Energy Shocks and Emerging Alternative Energy Technologies

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Abstract

Since the availability of cheap and suitable energy underpins in many ways both developed and developing economies, it is crucial that national economies are prepared for potential energy shocks. Shocks may arise from physical constraints, such as a peak in national and global production rate of oil, or from institutional constraints, such as economic incentives to reduce greenhouse gas emissions. We examine potential modelled scenarios for China and Australia, to explore the extent of such shocks. The models are based on stock and flow dynamics of the physical activity throughout national economies. The ‘what if’ scenarios allow us to analyse options that aim to reduce or eliminate the impact of energy shocks through the use of alternative energy technologies and other options. When considering these alternatives, it is necessary to incorporate in the analysis the rate of change required in any transition, and potential cross-sectoral side-effects.

Introduction

The importance of energy to the smooth operation of global and national economies is evident in the tight correlation of energy and GDP (e.g., (Foran, 2009)). Developed and developing economies rely on a range of energy carriers, but are critically dependent on oil for transport and electricity for a host of industrial and commercial purposes. Potential disruptions in supply of these energy carriers therefore imply significant risks to economies.

For example, the oil-shocks of in the 1970s and 80s demonstrated some economic impact of constraints in oil supply. However, the nature of even these important events is perhaps less critical than those facing global economies in contemporary times. In the earlier oil-shocks, which were triggered when US supply of oil had reached peak production, global resources were still abundant, and the shocks were more a question of establishing a suitable price for oil on the international market. By contrast in contemporary times, there are concerns from some commentators that global oil production may have peaked or be nearing that situation.

Energy shocks may also occur at the ‘tailpipe’ or emissions end of the energy system. A large proportion of greenhouse gas (GHG) emissions occurs directly from the combustion of fossil fuels in the production of electricity, heat and transport services. Reduction actions to-date have been negligible despite scientific advice from the IPCC and others (e.g., [Stern, Garnaut]) advocating early and large reductions to avoid dangerous climate change. As GHG emissions increase and climate change impacts worsen, there is the possibility that concern about the impacts of climate change may grow and galvanise action on reducing GHG emissions. This may occur quickly with a demand for rapid action, carrying with it the expectation that substantial changes be made to electricity generation and other energy supply systems.

This paper examines these potentially critical energy shocks and to what extent emerging energy technologies may help alleviate or avoid the shocks. The next section outlines the magnitude of these energy challenges facing national and global economies. An overview of alternative energy options is provided in the following section, which also describes other impacts or requirements that are associated with these options, but are rarely considered. This suggests the need for wider system analysis of alternative options, and the 'stocks and flows' modelling system of national economies for such analysis is subsequently described. In the final main section of this paper, results are presented from the stocks and flows analysis that are drawn from a collection of separate studies. These are compared with other recent studies dealing with transport fuel and greenhouse gas challenges, and a summary given of critical issues that will need to be addressed if energy shocks are to be averted. The paper concludes with a consideration of the likelihood of averting transport fuel and greenhouse gas related energy shocks.

Potential Energy Shocks

This section outlines the magnitude of two potentially critical energy challenges facing national and global economies.

Transport fuel

The issue of 'peak oil' has been recognised by some commentators for many decades (Deffeyes, 2001), and has its base in the estimates made in the 1950's by Hubbert on US oil production. Peak oil refers to the situation when production of oil reaches an upper rate and subsequently declines, and as such it does not imply exhaustion of a finite mineral resource. However, the concern around peak oil is simply that the supply rate will not be able to satisfy anticipated demand once the peak has occurred.

Production of oil in the US peaked in the early 1970's, as forecast by Hubbert (vindicating his analysis after much derision from the oil industry). Although fuel efficiency measures were encouraged and domestic oil fields expanded in the US, the gap between domestic supply and growing demand was largely solved by importing Middle-Eastern oil. This came with economic disruptions as OPEC manipulated production and regional wars substantially affected prices on the international market. Since this time, several other major fields (e.g., UK's North Sea oil) have reached peak production and are in decline (Sorrell et al., 2010). Despite this experience, it is only in recent years that the issue of global peak oil has gained credence beyond the previous small number of analysts promulgating the issue; for example, with the release of the World Energy Outlook 2008 (and Energy Technology Perspective 2008) the conservative International Energy Agency (IEA) formally recognised constraints in conventional oil supply. In Australia, domestic oil production is forecast by Geoscience Australia to decline over coming years, even with undiscovered resources factored in (GA, 2009). However, differing views remain about when a global peak may occur (or if it is in progress now) (see (Owen et al., 2010, Sorrell et al., 2010) for recent overviews), and what the effects will be (and potential geo-political responses such as those examined in (Friedrichs, 2010)).

