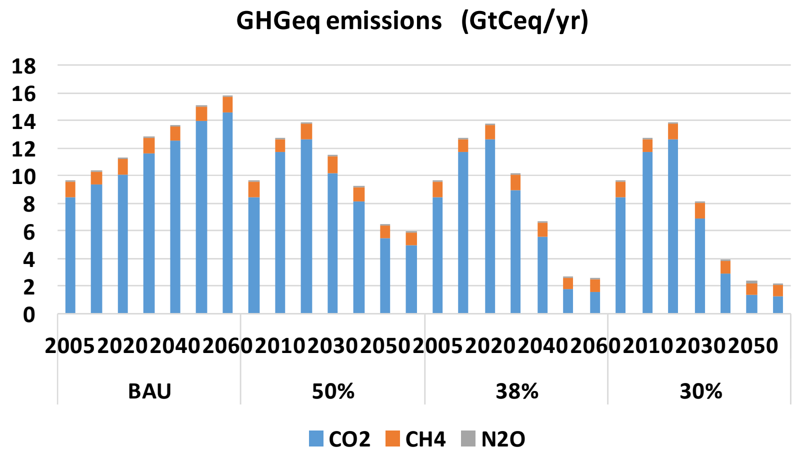


Table 2 Projected annual emissions (GtCe/yr); corresponding cumulative values 2000–2050 (GtCO2e); imposed bounds (2020–2060) and the probability to exceed 2°C warming

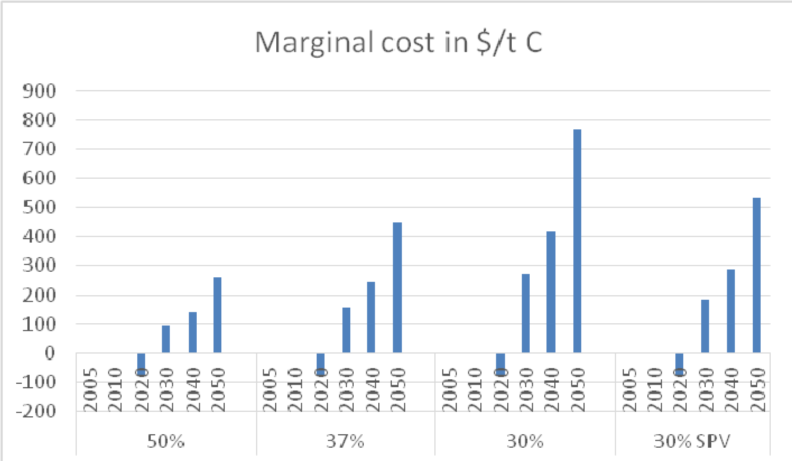
	2005 GtCe	*2010 GtCe*	*2020 GtCe*	*2030 GtCe*	*2040 GtCe*	*2050 GtCe*	*Cumulative emissions in $GtCO_2e$ 2000–2050*	*Cumulative CO_2 bounds GtC (GtCO2) 2020–2060*	*Probability to exceed 2°C warming*
BAU	9.62	10.28	11.23	12.8	13.62	14.99	2209	–	60%
50%	9.62	12.62	13.76	11.46	8.91	6.57	2011	348 (1276)	50%
33%	9.62	12.62	13.68	8.9	5.81	3.47	1744	240 (880)	37%
25%	9.62	12.62	13.67	7.5	3.67	2.3	1592	185 (678)	30%

3.2 Marginal costs of carbon control

The emission profiles for the low exceedance probability cases indicate significant reductions for the period after 2020. Figure 2 presents the marginal costs that correspond to the imposed cumulative CO_2 constraints. The prices and the level of emission reduction depends on the stringency of the REQ. The lower bound on emissions introduced for 2020 is binding and results to negative shadow prices. Interesting is also the sensitivity case shown in the graph (30% SPV) assuming reduced capital costs for Solar PV systems equal to $2000 per kw-peak in 2010 following their learning curves further reducing the capital costs to 1000 $/kw-peak. The shadow prices of carbon control are reduced as a consequence of the low cost of Solar PV from770 $/tC to 534 $/tC in 2050.

It is expected that imposing cumulative bounds for all GHGs (instead for CO_2 alone) would further reduce the concentration of GHGs, as shown for example by den Elzen (2010) in his default case. Notice that these results are obtained by considering bio-energy with carbon capture and storage (BECCS) as future technological option with negative emissions introduced in the second part of the 21st century.

Figure 2 Marginal cost of carbon control estimated under cumulative and global emission budgets from 2020 to 2060 for different probabilities to exceed 2°C of warming. 30% SPV is a sensitivity case



3.3 GDP development and economic implications by region

Most of the economic growth in the future will take place in non-Annex I countries. These countries assume also higher shares of energy use and carbon emissions in the future than the industrialised countries, a direct consequence of their aspiration for economic growth. The cumulative GDP reduction, associated for the cases analysed relative to the baseline, is low. The maximum cumulative and global GDP difference is 1.3 percent for the most stringent emission reduction case, but the regional impacts are significant for some developing world regions, e.g. the oil exporting countries where losses are above 5% over the baseline (Figure 3).

Figure 3 Regional and world cumulative and undiscounted GDP losses for the cases analysed relative to BaU

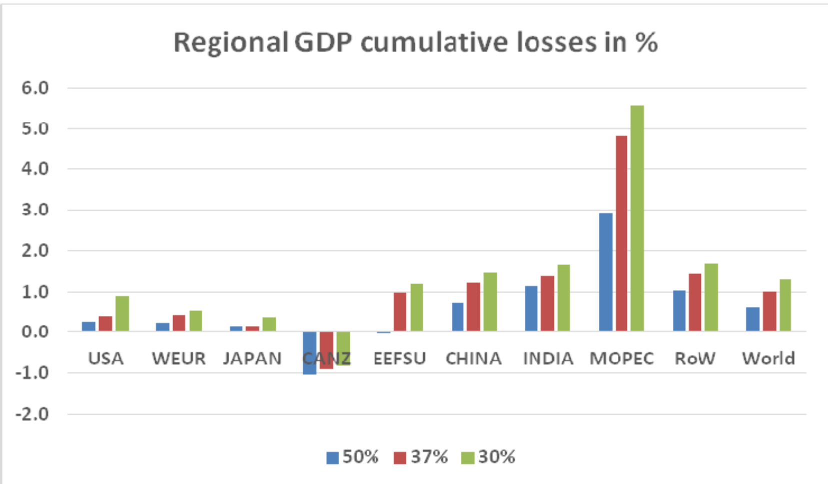
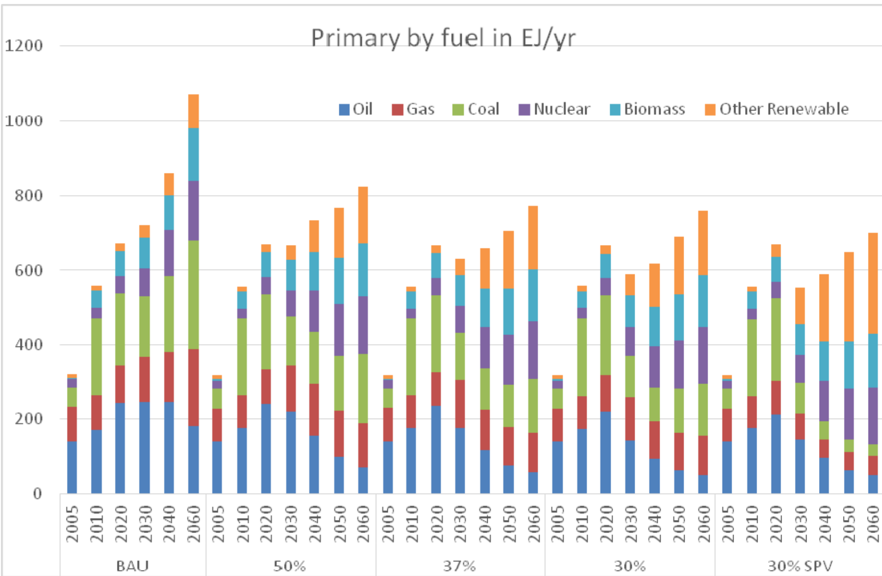


Figure 3 presents both the regional and the world undiscounted GDP losses for the period of analysis relative to the baseline. The cumulative constraint on CO_2 emissions defines efficient solutions across time and regions but is not evaluating any compensation transfers like in burden sharing (BS) policies or as in the case of technology protocols (Kypreos, 2012) to counter-balance these losses. The cost for non-Annex I countries is high with a maximum of 3–5.5% for the OPEC regions, as not only oil and gas exports are reduced but also their prices are fallen. The cost for the industrialised world is a fraction of the cost for the other world regions with CANZ having a net benefit, mainly due to the availability of biomass. This explains why DCs, and especially India, are reluctant to join a globally binding protocol. On the other hand, a full compensation of economic losses will conclude to very high capital transfers from Annex B countries (Jacoby et al., 2011). However, not only the undiscounted GDP losses of the world cumulative economic output are low (e.g., 1.3%), but also the secondary benefits of reduced local atmospheric pollution (i.e., due to reduced fossil fuel use) and the reduced level of damages due to climate change mitigation (lower temperature and see level rise) are not assessed in the analysis. It is expected that DCs will profit the most from climate mitigation policies counter-balancing the external costs of atmospheric pollution (Parry et al., 2015).

3.4 Primary energy and power generation

This section presents the primary energy consumption (PEC) and power generation for different remaining emissions quotas. We have already realised (Figure 2 and Figure 3) that the strong emission reduction obtained for the 30% probability case is associated with high marginal cost of around 800 \$ per ton of carbon in 2050. The high marginal costs of carbon control induce a strong degree of energy conservation for fossil fuels presented in the subsequent Figures 4, 5 and 6.

Figure 4 Global Primary Energy Consumptions for the cases analysed indicating significant efficiency improvements and substitution effects



The carbon constraint induces a significant substitution for fossil fuels relative to baseline and a reduction in energy use equivalent to 30% of the baseline's consumption. This is reflected in the changes of PEC induced for the period of 2030 relative to the previous period of 2020 where a lower bound of 39 $GtCO_2$ is imposed. Oil consumption remains below 15% of the total primary consumption and in absolute terms below 100 EJ/yr after 2040. Gas consumption is also reduced but to a lesser extent. Consequently the market shares of renewable, biomass and nuclear are increased. Actually in all constrained cases with the exception of oil and gas, all other primary energy forms have similar shares in the energy markets. Only in the sensitivity case with adjusted capital costs for Solar PV (30% SPV) the contribution of other renewables becomes 39% of the total primary.

Figure 5 Global electricity production for different probabilities to exceed 2°C of warming

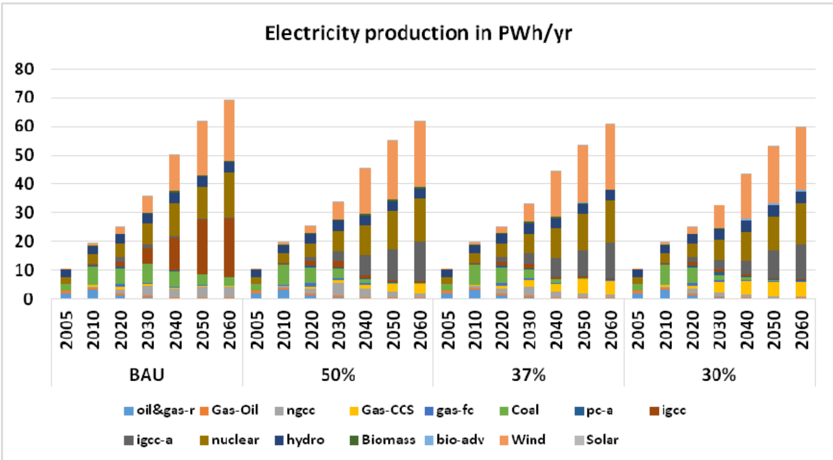
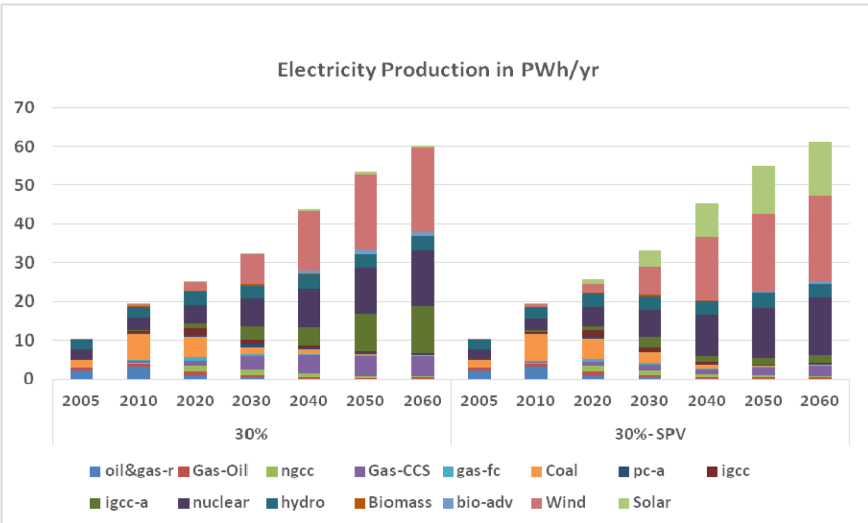


Figure 6 The case 30%-SPV assumes a capital cost of 2000 $/kW-peak based on recent literature

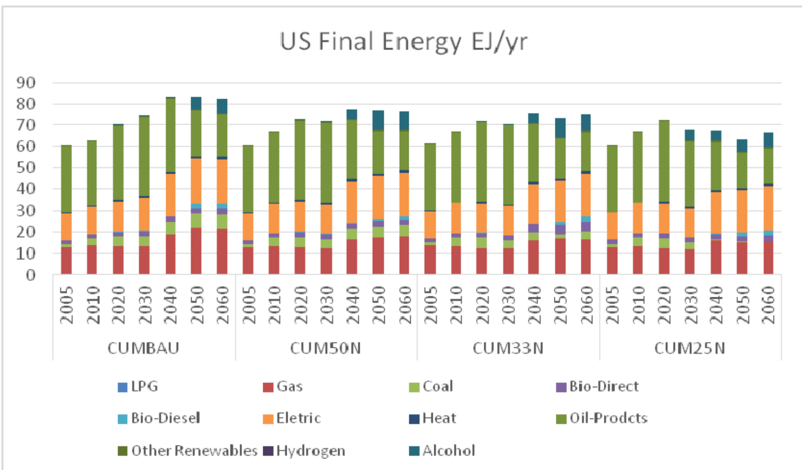


The carbon quotas reduce the level of electricity production by 10 PWh/a or 14% below the baseline for all three stringent emission cases while the structural changes in power generation are drastic as carbon free options become mature dominating the market. Winners are wind energy, nuclear energy, coal based on IGCC and gas combined cycle (GCC) with carbon capture and sequestration (CCS) options. Of interest is Figure 6 presenting a sensitivity analysis on the basic assumption concerning the capital cost of Solar PV systems which is now reduced to \$2000 per kW-peak in 2010, following recent literature, IEA-ETSAP and IRENA (2013). The Solar PV systems penetrate the markets of electricity against advanced IGCC systems.

4 The US energy system

A detailed description of the US energy system as projected with the TIMES-MACRO part of the model can be found in Kypreos and Lehtila (2015). CO_2 emissions in the USA follow the same pattern as in the global scale. The electricity sector becomes carbon-free under the carbon constraint while the transport and residential sectors are less efficient in carbon mitigation with their mobile or distributed emission sources not being adequate for capturing and removing CO_2 while carbon-free substitutes for oil products or gas, like synthetic fuels and hydrogen are expensive. The penetration of CCS systems removing carbon from coal, gas and biomass fuels in the electricity sector together with the use of wind, solar PV and nuclear energy explains these general patterns. However, the US primary energy consumption differs from the global fuel distribution as oil and gas shares cover more than 50% of PEC. Figure 7 that presents the US final energy use as function of carbon quotas, illustrates the induced level of energy conservation (energy use is reduced by up to 25%) and the fuel substitution obtained in the end-use markets. As the relative prices of energy services and fossil fuels increase, following the high marginal cost of carbon control, consumers reduce their demand for energy services by consuming less fuels while in the long run invest in capital intensive but efficient devices. Therefore, electricity use, together with alcohol fuels and bio-diesel, is significantly increased in the last periods substituting for fossil fuels.

Figure 7 Fuel use in the end-use markets of the USA



5 Conclusions

All UN Conferences of Parties failed to work-out a binding agreement to significantly reduce GHG emissions. However, the next Conference of Parties to take place in Paris (COP21) is expected to conclude the negotiations with the best possible arrangement shaping future mitigation and adaptation policies.

Perhaps the most important conclusion of our study is that the feasibility of policies sustaining global warming below 2°C is given. This proof is elaborated with the help of a new and innovative integrated assessment approach merging TIMES (a detailed engineering bottom-up model) for critical world regions, with the MERGE model for remaining regions. Conclusions can be summarised as follows:

- The study assumes efficient policies and measures where all world regions accept a Protocol (Accord) with stringent emission pathways starting in 2020. Further delays or low participation to the protocol will make the goal of 2° C warming a difficult, but not impossible task as very stringent actions will be required in the second half of the century. This will lead to higher marginal prices and costs (see also den Elzen, 2010). These extra costs are related to the inertia of the infrastructures in the energy system that locks-in conventional production technologies and the foregone learning by doing cost reductions.
- Some carbon-free technologies like wind and nuclear reactors together with more efficient end-use devices like conventional but advanced vehicles are contributing to the reduction of carbon emissions already in the baseline. Other systems like solar PV and advanced carbon capture and sequestration options for power generation and transportation fuels need the introduction of high carbon taxes or other instruments to become better competitive.
- Bio-fuel production and BECCS with negative carbon emissions become competitive under stringent cumulative bounds on emissions and have the potential to become one of the key future technological options to mitigate carbon emissions and reach the 2°C constraint. This technology-platform needs significant spending in public and private R&D&D to be commercialised in small scales and for demonstrating their technical feasibility prior their mass-commercialisation.
- Conservation options in buildings and the transportation sector together with efficiency improvement are key end-use policy options contributing to the reduction of carbon emissions. We notice the importance of electricity, alcohol fuels and bio-diesel for the substitution for coal and oil products in the end-use markets of USA.
- Finally, although the GDP reduction on the global level remains below 1.3%, the impact of the carbon constraint in the oil and gas exporting regions and the non-Annex I regions is significant asking for counter-balancing actions and measures and fair burden sharing.

After 20 years with the Framework Convention on Climate Change into force (1994) we are neither successful in reducing global emissions nor able to emphasise enough the uncertainties and the expected damages associated with the climate change convincing the public and politicians to take serious actions. Better scenario analyses with efficient but fair and differentiated emission pathways focusing on the historical responsibility of the industrialised world must balance the contribution and participation of DCs. The scientists and modelers should understand and quantify better the expected damages and the cost of adaptation and mitigation options in order to improve the allocation of capital and technology transfer between world regions and among mitigation and adaptation options.

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Appendix A The Integrated TIMES-MACRO & MERGE (ITMM) model

The first version of this hybrid model became available in the nineties (Kypreos, 1998) and it was developed together with Alan Manne and Gary Goldstein for five world regions. Afterwards it has been inactive. This was the first incarnation into the direction of regionalised general equilibrium hybrid and global models where simplified neoclassical growth models are linked with detailed bottom-up engineering models like MERGE (Manne et al., 1994, 1995). In the meantime, a series of well-known multiregional trade models became available as e.g., (a) the 6 region GMM model (Barreto, 2001; Barreto and Kypreos, 2004; Rafaj, 2005; Gül et al., 2009), modified recently for the World Energy Council (WEC, 2013) to generate global scenarios with 15 regions; (b) the ETP model (15 regions) applied in the IEA headquarters in Paris for publishing the biannual Energy Technology Perspectives (ETP, 2012); and (c) the 15 world regions TIAM model (Loulou and Labriet, 2008), all functioning as regionalised global models based on partial equilibrium algorithms. Only the recent work with TIMES-MACRO (Kypreos and Lehtila, 2015) which is solved via decomposition to a linear part (TIMES) and a simple non-linear macroeconomic model is going into the direction of general equilibrium model development. Finally, the coupling of TIAM with the applied general equilibrium model GEMINI-E3 (Vielle et al., 2009) is a very promising development in climatic change modelling, as it combines detailed engineering models with general equilibrium techniques focusing on sectoral economic impacts.

The development work described herein is less ambitious as it applies a NLP macroeconomic framework as driver of economic development and energy demands. It is rich in technological details and able to represent technological change driven by endogenous learning by doing and learning by searching. However, the model focuses on the macroeconomic implications of either energy or environmental related policies without any sectoral specification and labour impacts. The Integrated Assessment model used in the study derives conclusions on national GHGs mitigation policies while respecting global mitigation commitments and policies. This is done by merging together the TIMES-MACRO (TM) model of USA, rich in technological details, with the MERGE model of the remaining world regions. The link is obtained by defining one objective function combined with a complete set of the individual model constraints. This modelling approach enlarges the options given in evaluating the regional and technological details for key world players while simultaneously being consistent with global developments in terms of resource use, climate constraints, trade of fuels, and the endogenous treatment of technological change. The new model, called **ITMM** designs national energy and environmental policies under consistent international boundary conditions. The model maximises the global welfare while satisfying a set of constraints allowing for an endogenous, path- and policy-dependent ranking of technological options. ITMM is on the limits concerning the size of NLP problems able to be solved directly using commercial algorithms.

A.1 A simplified description of the ITMM Model

The two individual models are described elsewhere in a comprehensive way, as e.g., in Loulou and Labriet (2008) for the TIMES model and Kypreos (2007) for MERGE.

Therefore, only the basic model structure of ITMM will be given here related to the welfare function, the macroeconomic part and the links between demand and supply.

Welfare function and macro-economic constraints

We assume that the world regions are defined as the union of MERGE and TIMES regions, i.e., $r = r_M \cup r_T$, although in the equations below the index for TIMES is omitted for simplicity.

The **welfare function** U of ITMM maximises the discounted sum of regional utilities defined as the natural logarithm of consumption $C_{r,t}$ multiplied with some weights nw_r and subjects to a set of regional and global constraints.

$$Max\ U = \sum_{t=1}^{T} \sum_{r} nw_r \cdot pwt_t \cdot dfact_{r,t} \cdot \ln(C_{r,t})$$

$dfact_{r,t}$ is the utility discount factor for period *t* while *pwt* is a period-wise multiplier.[1]

T is the number of periods in the model horizon. The regional weights nw_r of the objective functions add to one and are defined based on the marginal utility of consumption. The NLP problem is solved via the sequential maximisation algorithm introduced by Thomas Rutherford that adjusts the Negishi weights iteratively based on the inverse of the marginal utility of consumption and takes trade into account such that the discounted trade imbalances per region and time are at the end of iterations balanced. Negishi has shown that such a solution is Pareto optimal (Negishi, 1972).