What distinguishes various forecasts of future oil production and peaking (if any) is uncertainty about the ultimate recoverable resource (URR) and to what extent non-conventional sources of oil, such as deep-water resources, tar-sands and extra heavy oil, should be included. Production from conventional oil yet-to-be-discovered is unlikely to contribute significantly, on the basis of substantial falls in discoveries since the major fields found in the 1960's. Consequently, energy agencies and large petrochemical companies make forecasts that see production continuing to increase (or peaking beyond 2020) through widespread use of non-conventional oil that is assumed to be developed to meet increasing demand. In contrast, independent researchers have forecast peak production to generally occur by 2020 at the latest (if not already taking place) (Sorrell et al., 2010).

Demand for oil is expected to increase due primarily to its fundamental role in powering transport. The increase is based on expectations of continued economic growth, increasing use of cars and other oil-based vehicles in developing countries, and population growth. Some alleviation of demand is likely as other fuels substitute for oil-based heating systems. Even without growth in demand, modern and developing economies are clearly critically dependent on oil-based transport. Without adequate transport services, essential components of society and economies would be jeopardised, such as mechanised food production, freight movement, business travel and even labour access to work.

A constriction in supply of oil may affect other economic functions. For instance, plastics and other by-products of the petrochemical industry are widely used throughout the economy. An increasing oil price affect food production by stimulating additional demand for natural gas, and thereby puts pressure on nitrogen fertilisers which use natural gas as a feedstock.

Greenhouse gas emissions

Shocks to energy systems may also occur indirectly through potential constraints applied to the emission of greenhouse gases in order to mitigate climate change. Currently, energy use accounts for the majority of GHG emissions, with the combustion of fuels for stationary energy use contributing a large fraction, along with transport use. Therefore, any substantial reduction in GHG emissions will involve large changes to the energy system.

In order to avoid the potential for dangerous climate change, the IPCC has recommended a range of reductions of GHG emissions that should be achieved by 2050. Relative to 1990 levels of emissions, the global target reduction in 2050 is 80-

90%. Different reduction targets are suggested for reductions attributed to developing and developed nations (e.g., 50% and 90% respectively).

Unless large changes are made, emissions are likely to be substantially higher than current emissions. Recent measurements indicate that global emissions are closely tracking on the A1Fl scenario produced in the IPCC Fourth Assessment, which effectively constitutes 'business-as-usual' (BAU). Relative to this BAU situation in 2050, the recommended emission reductions are therefore even more substantial.

Alternative Energy Options

An overview of alternative energy options is provided in this section, which also describes other impacts or requirements that are associated with these options, but are rarely considered.

Overview of potential transport fuel technologies

A range of alternative energy technologies and options exist for providing transport fuels. Arguably the most similar with current petroleum fuels is simply the expansion into so-called non-conventional oils. These are liquid fossil fuels that exist in forms or locations that require significantly different processes to extract them. Other fossil fuels can be used for transport, most notably natural gas; and coal can be converted to a liquid fuel. Several different liquid fuels can also be produced from crops and other biomass, and even potentially from algae. Finally, land and sea transport can be powered by electric systems using batteries or hydrogen fuel cells to store the energy.

All options for transport fuels, including conventional oil, have implications that need to be considered for their feasibility and desirability in terms of impacts on the environment, resources and economy. In most cases, the implications may be substantial and complex, as Table 1 summarises.

For the fuel alternatives listed, additional resources are often needed, such as water, land and minerals. These may already be constrained, so that the additional impost associated with fuel production would increase stress on these resources. Some fuel options are likely to lead to higher GHG emissions per unit of fuel consumption, though this could be reversed in the case of electric power systems with the use of renewable electricity generation. When higher GHG intensities are combined with increased demand anticipated with economic growth, absolute emissions would increase rapidly. A similar recent review of alternatives is available in (Diesendorf et al., 2008).

Table 1. Alternative technology options for providing transport and fuels, and some requirements (inputs and infrastructure) and potential environmental impacts.