The other macroeconomic constraints of importance for understanding the link of the two models are as follows:

$Y_{r,t} = C_{r,t} + INV_{r,t} + EC_{r,t} + NTX(nmr)_{r,t}$: Use of economic output $Y_{r,t}$

$Y_t = \left(a \cdot K_t^{kpvs \cdot \rho} \cdot l_t^{(1-kpvs_r)\rho} + \sum_k b_k \cdot DEM_{t,k}^{\rho} \right)^{\frac{1}{\rho}}$: TIMES production function

$DET_{t,k} = aeeifac_{t,k} \cdot DEM_{t,k}$: Relation of Macro and TIMES demands

$Y_{r_M,t} = \langle a \cdot K_{r_M t}^{\rho\alpha} \cdot l_{r_M t}^{\rho(1-\alpha)} + b \cdot E_{r_M t}^{\rho\beta} \cdot NE_{r_M t}^{\rho(1-\beta)} \rangle^{1/\rho}$: MERGE production function

$\sum_j PE_{tjr_M} = E_{tR_M} e^{-aeei_{t,r_M} \cdot \Delta t}$: MERGE electricity production per technology *j*

$\sum_i PNE_{itr_M} = N_{tR_M} e^{-aeei_{t,r_M} \cdot \Delta t}$: MERGE non-electric production per technology *i*

$l_{r,1} = 1$ and $l_{r,t+1} = l_{r,t} \cdot (1 + growv_{r,t})^{\frac{d_t + d_{t+1}}{2}}$: Labour growth index

$\sum_r XTR_{r,g,t} = 0.0$: Global net export balance where

- $C_{r,t}$:annual consumption in period t, region r (variable)
- $Y_{r,t}$: annual production in period t, region r (variable)
- $K_{r,t}$: total capital in period t, region r (variable)
- $INV_{r,t}$: annual investments in period t, region r (variable)
- $XTR_{r,g,t}$:net regional r, exports for each time period t and product g
- XTR_{nmr}: net exports of a numéraire good, a composite commodity of all non-energy sectors, balancing the national accounts
- PE_{tjr_M} : production of electricity in period t, by j, in region r_M (variable)
- PNE_{tjr_M} : production of non-electric energy in t, by j, in region r_M (variable)
- E_{tjr_M} : electric demand in period t, by j, in region r_M (variable)
- NE_{tjr_M} : non-electric energy demand in t, by j, in region r_M (variable)
- $DEM_{r,t,k}$: annual demand in Macro for commodity k in period t (variable)
- $DET_{r,t,k}$: annual demand in TIMES for commodity k in period t (variable)
- $EC_{r,t}$: annual energy system costs in period t (variable)
- a_r: production function constant
- $b_{r,k}$: production function demand coefficient for demand commodity k
- $aeeifac_{r,t,k}$: autonomous energy efficiency improvement
- d_t : duration of period t in years
- $growv_{r,t}$: growth rate in period t (calibration parameter)
- $kpvs_r$: capital value share
- $l_{r,t}$: annual labour growth index in period t

The annual energy system costs EC_{rt} as defined in MERGE accounts for the annualised production costs of electric PE, and non-electric PN energy, using the corresponding unit cost, i.e., *ce* for the electric and *cn* for the non-electric energy. Conventional energy taxes *taxe* and *taxne*, carbon taxes tax_{CO2} and the transaction costs *csttrng* of exported good minus the tax revenues, are also taken into account (regional and time indices omitted).

$$EC = \sum_j PE_j \cdot ce_j + \sum_i PN_i \cdot cne_i + taxe \cdot E \cdot e^{-aeei_E \cdot \delta t} + taxne \cdot N \cdot e^{-aeei_{NE} \cdot \delta t} +$$
$$\sum_g csttrn_g \cdot EXP_g + E_{CO2} \cdot tax_{CO2} - TAXREV + QP$$

The model introduces a quadratic cost penalty function *QP*, for technologies which penetrate the market above normal rates. Similar *QP* functions are introduced in TIMES.

In order to express the energy system cost in TIMES as in MERGE, the standard TIMES LP formulation can be rewritten in terms of period-wise average annual costs and period-specific discount factors, as follows:

$$Min\ NPV = \sum_{t=1}^{T} pvf_t \cdot EC_t \text{ : Net present value of TIMES (objective function)}$$

where:

- pvf_t : present value factor for period t in region r
- ECt : annual energy system costs in region r and period t
- T: number of periods in the model horizon

Cap & Trade

The maximisation of the global welfare defines efficient solutions in the economic sense, and among others, the actual CO_2 emissions by region. This is the case either without policy constraints (baseline) or under policy constraints defined as a global cumulative bound (carbon cap) or as annual but global emission constraints. To estimate fair solutions, from the equity point of view, we can impose a carbon cap as before, define the initial endowments of permits per region based on some burden sharing rules like equal emissions per capita, and trade emission permits across regions. The solutions are the same in the case of direct optimisation of under cap & trade but at zero transactions cost.

In the case of cap & trade two equations apply:

- The trade balance for each period and product (including permits) $\sum_r XTR_{r,g,t} = 0.0$, the dual of the trade balance constraint defines the price of traded products.
- The relation between actual emissions and permits (IE), where carbon emissions of electric and non-electric energy use (i.e., activity variable times specific emissions coefficient *se*), minus the net regional exports of fossil fuels *XTR*, must be less or equal to the initial endowments *IE* of emissions rights, minus the net exports of emission certificates XTR_{crt}.

$$\sum_{i \in Elec} PE_{i,r,t} \cdot se_{i,r} \cdot HTRate_i + \sum_{n \in N} PN_{n,r,t} \cdot sn_{n,r} / eta_{n,r} - \sum_{i \in fossil} XTR_{i,r} \cdot se_i \le IE_{r,t} - XTR_{c,r,t}$$

The other TIMES balances refer to the production, depletion and use of energy resources, mainly hydrocarbons, the capacity built-up and the load management for electricity and heat. See also the detailed model documentation given in Loulou and Labriet (2008).

The treatment of learning in MERGE-ETL for clusters of technologies that learn together and on a global level is described, among others, by Magné et al. (2010). This definition of cumulative capacity of learning by doing is obtained by mapping individual technologies appearing in the model to a set of key technology clusters via matrices. The summation of the individual technologies multiplied by the coefficients of the matrix defines the cumulative capacity of the key components of a technology cluster. This matrix is now extended to include learning technologies appearing in the database of

TIMES for either electric or non-electric systems while a new cluster of learning technologies includes end-use devices. This is a simple and intelligent way for a NLP formulation of LbD and LbS in TIMES-MACRO.

One should conclude the Appendix with the remark that in the final stage of integration, ITMM could represent all key global players contributing to carbon emission balance as TIMES regions while the other world regions will be represented as MERGE regions. This large scale NLP problem formulation with more than 20-30 world regions would become solvable only when the LP model TIMES (and eventually the energy model of MERGE) are decomposed and solved separately from the NLP MACRO drivers following the algorithm applied in Kypreos and Lehtila (2015).

Note

1 The objective function has introduced period-wise multipliers pwt_t, representing period-length-dependent weights in the utility function. These multipliers are applied exactly in the same way as the $dfact_t$ multipliers. The multipliers are all 1 if all period lengths are equal to each other.

Alternative integrated energy chain for Caribbean power markets: methanol/vegetable oil fuel blends

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Abstract: The high price volatility of crude oil and its derivatives has resulted in unmanageable power generation costs in many regions worldwide. This paper proposes a unique alternative fuel blend, namely methanol and biofuels that have hitherto escaped the purview of policy-makers. Availability of fuel supply, lower environmental impact, job creation and reduction in fuel subsidy are some of the socio-economic benefits. A framework was developed for examining the economic feasibility of this alternative considering the entire energy value chain. The case study used is the power generation markets of the Caribbean. A probabilistic approach using Monte Carlo simulations was adopted to account for uncertainty in key input parameters. The results indicated that the methanol/vegetable oil chain is a feasible alternative for the Caribbean. The methanol/vegetable oil chain was also found to be more economically competitive than most other energy supply chain options.

Keywords: energy supply chain; alternative fuel; natural gas; biofuel; decision analysis under uncertainty; Caribbean energy supply.

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1 Introduction

The need for alternative energy arrangements is an issue that is being addressed by many countries worldwide. Climate change, decreasing fossil fuel resources and increasing global energy consumption are but some of the factors driving this phenomenon. The Caribbean region makes a good case study in this regard. It is marked by fragile economies and almost 90% dependence on crude oil-based fuels; the recent extraordinary volatility in the price of crude oil has emphasised the fragility of the current arrangement (e.g. Dominican Today, 2007; see Figure 1). As an archipelago of Small Island Developing States, the Caribbean is particularly vulnerable to the effect of climate change and as such has a vested interest in pursuing and promoting energy sources that are not only economically feasible but also ‘green’. Furlonge (2012) examined the multiple dimensions of a broadened economic envelope suitable for capturing all the value elements from renewable energy technologies. The Caribbean Community Energy Policy (CARICOM, 2013) takes note of both these dimensions. By a study of countries of Latin America and Caribbean, Bozo (2008) demonstrated the influence of energy policy on sustainability from social, economic and environmental perspectives. Blechinger and Shah (2011) and Shah et al. (2014) examined policy formulations suitable for overcoming some of the market penetration challenges of renewables in the Caribbean.

Various studies on the subject have been conducted in the past (e.g. Hertzmark, 2006), many of which have identified natural gas as a possible alternative fuel for the region. Natural gas is already a key fuel in many regions of the world and is gaining even greater prominence due to its relative abundance, as compared to crude oil and its cleaner burning characteristics. Owing to the availability of regional resources and the Caribbean’s proximity to South and Central America, natural gas is an alternative with great promise. However, the topography of the region necessitates specialised natural gas transportation routes. Kromah et al. (2003) discussed some of the key possible transportation routes for natural gas within the region and conducted a qualitative assessment of these. Among them were LNG (Liquefied Natural Gas), CNG (Compressed Natural Gas) and undersea pipeline technologies. It should be noted that the CARICOM Energy Policy placed emphasis on LNG and Pipeline Natural Gas (PNG) options, despite the fact that these have been examined for a long time and have as yet proven to be economically feasible. LNG is highly capital intensive and relies on economies of scale, which is not achievable in the small energy markets of the region. Pipeline feasibility is challenged by the long distances between islands and will also be expensive due to offshore conditions.

Clearly, the traditional modes of gas transportation technologies have not materialised. Murray and Furlonge (2009) proposed an alternative technology, involving the use of methanol as a fuel for power generation. The rationale for the consideration of the methanol route rests in the fact that Trinidad and Tobago is a major global producer and exporter of methanol and is aptly positioned in the region to export to other Caribbean countries. Additionally, as a derivative of natural gas, methanol offered a more environmentally friendly alternative to crude oil-based fuels, which is of particular significance to the countries of the Caribbean. The results of their study indicated that the methanol route was potentially more economical than the current crude oil-based fuels. It should be noted that this study did not address the fundamental shortcomings associated with the fuel property limitations of using methanol directly. It also examined each island separately.

Another alternative energy source for the region lies in the use of biofuels. The rich tropical climate of the Caribbean has made it ideal for several species of plants and trees. Consequently, there already exists within the region a capacity for the development of vegetable and plant-based biofuels, more specifically liquid biofuels are vegetable oils and biodiesels. A report by the Energy and Security Group (2006) identifies the main regional sources of biofuels, the current generation capacities and the maximum potential capacities for various regional countries.

The use of fuel blends presents one other key alternative for the region. As is well known, there are a number of challenges associated both with the use of neat methanol (Seko and Kuroda, 1998; Seko and Kuroda, 2001) and with neat vegetable oils (Haldar et al., 2008; Ramadhas et al., 2004) with respect to high flammability, relatively low heat content, and low lubricity. However, investigations have shown that fuel blends of methanol and vegetable oils overcome the challenges associated with each fuel while offering even better engine performance (Agarwal and Rajamanoharan, 2008; Cheng et al., 2008; Senthil Kumar et al., 2003). Accordingly, blends of both methanol and vegetable oils, which are both readily accessible within the region, present a critical alternative.

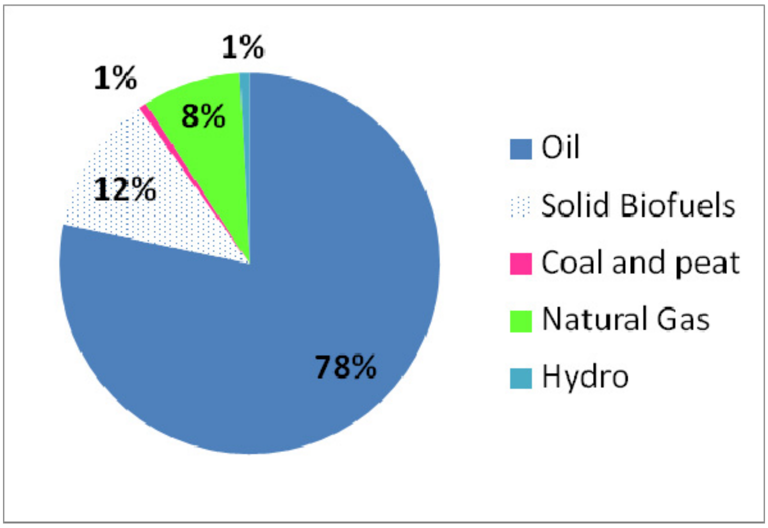
The consideration of these alternatives, and the various modes of their implementation, leads to a number of varying energy chains. As is the case with any proposed energy chain, the critical issue that arises is that of feasibility. Several investigators have assessed energy chains that are unique to a particular regional context using techno-economic models. Blanco (2009) investigated the economics of wind energy in Europe as the technology becomes more developed. Luo et al. (2009) considered the use of bioethanol fuel from sugarcane in Brazil. Hekkert et al. (2005) investigated the viability of various natural gas automotive energy chains, while Najibi et al. (2008) investigated the feasibility of varying transportation technologies for natural gas transportation from Iran's South Pars field to various markets. In all of the cases examined, it was evident that there are key aspects of feasibility that are dependent on the regional context being considered and the structure of the energy chain.

In light of this, the current work considers methanol/vegetable oil blends as an alternative fuel arrangement for the Caribbean. The primary contribution is the proposition of an *integrated* energy chain business model, with blend components of the fuel being sourced from a supply country as well as from the end-user country, with a 'spoke and hub' concept. Interestingly, the Caribbean Community Energy Policy stated as one of its considerations, coordinated investment in the regional energy sector, and the proposed concept here advances the idea to a practical level.

In the wider sense, the energy supply chain considered here presents potential solutions to other markets around the world that are heavily dependent on the import of crude oil and derivatives. The fuel blend considered can be adopted in other regions which have significant biofuel resources, such as some African and South American nations. In addition, the implementation strategies are also relevant and readily applicable to other developing nations with similar topographical challenges, such as the countries of the Pacific region. As such, the Caribbean region serves as a representative model for a wider global group, i.e. it acts as a suitable case study for developing the concept and for demonstrating the economic and environmental potential of methanol/vegetable oil blend for power generation.

The current paper proposes a methanol/vegetable oil integrated energy chain, which brings together the fuel components from different countries to suit the needs of the Caribbean power market. Secondly, the work seeks to identify the key economic and technical factors that critically influence the viability of this energy supply chain. Lastly, this study seeks to compare the viability of this energy supply chain to other regional conventional chains currently under consideration. These analyses will be principally conducted using a series of techno-economic models with a superimposed probabilistic methodology.

Figure 1 Caribbean energy supply portfolio, 2010



2 Conceptual approach

2.1 Regional context

The geographic location of the Caribbean and its climate play a critical role in determining the energy alternatives that are possible. Trinidad and Tobago is a leading producer of natural gas, methanol and other downstream products within the Caribbean and wider region. Its production capacity easily allows it to supply the potential natural gas fuel requirements of the other Caribbean countries, which generally have small power generation markets. In addition, Trinidad and Tobago is well positioned to supply the other regional countries and also has experience and expertise in the use of natural gas for power generation. These factors make Trinidad and Tobago the ideal point for the distribution of natural gas within the region. As such, in this study all the natural gas and methanol that are to be used for power generation are assumed to originate from Trinidad and Tobago. Accordingly, the various transportation modes would involve transportation from Trinidad and Tobago to the other Caribbean countries. Notwithstanding this, the Caribbean is also located relatively close to many natural gas producing countries within South and Central America. As such, natural gas originating from these countries is an added alternative.

As was mentioned earlier, several Caribbean countries already produce various liquid biofuels, namely several varieties of vegetable oils. The study conducted by the Energy and Security Group indicated that the three most abundant vegetable oil sources in the region are coconut, cottonseed and corn, with coconut oil having a significantly higher potential than the others. Consequently, the biofuels being considered are in most cases developed locally. The local development of these biofuels removes the requirement for and the associated costs of shipping; in addition, there are many other local social benefits to be had. However, current biofuel production levels within the regional countries are lower than what would be required to support the local power generation fuel requirements. It would therefore require a boosting of the local production capacities to fulfil the local power generation market needs. Alternatively, the possibility of acquiring biofuels from South and Central American markets also exists.

The current energy arrangement of the region is unique and leads to a number of characteristic features of Caribbean power generation. Firstly, the region is about 90% dependent on fossil fuels for power generation (Energy Information Agency, 2007). With the exception of a few countries, there is little to no fossil fuel production or refinement capabilities in the region; consequently, these fossil fuels are imported. Accordingly, fuel storage is a critical component in the general power generation arrangements of most Caribbean countries. Secondly, most of the regional power generation markets are small, i.e. below 100 MW of installed capacity. In previous work done by Murray and Furlonge (2009), a market survey of the historical developments of these markets indicated that they are usually marked by distributed arrangements, with reciprocating engines being the primary power generation machinery. Alternatively, the larger markets also utilise gas turbine power plants as part of the overall arrangement.

2.2 The methanol/vegetable oil energy chain

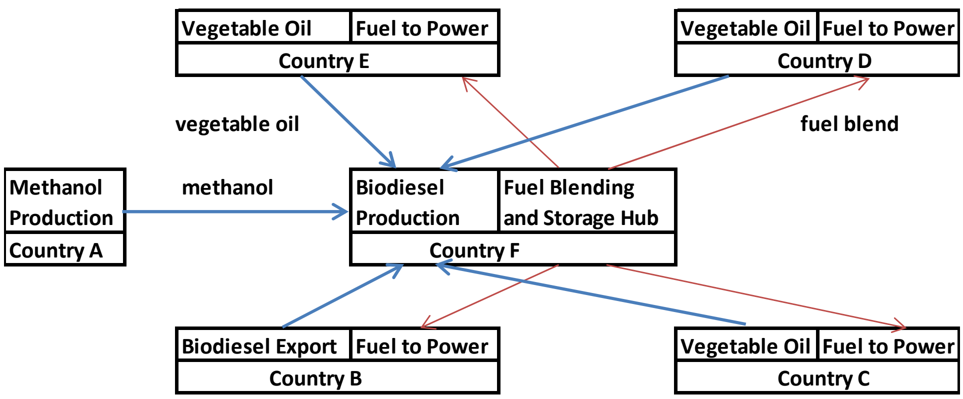
The proposed energy supply chain is based on the use of methanol/vegetable oil fuel blends. In a study conducted by Murray et al. (2012), methanol/coconut oil blends were shown to have similar and even higher engine performance in diesel reciprocating engine test units, than neat diesel. The performance of these blends increased with increasing methanol concentration in the blend. The study indicated that, although coconut oil was used, similar blends could be developed with other vegetable oils, with the expectation of similar engine performance results. Critical to the blends tested was the use of biodiesel as a co-solvent for methanol and coconut oil, as these are immiscible in each other. The biodiesel used was developed by the trans-esterification of the methanol and coconut oil. As such, the resulting fuel blends were constituted of methanol, coconut oil and biodiesel (coconut oil methyl ester). The blends were developed simply by mixing the three components together and can be used in diesel reciprocating engines with minimal to no retrofitting of the machinery.

A typical energy chain for Caribbean power generation would comprise fuel acquisition, fuel shipment, fuel storage and power generation via engines. To manage the associated costs, this work proposes an additional critical segment: a 'spoke and hub' collaborative approach for incorporating the biodiesel production aspect of the methanol/vegetable oil blend. In the proposed energy supply chain, the methanol to be used will be obtained from Trinidad and Tobago, via standard shipping practices. The vegetable oil component of the blend will be developed locally. As mentioned earlier, the source of the vegetable oil may differ from country to country, as different countries produce different oils. This local production of the vegetable oil removes the requirement for shipping. Ideally, the local development of biodiesel is likely the preferred option; however, regional biodiesel production is in the nascent stages. Consequently, large-scale biodiesel production facilities will have to be developed.

In this approach, a group of countries could enter a cost-sharing agreement. One of the countries will be designated the biodiesel production centre and a large-scale biodiesel production facility can be established in that country. The countries will then share the cost of the biodiesel production, with each country contributing to the overall costs based on its consumption of biodiesel. The biodiesel from the production centre will then be shipped to the various countries that are a part of the agreement. As an alternative arrangement, biodiesel can be obtained from a nearby South American market. As a next step, the various blend components will be stored where necessary. This may require additional storage facilities for the methanol and biodiesel components in some countries. Subsequently, the blend will be developed in the country in question, at the site of the power plant. Accordingly, the proposed energy supply chain incorporates the four characteristic stages of Caribbean power generation, but in a different manner from the diesel and fuel oil energy supply chains.

In summary, Figure 2 shows a schematic of the proposed methanol/vegetable oil integrated energy chain. It shows Country A, which is a producer and exporter of methanol (Trinidad and Tobago in this case); Country B is a producer of biodiesel and it exports to the 'hub' Country F. The remaining countries (C, D and E) all export vegetable oil to the blending plant in Country F and import the resulting blended fuels.

Figure 2 Schematic of methanol/vegetable oil blend energy supply chain (see online version for colours)



3 The techno-economic model

3.1 Model structure

The techno-economic model utilises the four-component regional power generation structure as a template. The first component of the chain is constituted of all the activities surrounding the acquisition of the fuel. For the methanol/vegetable oil blends, this involves the purchasing of methanol at market price and the acquisition of vegetable oil from a local supplier. This component also includes the acquisition of biodiesel from a biodiesel centre under the country cost-sharing agreement, or by purchasing it at market prices from an extra-regional supplier. The second component concerns the shipping of the fuel to the country in question. For the proposed chain, this includes the shipping of methanol from Trinidad and the shipping of biodiesel from a biodiesel production centre or extra-regional supplier.

The third component of the proposed energy supply chain involves the storage of the fuel. This considers the storage of all fuel components required for the blend. As many Caribbean countries already have storage facilities, the construction of new facilities may not be necessary; however, for some countries it may be a requirement. There are also a number of options to be considered here; vegetable oil storage at the local supplier may be a viable option. In addition, the storage of the blend as opposed to its separate components may present another alternative. The final component of the chain concerns the development of power at the power plant. For the proposed chain, this involves the preparation of the blend at the plant site and, subsequently, power generation via combustion in diesel engine generation sets.

The techno-economic model will determine the power generation cost for the methanol/vegetable oil energy supply chain on a US$/kWh basis, by calculating the contribution of each of the chain components necessary to produce 1 kWh of energy. The overarching equation is as follows:

$$C_{PG} = C_f + C_S + C_T + D_P \tag{1}$$

where C_{PG} is the total electricity generation cost for the chain and all costs are in units $/kWh. Note that all currency figures are in US dollars.