Technology	Description	Resource inputs	Infrastructure	Environmental / resource impacts
Non-conventional resources	Petroleum products derived from deep-water resources; tar sands; extra heavy oil	Higher energy inputs; Water	Extraction and processing plant	Increased GHG; Water pollution; Environmental accidents (e.g., Gulf of Mexico Deepwater Horizon)
Lower fuel consumption engines				
Modal shift	Rail-based freight and passenger transit	Electricity (or other conventional fuel)	Expanded rail network	GHG from electricity generation
Natural gas	Compressed and liquefied natural gas	Energy for compression, etc.	Pipelines; Shipping; Fuel station refit; Engine changeover	Reduced GHG per unit fuel consumption; Competition for finite resource (similar to oil in energy terms)
Coal-to-liquids	Oil produced from coal	Coal; Water; Energy for processing	Manufacturing plant	Increased GHG; Competition for water resources
Bio-fuels (e.g., Ethanol, Methanol, Biodiesel)	Production of liquid fuel based on e.g.: Crops and stubble; Second generation biomass; Oil-producing algae	Land; Water; Fertilisers; Energy to harvest and process	Manufacturing plant	Competition with food systems (& forests); Soil degradation; Competition for water resources
Compressed air power	Other energy used to compress air, which is later released to develop power	Electricity?	Minimal?	GHG from electricity generation
Electric vehicles (and hybrids)	Battery-based power for electric motors; Not applicable for aircraft	Heavy metals (Lithium?); Electricity production	Transmission / distribution network; Recharging stations or battery exchange	Increased GHG depending on source of electricity; Waste batteries and toxic chemicals
Hydrogen fuel-cells	Fuel-cell power for electric motors; Not applicable for aircraft	Natural gas; Water; Catalysts (e.g., xxx); Electricity for electrolysis	Manufacturing plant Pipelines; Recharging stations	Increased GHG depending on source of electricity

Of the options and criteria in Table 1, potentially the least demanding is the use of natural gas. In this case, a transition to gas would necessitate the creation of new infrastructure (and engine technology) to replace that for the delivery of oil, even before allowing for expansion due to economic growth. Gas as a transport fuel would compete with that used in electricity production and heating. While non-conventional resource estimates have increased recently, the URR is of the same order as that for oil. Therefore, given exponential growth in demand the gas resource could reach peak production in several decades.

Overview of technologies for GHG reduction in electricity generation and use

A similar summary of alternative technology options for reducing GHG emissions associated with electricity generation (and use) is provided in Table 2. The list of technologies is not exhaustive but captures the wide range in potential options available. The technologies are assessed according to their stage of development and the related issue of when the technologies could realistically be available for large scale deployment. It is also important to review technologies for their impacts on or requirements for resources and infrastructure.

It is evident from this brief overview of potential technology options that there are several alternatives that appear to be more readily available and could be deployed relatively quickly. All options also involve some impact on resources or infrastructure development, to some extent. It is not clear from such a qualitative review however, whether the additional implications and timeframes would inhibit rapid reductions in GHG emissions sufficient to avoid dangerous climate change.

A similar high-level assessment has been made by Macgill (Macgill, 2008), concluding that energy efficiency and gas-based and renewable energy options offer better possibilities for reducing GHG emissions rapidly. Macgill notes the need for scenario simulations that deal with the many critical aspects of alternative technologies, not just the ultimate size of the resource.

Such reviews point to the need for system-wide assessment of alternative technology options. A description of such an approach is provided in the next section, and results from a selection of studies using this system given in the following section.

Table 2. Characteristics of stationary energy technologies for reducing GHG emissions.

Technology	**variations**	**Development phase**	**Potential deployment**	**Resources / infrastructure**
Energy efficiency	end-use; generation & distribution	mature mature	immediate	turnover of inefficient devices
Gas fueled	Combined-cycle Gas	mature	immediate	access to gas resources
Nuclear energy	Fission; 3rd Generation	mature well researched	immediate	uranium resources, processing, disposal and security issues
	Fusion	early research	many decades	massive infrastructure; sea-water feedstock
	Thorium	very early research	decades?	unknown infrastructure requirements; large thorium resources are available
Carbon Capture and Storage (CCS)	Geological	research, with little deployment at scale	decades	pipeline transmission; compression; security of storage (& related size of storage)
	Biochar	early research	years–decades	potential soil implications (positive & negative?) and limits
Renewable electricity generation	Wind	mature	immediate	energy storage, redundant farms or transmission network for variability
	Solar (PV & Thermal)	mature	immediate	access to specific minerals for PV systems
	Hydro	mature	immediate	environmental water resource impacts
	Biomass	early research, through to mature	immediate–decades	land, water, fertiliser (and other?) inputs
	Other – tidal…	research	years–decades	suitable coastal environments
Geothermal	Thermal energy	mature	immediate	new infrastructure;
	Electricity generation	research	decades	not demonstrated at scale; electricity transmission network

System Modelling of Options

Given the need for wider system analysis of alternative options, the 'stocks and flows' system for modelling national economies for system-wide analysis is described in this section.

The Australian Stocks and Flows Framework (ASFF)

The ASFF model is a technology- and process-based simulation of the physical activity in all sectors of the national economy. It is a highly disaggregate simulation of all physically significant stocks and flows in the Australian socio-economic system (Poldy et al., 2000, Foran and Poldy, 2004, Turner et al., 2010a). In the current version of the ASFF there over 800 multi-dimensional variables (about 300 that are exogenous). Stocks are the quantities of physical items at a point in time, such as land, livestock, people, buildings, etc., and are expressed in numbers or SI units. Much of the physical capital in the APSFF, such as vehicles, buildings and factories, is vintaged according to the year the additional capital or machinery was introduced. Consequently, efficiencies can be associated with particular vintages, and the aging and decommissioning of vintaged capital is simulated. Flows represent the rates of change resulting from physical processes over a time period, such as the (net) additions of agricultural land, immigration and birth rates, etc.