C_f represents the cost associated with purchasing the fuel components required to generate 1 kWh of power. Here, C_f is given by:

$$Cf = \left[Pf\left(n_1, n_2, \ldots n_n\right) / \rho \right] * \left[\text{H.R}\left(n_1, n_2, \ldots n_n\right) / \text{H.V} \right] \tag{2}$$

where $P_f(n_1, n_2,\ldots n_n)$ is a function that represents the variation in market price of the fuel in $/gallon. This variation is influenced by a number of differing factors including market demand and fuel availability. By using historical data to define P_f, the total number of variables n is implied. ρ is density in lbs/gallon and [H.R (n_1, n_2,…n_n)/H.V] is a conversion constant based on the machinery used. H.R is representative of the power plant conversion efficiency or engine efficiency. It is a constant for all chains except the methanol/vegetable oil chain, in which it is a variable. The variation in H.R is a function of several factors including fuel composition, engine parameters and environmental conditions.

C_S represents the cost associated with shipping the fuel required to generate one unit of power. This is only applicable in cases where shipping is necessary. C_S is given by:

$$C_S = P_S\left(n_1, n_2, \ldots n_n\right) * \left[\mathrm{H.R}\left(n_1, n_2, \ldots n_n\right) / \mathrm{H.V}\right] \tag{3}$$

The function $P_S(n_1, n_2, \ldots n_n)$ captures the variation in shipping costs and is given in \$/ton. Among the factors influencing it are fuel type and the shipping distance.

C_T represents the contribution of the yearly amortised cost associated with obtaining storage tanks, to the generation of a unit of power. This is only applicable in cases where storage is required.

C_T is given by:

$$C_T = A_m\left[P_T\left(n_1, n_2, \ldots n_n\right)\right] * \left[\left(\mathrm{V}_{\mathrm{G.C}} / \mathrm{V}_{8.5}\right) * \alpha T\right] \tag{4}$$

The term $[(\mathrm{V}_{\mathrm{G.C}}/\mathrm{V}_{8.5})*\alpha T]$ is a scaling term that accounts for the variation in tank volume required due to the generation capacity of a country. $P_T(n_1, n_2, \ldots n_n)$ is given in million USD and is influenced by similar factors as P_{Capex}.

Finally, C_P represents the contribution of the yearly amortised costs associated with the power plant and related power generation infrastructure, to the generation of one unit of power. This cost can be due to the installation of a new power plant, the retrofitting of an existing plant or any significant initial capital outlay associated with the acquisition of key power generation machinery and components. It includes both the capital expenditure required and the operational expenses, both considered on a yearly basis. For the proposed chain, P_{Capex} is the capital expenditure associated with the retrofitting of the plant to facilitate the use of the fuel blend. C_P is given by equation (5).

$$C_P = A_m\left[P_{\mathrm{Capex}}\left(n_1, n_2, \ldots n_n\right)\right] * \left[\left(\mathrm{G.C}/8.5\right) * \alpha P\right] + \left[P_{\mathrm{Opex}}\left(n_1, n_2, \ldots n_n\right)\right] \tag{5}$$

The functions $P_{\mathrm{Capex}}(n_1, n_2, \ldots n_n)$ and $P_{\mathrm{Opex}}(n_1, n_2, \ldots n_n)$ are given in million USD. The variations in P_{Capex} are due to market factors, inflation, construction location and the like; the variation in P_{Opex} is due to factors such as plant size and several other labour-related parameters. The term $[(\mathrm{G.C}/8.5)*\alpha P]$ is a scaling factor adjuster, which alters the capital cost of a plant based on the generating capacity required.

Moreover, the model utilises a probabilistic approach in determining the power generation costs. In equations (1)–(5), the main variables are represented as functions. The model uses a Monte Carlo simulation approach to account for the variations in these variables. In keeping with this, the model calculates the expected values of the power generation cost and generates a probability distribution function of its variation. This was accomplished using Palisade Decision tool's @Risk software package (Palisade Corporation, 2009). The variations in these variables were determined either from historical data available from several literature sources, or from via experimentation. As an example, the market price of methanol is considered to vary between US\$102 and US\$440 per metric ton, which covers the widest possible spectrum of market conditions. This takes into consideration the relationship between methanol and crude oil price, both of which are linked to world energy supply-demand (CMAI, 2011). Based on this information, the variables were modelled as suitable probability distribution functions in @Risk. The Monte Carlo simulations were then performed using 10,000 iterations and a convergence tolerance of 3%.

3.2 Scenario specifications, model assumptions and parameter variability

This study proposes two possible implementation scenarios for the methanol/vegetable oil blend energy supply chain. The first scenario to be considered will be designated the 'stand-alone' option. In this scenario, the country that will be employing the blend will obtain methanol from Trinidad and Tobago, utilise its local vegetable oil and acquire biodiesel from an extra-regional supplier at market prices.

The main assumptions associated with this scenario are as follows:

1 An average retrofit plant cost of US$65,000 for a 10 MW diesel reciprocating engine plant for use with an alternate fuel.

2 An average cost of US$10 million for a 7.7 million gallon tank.

3 The infrastructure for the various options is 100% financed by a mix of shareholders and banks, on commercial terms for the purpose of this analysis, i.e. no subsidy.

4 The power plant is operating at an annual capacity factor of approximately 92%.

5 The vegetable oil considered is coconut oil and it is assumed that the coconut oil is made locally.

6 The country in question obtains its biodiesel from an extra-regional supplier at market prices.

These assumptions take into consideration the unique characteristics of the Caribbean case. In previous work done on the use of neat methanol for power generation, Furlonge and Chandool (2007) collaborated with Trinidadian companies to conduct a pilot plant study in which a power plant was retrofitted for use with methanol. Assumptions 1 and 2 are informed by the project costs associated with this work (Murray and Furlonge, 2009). The current regional economic situation has led to the need for private sector investment and/or external funding for projects of this nature. Assumption 3 reflects this. The fourth assumption takes into consideration plant operations, including maintenance schedules, change-outs and other factors that affect total operational time. Lastly, assumptions 5 and 6 are representative of the regional scenario for implementation, as described earlier.

The key variables and factors used in the development of the thermo-economic model are presented in Tables 1 and 2. In Table 1, the upper and lower limits used for each variable are given, along with the probability density function used to simulate the variation of the variable. Additionally, 'N/A' in the table indicates that the particular limit is not applicable, as the variable's distribution function is defined fully by other parameters. For most of the variables, the Inverse-Gaussian distribution was used to model their variations. The Inverse-Gaussian was selected because it generally was the best fit distribution for the historical data obtained. More importantly, however, most of the data was cost data; the Inverse-Gaussian distribution allows for there to be a lower limit on the variable, but an infinite upper limit with a decreasing probability of occurrence. This is generally more likely, as the lowest value of the variable is unlikely to decrease below the historical values, but increase due to inflation. Figure 3 shows the distribution for the plant operating cost, one of the variables modelled by the Inverse-Gaussian distribution.

The Inverse-Gaussian distribution was also used to model the plant heat rate for the fuel blends. The justification for this is somewhat similar to that for the historical data; it places a lower limit on the heat rate, which does exist from experimentation, but an infinite upper limit with decreasing likelihood. The Weibull function was generally used to model the variation in the fuel price data. This offered a better fit for the larger historical data sets of the fuel prices. Figure 4 shows a diagram of the Weibull probability distribution function for the coconut oil market price data. In most cases, the variable limits were easily specified based on information availability. However, in certain instances where only an average value for the variable was available from data sources, the average value was used as the mean of a probability distribution function. The Inverse-Gaussian was generally used for reasons previously stated.

Table 1 Key input variables for the methanol/vegetable oil chain options

Variable	*Lower limit*	*Upper limit*	*Mean*	*Number of sample points*	*Type of probability distribution function*
Engine retrofit costs ($/MW)	N/A	N/A	6500	1	Inverse-Gaussian
Storage tank costs ($/MW)	N/A	N/A	1,000,000	1	Inverse-Gaussian
Power plant Opex ($/kWh)[1]	0.004	0.02	N/A	7	Inverse-Gaussian
Methanol shipping costs ($/ton)	N/A	N/A	20	1	Inverse-Gaussian
Small-scale biodiesel shipping costs ($/ton)[1]	N/A	N/A	10.7	1	Inverse-Gaussian
Large-scale biodiesel shipping costs ($/ton)[1]	N/A	N/A	5	1	Inverse-Gaussian
Methanol market price ($/ton)	102	442	N/A	13*	Weibull
Coconut oil market price ($/gallon)	1.122	4.317	N/A	13	Weibull
Reciprocating engine plant heat rate (MJ/kWh)[1]	14.86	10.53	N/A	8	Inverse-Gaussian
Country replaceable generating capacity (MW)	14	57	N/A	5	Uniform
Biodiesel plant capital rate ($/gal-yr)[2]	N/A	N/A	1.04	1	Inverse-Gaussian
Biodiesel plant Opex ($/gallon)	N/A	N/A	0.3	1	Inverse-Gaussian

Note: *Based on historical annual average prices over the period 1996–2008.

Source: [1]Nexant (2010); [2]Radich (2004)

Table 2 Key input factors for the methanol/vegetable oil chain options

Factor	*Value*
Biodiesel facility capacity (gallons per year)	200,000
Power plant annual capacity factor	0.92
Biodiesel facility annual capacity factor	0.15
Biodiesel trans-esterification process yield	0.8

Figure 3 Schematic of probability distribution for power plant Opex

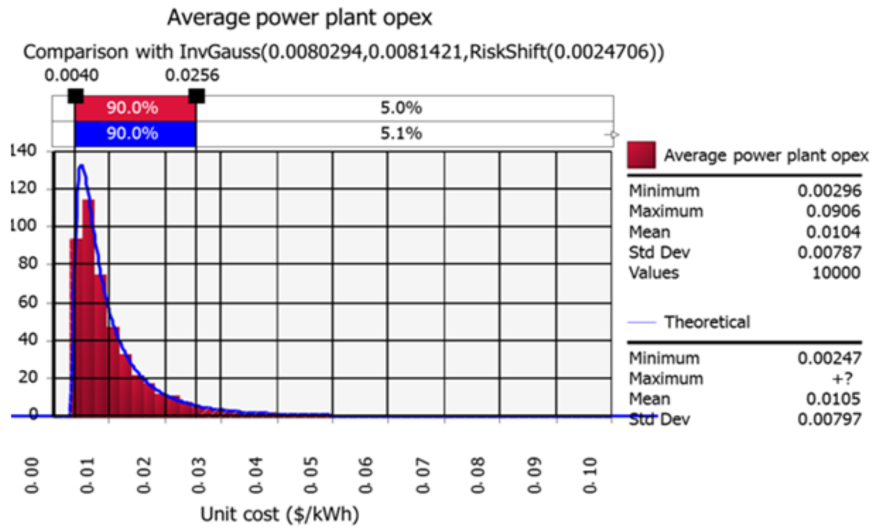
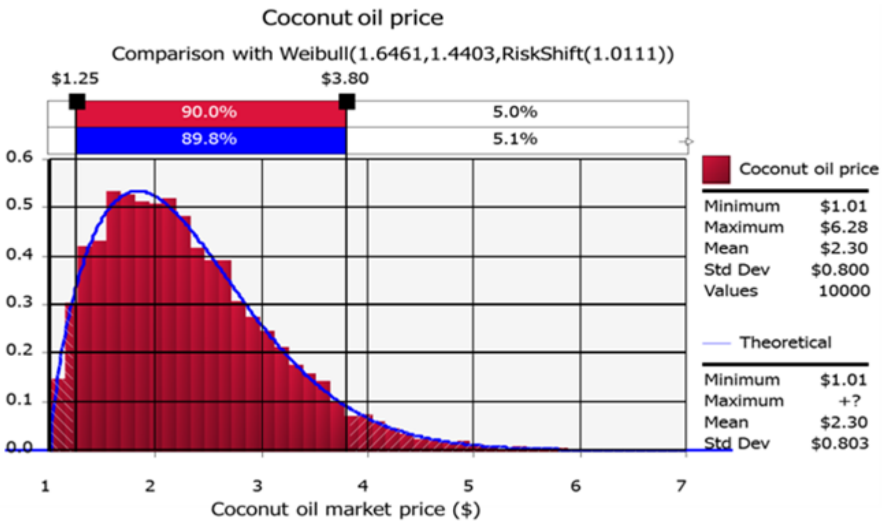


Figure 4 Schematic of coconut oil market price probability distribution



The proposed second scenario is the integrated energy chain option which involves country collaboration. In this scenario, the country in question will obtain methanol and its vegetable oil as in the stand-alone option. Here, however, it is proposed that a biodiesel production facility be constructed. Key to this option is the forming of the collaborative group of countries that all agree to cost-sharing. In the group, one of the countries will be designated the biodiesel production centre. All of the countries in the group will then send vegetable oil to this production centre and in turn the facility will produce biodiesel for all of the countries in the group. The proposed cost-sharing agreement entails the countries in the group paying a contribution to the biodiesel facility costs that is dependent on each country's consumption of biodiesel from the plant. Each country would pay a fraction of the amortised capital cost, the facility operating cost and the vegetable oil cost. The overall biodiesel cost is calculated as given in equation (6) and is likely to be substantially lower than the average market price.

$$\begin{aligned} \text{Biodiesel cost per gallon} = &\left(\text{Amortised facility Capex per gallon} * \Psi\right) \\ &+\left(\text{Facility operating cost per gallon} * \Psi\right) \\ &+\left(\text{Coconut oil cost per gallon} * \Psi\right) \\ &+\left(\text{Methanol cost per gallon}\right) \end{aligned} \tag{6}$$

where Ψ is the 'sharing fraction'.

Assumptions 1–5 of the stand-alone scenario are also applied in this scenario. Beside these, the main assumptions for this scenario are stated below:

1 A sharing arrangement for the production of biodiesel exists between countries such that each country pays a portion of the biodiesel costs based on their consumption capacity.

2 In the analysis, the four countries of the Organisation of Eastern Caribbean States (OECS) (i.e. Dominica, Grenada, St. Lucia and St. Vincent & the Grenadines) are used as an example for the collaborative group.

3 The sharing fraction, Ψ, is defined as country replaceable installed capacity/total group replaceable capacity.

4 The biodiesel facility built at the production centre has an annual capacity of 200,000 gallons, and operates at an annual capacity factor of 0.15.

5 The biodiesel trans-esterification process has an average yield of 80%.

Assumptions 1–5 immediately above are generally informed by best practices for such arrangements, as well as current relational dynamics within the region. Though biodiesel production can easily be done on a smaller scale utilising a subsistence approach, there are significant benefits to be had from economies of scale. However, a large biodiesel plant running at full capacity will produce far more product than is required by the proposed initiative. The annual capacity factor of 0.15 is representative of a plant producing just enough biodiesel to supply the fuel blend needs of the four countries identified, based on their needs at the time of writing. Additionally, despite the common reality of yields exceeding 90%, an average yield of 80% is assumed here as a lower limit (Balat and Balat, 2008). The countries of the OECS present an ideal representative group. Each of these countries already has local vegetable oil production capacity. In addition, there are existing trade relationships, levels of economic cooperation and common interests among the countries, forming a platform for a collaborative approach.

The main variables and factors used in the techno-economic model of the chain are presented in Tables 1 and 2.

4 Comparative feasibility of methanol/vegetable oil chain

The methanol/vegetable oil chain proposes to use regional fuel sources that are also being considered for other possible energy supply chains. To assess the competitiveness of the methanol/vegetable oil chain, it will be compared to other potential energy supply chains; the chains considered are PNG, LNG and neat vegetable oils. As it is known that a large-scale LNG supply chain would not be viable in a Caribbean context, a more novel mid-scale arrangement would be considered here. The PNG chain has been proposed in a sharing agreement and is limited to a selected group of countries. As such, it does not present an option to all countries in the region. The vegetable oil considered for the analysis is coconut oil, due to its relative prominence in the region. To assess the viability of each of these chains the power generation costs will be compared to the electricity prices of several countries.

To conduct the comparison, thermo-economic models are developed for the three stated energy supply chains. These models are built on the same template of the four-component structure used in the methanol/vegetable oil chains. However, the models are adapted to suit the specific chain such that only the relevant components are considered. Accordingly, for the example of the PNG chain, the shipping component is omitted as it is not a consideration for this chain. In keeping with this, the general set of equations (1)–(5) are used in the models and adapted where necessary. The details of the energy chains considered and the key assumptions associated with the development of their models are detailed below. The main variables, their limits and approximated probability distribution functions for each of these chains are presented in Table 3. A summary of all the chains is given in Table 4.

4.1 LNG alternative

The main variable inputs for the LNG chain (described more fully in Furlonge, 2011) are stated below. The upper and lower limits of their variation are given in Table 3.

- Liquefaction costs
- LNG shipping costs
- Regasification costs
- Power plant operational costs
- Natural gas market price

The main assumptions for the chain are as follows:

- The Caribbean country in question does not need a liquefaction plant, as they are purchasing the LNG as a commodity and not natural gas.
- The Caribbean country enters into an agreement to contract regasification services.
- The Caribbean country in question also enters into an agreement to contract LNG shipping services.
- The size of the power plant being considered is 10 MW.
- There is 100% financing from bank loans and investors for the construction of the plant and the purchasing of other equipment and components.
- The power plant being considered will be operational at an annual capacity factor of 92%.

4.2 PNG alternative

The main variable inputs for the pipeline chain are stated below. The upper and lower limits of their variation are given in Table 3.

- Gas pipeline installation capital
- Gas pipeline operational expenses
- Country installed capacity
- Installed capacity

The key techno-economic-based assumptions for the chain are as follows:

- The capital cost for the construction of a gas pipeline includes the cost of the pipe, compressors, substation and maintenance equipment, as well as the cost of installing them.
- The implementation of the PNG energy supply chain is based on a cost-sharing agreement between several countries.
- Pipeline equipment and installation capital costs are shared among the members of the cost-sharing agreement based on consumption of natural gas from the pipeline.
- The size of the power plant being considered is 10 MW.
- There is 100% financing from bank loans and investors for the construction of the plant and the purchasing of other equipment and components.
- The power plant being considered will be operational at an annual capacity factor of 92%.

These assumptions are consistent with those made for the other options and reflect the main considerations and rationale outlined in detail by Hertzmark (2006), regarding the supply of PNG to the various Caribbean countries from Trinidad and Tobago.

Table 3 Alternate supply chain variable input parameters

Energy alternative	*Variable*	*Lower limit*	*Mean*	*Upper limit*	*Number of sample points*	*Type of probability distribution function*
All chains considered	Power plant Opex ($/kWh)[1]	0.02	N/A	0.033	5	Inverse-Gaussian
All chains considered	New gas turbine plant Capex ($/MW)	0.5 million	N/A	1.2 million	6	Inverse-Gaussian
LNG chain	Liquefaction process costs ($/MMBTU)[2]	N/A	3.48	N/A	1	Inverse-Gaussian
LNG chain	LNG shipping costs ($/MMBTU)[2]	1.00	N/A	5.28	3	Inverse-Gaussian
LNG chain	Regasification and storage costs ($/MMBTU)[2]	1.50	N/A	3.48	5	Inverse-Gaussian

Table 3 Alternate supply chain variable input parameters (continued)

Energy alternative	*Variable*	*Lower limit*	*Mean*	*Upper limit*	*Number of sample points*	*Type of probability distribution function*
LNG chain	Nat gas price ($/MMBTU)	3.95	N/A	8.93	6	Weibull
PNG chain	Gas pipeline installation Capex ($/mile)[1]	0.7 million	N/A	1.57 million	5	Inverse-Gaussian
PNG chain	Average pipeline Opex ($/year)[3]	2.75 million	N/A	4 million	5	Inverse-Gaussian

Source: [1]Hertzmark (2006); [2]Fisher (2012); [3]Breeze (2005)

Table 4 Summary of energy chains considered

Chain	*Fuel acquisition costs*	*Fuel shipment costs*	*Fuel storage costs*	*Power conversion costs*	*Other details*
Methanol/ vegetable oil	Methanol acquired from origin at market price; vegetable oil acquired from local source; biodiesel acquired from extra-regional supplier at market price or at cost-sharing price	For the methanol and biodiesel fuel components	Storage required	Minimal to no retrofitting of power plant machinery	Two potential options: stand-alone and country-collaboration; biodiesel acquired differently in each case
LNG	Natural gas acquired at origin	LNG tankers are contracted; a shipment fee is to be paid	Regasification and storage services are contracted; a regasification fee is to be paid	Gas turbine plant required	It is also assumed that liquefaction is done at origin and a liquefaction fee must be paid
PNG	Natural gas acquired at origin	N/A	N/A	Gas turbine plant required	Nil
Vegetable oil	Vegetable oil developed locally	N/A	Storage may be required	Retrofitting of power plant machinery	Coconut oil is the vegetable oil example used here; retrofitting would involve the costs of modifying either the GTE or reciprocating engine plant

5 Results and discussion

5.1 Cost of electricity from proposed methanol energy chain

The expected value and the 90% confidence interval of the power generation cost for each chain, as determined by the Monte Carlo simulations, are presented in Table 5. We focus firstly on the methanol/vegetable oil chain. Figure 5 shows the resulting probability distribution of the power generation cost.

Table 5 Energy chain expected values

Energy alternative	*Expected value ($/kWh)*	*90% confidence interval ($/kWh)*
Methanol/vegetable oil 'stand-alone' option	0.248	0.162–0.373
Methanol/vegetable oil 'country-collaboration' option	0.230	0.137–0.366
LNG	0.201	0.156–0.253
PNG	0.291	0.141–0.505
Vegetable oils route (coconut oil)	0.298	0.167–0.477

Figure 5 Probability distribution of power generation cost for 'country-collaboration' option

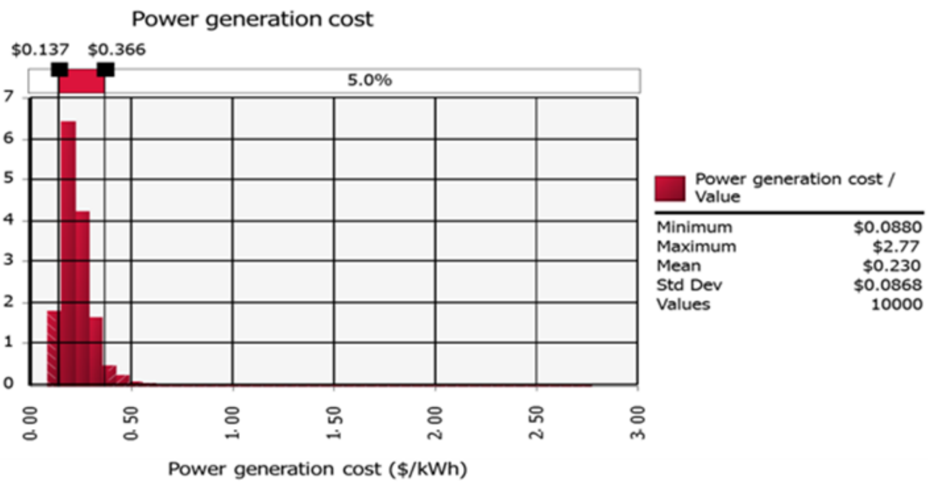


Table 6 presents the electricity prices for several Caribbean countries in 2010. These electricity prices are based on the countries current use of diesel and/or fuel oil. If feasibility is defined as a lower power generation cost than the current electricity prices, the methanol/vegetable oil blend chain clearly presents a viable option when compared to the crude oil-based fuels currently used in the countries. The chain is feasible in every country, with the exception of Belize.

Another key result to note would be that the methanol/vegetable oil blend chain options are most viable in countries that are 100% dependent on diesel/fuel oil for power generation and have small installed capacities (Table 6). The result corresponds to the findings identified by the authors in an earlier study (Murray et al. 2012). The key reason for this is that these countries generally have a distributed power generation arrangement, which consists of several small power plants. This arrangement usually does not benefit from economies of scale. Additionally, these countries do not have the benefit of a cheaper renewable energy component in their energy mix, such as hydropower; therefore, the electricity prices are higher.

Figure 6 Methanol/vegetable oil 'country-collaboration' option chain regression sensitivity analysis results (see online version for colours)

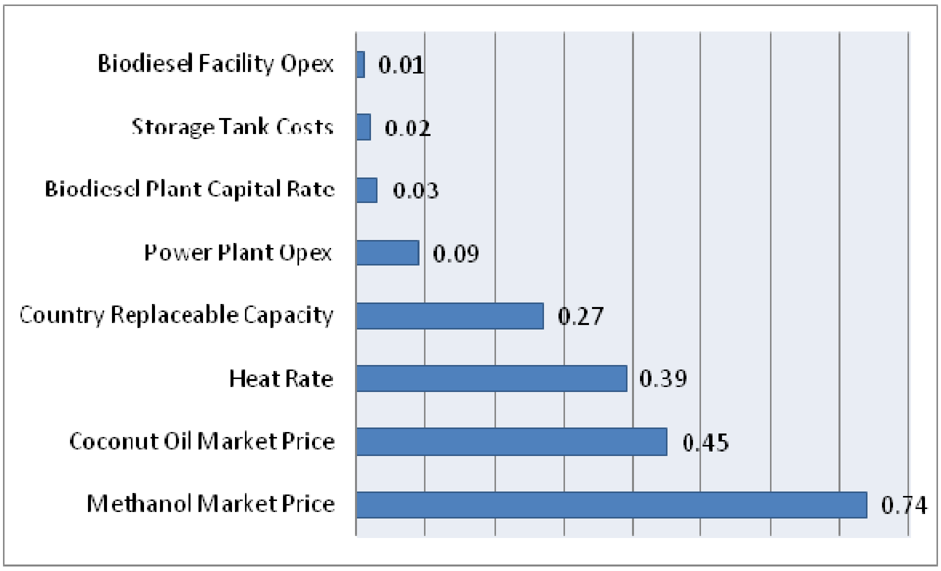


Table 6 Regional country installed capacities and electricity prices

Country	*Installed capacity (GW)*	*Fossil fuel dependence (%)*	*Residential electricity price in 2010 ($/kWh)*
Antigua	27	100	0.390
Bahamas	401	100	0.298
Barbados	210	100	0.309
Belize	52	52	0.222
Cayman Islands	115	100	0.414
Dominica	22	64	0.338
Grenada	32	100	0.350
Jamaica	1469	90	0.303
St. Lucia	57	100	0.243
St. Vincent & the Grenadines	24	75	0.308

Figure 7 shows the results of the regression sensitivity analysis for the methanol/ vegetable oil integrated energy chain option, conducted using @Risk. The numbers on such plots are referred to as 'regression coefficients', where '0' implies there is no relationship between the input and output variables, and '1' means that a standard deviation change in the input equates to a similar change in the output variable. As such, a larger number indicates that the specific variable has a higher level of influence on the overall power generation costs. Conversely, a smaller number indicates that the variable has less influence on the power generation costs.

It would be noted from Figure 6 that the variables of greatest significance are the fuel prices and the plant heat rate. This indicates that maintaining low fuel prices is the most critical issue to ensuring a low power generation cost. The plant heat rate is significant because a lower heat rate would mean a more efficient power generation process and consequently a more economical one. Murray et al. (2012) identified increasing reciprocating engine performance and hence a lower heat rate, to be directly related to increasing methanol concentrations in the fuel blend. Increasing methanol content would also lead to a lower overall blend cost and consequently lower power generation costs. However, there are other factors that limit the methanol content of the blend. Consequently, the exact constitution of the blend will have to be determined by the country in question and a balance struck depending on the country's specific agenda. Conversely, the regression sensitivity analyses do not indicate the shipping costs or plant retrofit costs to be of significant influence on the power generation cost. As such, there is a degree of slack allowed with these variables, as long as they remain in the ranges stated for the analysis.

The implementation of either methanol/vegetable oil chain option in any of the regional countries will encounter unforeseen costs. The nature of these costs may be due to the retrofitting of the plant or some other operational factor and it is not possible for any model to fully capture all such considerations. However, the results of the regression analyses do indicate the nature of the influence of such factors on the overall feasibility of the chain. The analyses results identified the retrofitting capital as having negligible influence on the chain's feasibility and consequently it is not shown in Figure 6; similarly, Figures 6, 7 and 9 identify the storage tank costs and the plant costs as being minimal contributors, as compared to the fuel costs. It stands to reason; therefore, providing these unforeseen costs are capital costs within the orders of the aforementioned parameters, the feasibility of the chain will remain relatively unchanged.

5.2 Comparison of methanol value chain to other conventional energy chains

Figures 6–8 show the results of the regression sensitivity analysis of the LNG, PNG and vegetable oil options.

Table 5 also shows the expected values and the 90% confidence intervals for the power generation costs of these chains.

The results of the analyses identify the mid-scale LNG chain as the most attractive of all the chains; with an expected value of approximately \$0.201/kWh, the methanol/ vegetable oil chain (\$0.230/kWh) is the second most attractive of the chains considered. Notwithstanding this unit price competitiveness, it must be noted that a disadvantage of LNG is that it requires sizeable capital outlay in infrastructure (including the use of cryogenic materials in shipping and for regasification), as opposed to the methanol/ vegetable oil route.

Similar to the methanol/vegetable oil chain, in the mid-scale LNG chain the most influential parameter is the fuel market price. Conversely, however, the LNG chain has a narrower range of variation than the methanol/vegetable oil chain, as identified by the 90% confidence intervals. This is a result of the fact that there are two primary fuel sources that influence the methanol/vegetable oil chain as opposed to only one in the LNG chain. Nonetheless, the methanol chain has the potential for a lower power generation cost than the LNG chain.

Figure 7 LNG chain regression sensitivity analysis results (see online version for colours)

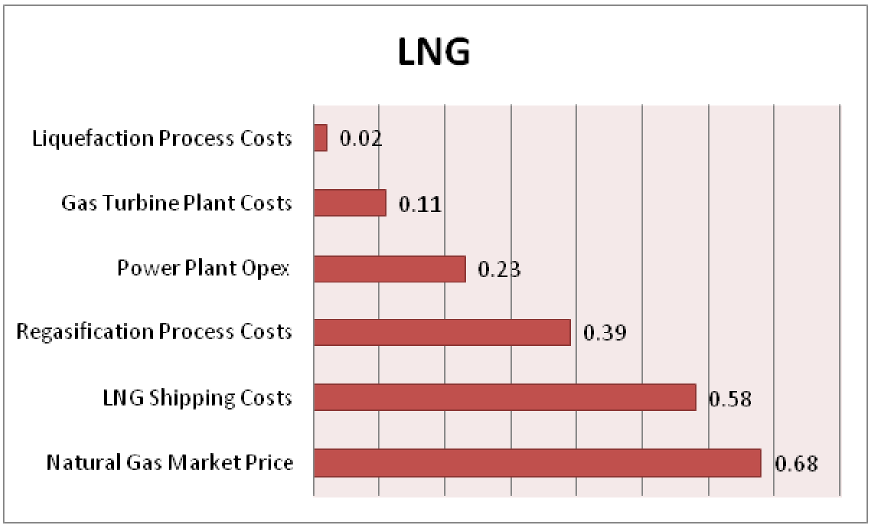


Figure 8 PNG chain regression sensitivity analysis results (see online version for colours)

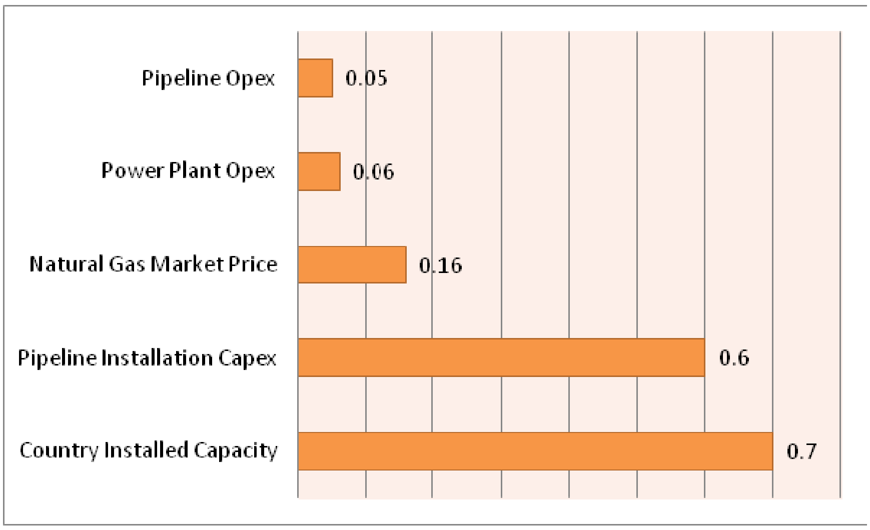
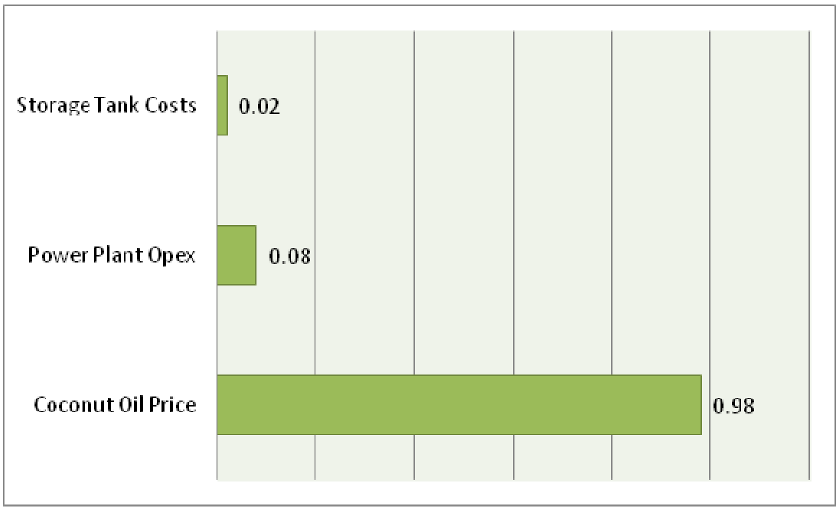


Figure 9 Vegetable oil chain regression sensitivity analysis results (see online version for colours)



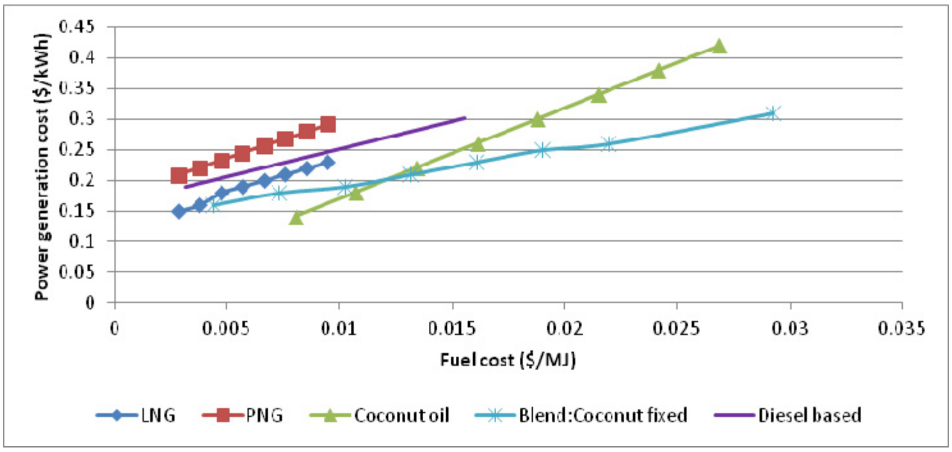
The PNG chain appears to be more competitive than the neat vegetable oil option, with a fractionally lower expected value. The most influential variable in the PNG chain is the country installed capacity. The country installed capacity here is similar to the country replaceable capacity in the methanol/vegetable oil integrated chain option. St. Lucia and Barbados are two of the countries that are likely to be part of the PNG group agreement. The analysis indicates that the PNG chain is potentially feasible in one of the two countries based on the current costs. The sharing agreement is critical to the lower cost for this chain, and without it the resulting power generation costs would have been exorbitant. These results, along with those of the methanol/vegetable oil integrated chain option, suggest that sharing arrangements could potentially lower regional power generation costs significantly and should be seriously considered as a critical strategy for the region's energy future.

The neat vegetable oil chain is feasible in many of the countries considered based on the prices in Table 6. Although it has a slightly higher expected value than the PNG option, it is probably a more stable alternative, as its range of variation is much smaller (see Table 5). Additionally, the PNG chain is not an option for all the regional countries, unlike the vegetable oil option. Further if CO_2 costs were to be considered, the vegetable oil chain option would have a lower net power generation cost than the PNG chain, as the primary fuel used is a carbon neutral, renewable source.

5.3 Impact of fuel price variations

The regression sensitivity analyses identified the fuel price to be the most influential parameter in most of the chains considered. In keeping with this, it was expected that there exists a similar level of influence of the diesel market price on the electricity prices paid in the Caribbean countries. Correlation analyses were conducted using electricity price data for several regional countries from the year 1996 to 2010, and diesel market prices for the same range. A correlation coefficient of 0.8 and higher was obtained in all cases, identifying a similar level of influence of the fuel price as in the chains considered. In light of this, Figure 10 depicts the response of the various chains to changes in the fuel price. In the plots of Figure 10, all other chain parameters were held constant at their mean values, while the fuel price was varied. Additionally for the methanol/vegetable oil blend, the coconut oil price was also held at its mean value and only the methanol price was varied.

Figure 10 Plots of fuel price against power generation price for the various chains



The plots in Figure 10 show that per unit of energy contained in the fuel, the methanol/coconut oil blend supply chain is more economical than the current diesel-based energy chain. It can be seen that the cost of power generation for the methanol/vegetable oil blend chain is usually equal to that of the diesel chain, when the cost of the methanol is twice as much as that of diesel. One instance of this can be seen when the cost of diesel is \$0.0083/MJ (or \$1.91/gal) as compared to a methanol cost of \$0.016/MJ (or \$1.1/gal). This is a consequence of the fact that the methanol/vegetable oil blends make better use of the fuel's energy in the power generation process, as well as the high cost associated with crude oil-based fuels.

In general, it can be found that on a cost per unit of fuel-energy basis, the methanol/vegetable oil blend chain is the most competitive. The methanol/vegetable oil chain shows a lower power generation cost for a fixed fuel cost per unit energy than every other chain considered except the neat vegetable oil chain. This is a consequence of the fact that the methanol/vegetable oil chain uses the current energy architecture in the regional countries and as a result very little additional input capital is required. Accordingly, a low fuel cost directly leads to a low power generation cost for the chain. The neat vegetable oil chain becomes more economical at fuel costs lower than \$0.013/MJ (or \$1.76/gal for coconut oil). However, it must be remembered that the analysis for the methanol/vegetable oil blend assumed a constant value for the coconut oil; the value used was \$2.3/gal. At a market price of \$1.76/gal for the coconut oil, the power generation cost for the methanol/vegetable oil blend would be lower than shown in Figure 10, and in general lower than the neat vegetable oil chain.

It should also be noted that, although the LNG chain had a lower expected value than the methanol/vegetable oil chain, the latter is still more economical on a cost per unit fuel-energy basis. Figure 10 shows that as the costs of the respective fuels increase, the LNG chain becomes increasingly less competitive than the methanol/vegetable oil chain. Conversely, based on the slope of the plot of the methanol/vegetable oil chain line, the LNG chain would become more economical at fuel prices below \$0.0028/MJ; this is equivalent to a natural gas price of \$3/MMBTU and lower.

5.4 Environmental and social impact

The methanol/vegetable oil blend considered in this study comprises of 50–80% vegetable oil, with the remainder being methanol. The variations in proportions were dependent on the technical requirements and objectives of the power generation machinery employed. Thus, the proposed fuel seeks to displace at least half of the fossil fuel content with renewable biofuels. There are two key implications that must be addressed here. The first of these concerns the use of biofuels. For the Caribbean case, this seeks to move a region that is principally dependent on fossil fuels, towards the use of biofuels. This positively impacts on energy security given that most countries of the region are major net importers of fossil fuels, and having an indigenous natural source can only contribute to a level of energy independence. Further, reduced reliance on foreign sources of fuel will decrease their energy import bill, freeing up the demand for limited foreign currency (Weisser, 2004).

Biofuels are in general considered to be effectively carbon neutral and their usage leads to a significant reduction in greenhouse gases, earning them a place among the class of green technologies. In addition, natural gas derived methanol, though fossil fuel-based, does result in a significant decrease in carbon output when compared to crude oil-based fuels. Consequently, the proposed fuel blend presents a greener fuel substitute for diesel in the regional countries, leading to a net reduction in carbon dioxide and other greenhouse gas (GHG) emissions. This is of major environmental importance for the Caribbean region and can also be incorporated in its contribution to the global efforts towards more environmentally sustainable practices. Additionally, given that the countries of the Caribbean do not pay carbon taxes, this decrease in GHG emissions does not have direct financial implications. However, if structured as a Clean Development Mechanism project where certified emission reduction credits can be quantified and sold, there may be further improvements to the overall economics.

Secondly, the use of biofuels would reinvigorate the currently dormant and underproductive vegetable oil industry in the regional countries. For many of the countries, vegetable oil production declined significantly due to their inability to compete in extra-regional markets, a consequence of distance and the relatively smaller production capacities, which do not benefit from economies of scale. The use of biofuels would present new and larger regional markets for the regional vegetable oil industry. Accordingly, this has significant socio-economic implications for these countries. It is expected that these benefits will also be mirrored in other regions of similar demographics.

5.5 Other considerations

A critical consideration that must be had is that the analysis presented in this study does not incorporate the impact of incremental sales revenue on the overall power generation costs in the integrated energy chain option. A by-product of the trans-esterification process used to produce biodiesel is glycerol, which is a valuable chemical and can be sold at market prices to regional or extra-regional industries. Additionally, in the example used for the analysis of the integrated energy chain option, the four countries of the OECS were considered. Based on country data of installed capacity and fuel consumption, the total replaceable capacity of these four countries would lead to a biodiesel consumption of approximately 28,000 gallons per year. The biodiesel plant built at the biodiesel centre has a proposed capacity of 200,000 gallons per year and operates at a 0.15 capacity factor. Several additional scenarios can be explored such as widening the collaborative group or increasing facility production and selling the surplus biodiesel to regional and/or international markets. The result of any of these options would be to significantly decrease the associated power generation cost of the integrated energy chain option, likely making it even more competitive than the LNG chain.

It should further be noted that the comparison here is between the power generation cost and the electricity prices. In most of the regional countries, the electricity prices are heavily subsidised; as such, it is likely that the true cost of power generation is higher than indicated by the electricity prices stated in Table 6. Accordingly, the difference in prices from that of the methanol/vegetable oil blend options is likely to be even greater and there are greater savings to be had. Additionally, the potential for a lower integrated energy chain option must also be considered.

The energy supply chain and the analysis presented here offer a potentially feasible approach to the migration away from dependence on crude oil-based electricity generation for other economically vulnerable nations. It has the advantage of a short implementation time frame and higher power generation efficiencies. Additionally, it affords both the flexibility of fuel switching and the removal of the requirement for significant capital investment, as it uses the current crude oil-based energy infrastructure. These issues are of critical concern to many nations of the Small Island Developing States designation and the ACP (African, Caribbean and Pacific) Group of States, which are currently challenged by similar problems in their energy arrangements. More importantly, they are generally faced with many other critical challenges and often are not in a position to finance significant investment in new energy technologies.

Lastly, the collaborative approach considered here is also one that can be fully explored and tailored to the economies and competitive advantages of the countries involved in the arrangement. This allows for other countries to exploit native opportunities that can further lower the cost of implementation in that region.

6 Conclusion

This work considered the feasibility of methanol/vegetable oil fuel blends as a power generation alternative for the countries of the Caribbean region. A techno-economic model of the power generation cost was developed based on a generic operational energy chain for the region. Uncertainty in key variables was taken into account using a Monte Carlo simulation approach. The methanol/vegetable oil chains were also compared to PNG, LNG and neat vegetable oil energy supply chains. Economic feasibility was determined by the comparison of power generation cost for the specific energy chain to current regional electricity prices.

The results of the models indicated that the methanol/vegetable oil blend chains had lower power generation costs than the electricity prices in almost all of the regional countries examined. More specifically, the integrated energy chain model, i.e. the country-collaboration approach of cost-sharing, results in the lowest power generation cost of \$0.23/kWh. This was approximately 8 cents lower than the average regional electricity price. It was also found that fuel prices and its associated engine performance were critical in determining the feasibility of these chains.

In addition, the results of the models indicated that the methanol/vegetable oil blend chain was more economical on a cost per unit fuel-energy basis than PNG and neat vegetable oil. While LNG below a natural gas cost of US\$3.00/MMBTU proved to be slightly cheaper on an expected value basis, it must be noted that this option is more capital intensive. This may prove problematic for Caribbean countries, given the prevailing financial circumstances.

A key issue for the economies of the region is that of volatility of imported fuel prices, which makes for unpredictable macroeconomic planning and financial management. In this regard, the results of a sensitivity analysis showed that power generation cost is more influenced by natural gas and by diesel than it is by methanol market prices. As such, lower volatility of the ensuing power generation cost as achievable via methanol is another important advantage to vulnerable economies like the Caribbean. It can be deduced therefore that the methanol/vegetable oil blends present a feasible energy alternative for the Caribbean that is likely to result in significant savings for the regional countries. The potential for this alternative fuel and integrated model may be applicable to other regions of the world, but this is yet to be explored.

The feasibility of the current study is largely predicated on the price differentials between crude oil-based fuels and the proposed blend components. Even without considerations of environmental impact, the blend is feasible for the scenario of high oil prices. Similarly, high natural gas prices will favour the blend as compared to the other natural gas initiatives considered. However, when comparing the blend to other natural gas modes, it is the relative costs of the associated technologies and infrastructure that is of greatest importance. Accordingly, advances in the technologies and decreases in the associated costs could see these alternative modes emerging as potentially more viable routes.

Currently, there is ongoing research aimed at optimising the fuel blend and improving its performance in the existing diesel power generation chain. Increases in power generation efficiency would serve to make the blend even more attractive. Additionally, there are concurrent studies aimed at identifying additional influencing factors that may be inherent to the arrangement of the value chain and which may serve to increase the advantage of the blend over the alternative power generation chains considered. Future work may also seek to quantify the reduction in GHG emissions, as well as the macroeconomic benefits related to energy import bill, foreign exchange and jobs and business activities which may arise from the implementation of the fuel blends proposed in this paper.

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