The ASFF simulates the dynamics of major capital and resource pools, and the flows associated with these stocks such as inputs of natural resources, manufacturing output, and changes in capital including buildings, infrastructure and machinery (Figure 1). Natural resources (land, water, air, biomass and mineral resources) are represented explicitly, and flows of raw materials are harvested or extracted from the domestic environment (bottom of Figure 1). Materials are generally progressively transformed to become goods and to provide the basis for services for the population (following flows upward in Figure 1). Part of the framework incorporates a physical input-output model for the transformation of basic materials and energy types (Lennox et al., 2005). Some transformations involve the creation of secondary energy flows (to the left in Figure 1), which are used throughout the economy. Allowance is also made for recycling of waste flows, and for improvements or additions made to the environmental resources (e.g., forests). Otherwise, wastes and emissions return to the environment. Materials at various stages of transformations and energy may enter or exit the national economy as imports or exports (to the left and right of Figure 1 respectively). Likewise, immigration and international travellers add to the permanent and temporary population dynamics. Finally, the population provides a labour force for the various sectors of the economy (top of Figure 1).

Geographically, the ASFF covers continental Australia, including the marine area within Australia's economic exclusion zone (for fishing and fuels). Within specific sectors of the framework different geographic resolutions are used. The temporal extent of the ASFF is long-term: scenarios over the future are calculated to 2100, and the model runs over the historical period to reproduce the observed data.

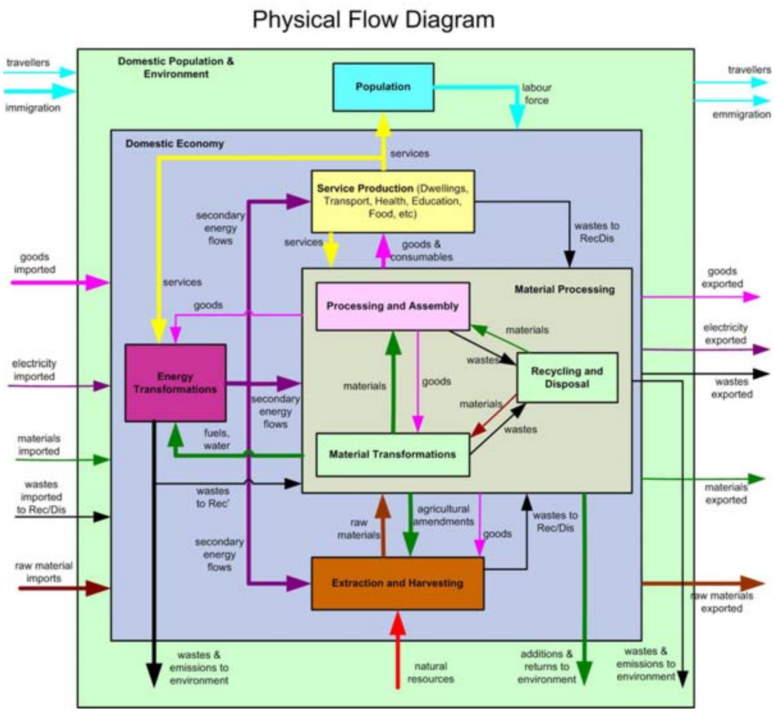

Figure 1. Flows of physical quantities into, out of, and through a national economy, modelled in the Australian Stocks and Flows Framework.

The Asia-Pacific Stocks and Flows Framework (APSFF)

A similar stocks and flows framework was developed to cover the Asia-Pacific region for a United Nations Environment Program study into the region's resource use and emissions (Turner et al., 2010b). Structurally, the APSFF borrows many of its features from the detailed Australian framework. Geographically, the APSFF represents nations as discrete entities. Distinctions are also made between rural and urban areas, but these are not explicitly located. Scenarios simulations extend to 2050, and the model is also run over an historical period of 1970–2009.

The APSFF is calibrated for the period 1970–2009, in annual steps using data from a wide range of sources e.g., UN trade statistics, FAO food and agriculture database, IEA energy production and consumption data, and USGS mineral resource database. In this approach, the aim of calibration is to reproduce historical data exactly at each time step, in order to preserve widely recognised and available data. This is quite different from the calibration of an econometric or regression model where the aim is to fit mathematical functions to data. Calibration to date has focused on eight major economies, representing 74% of the Asia-Pacific population and 84% of its economic activity.

Interactions and feedbacks between the physical and economic systems

The stocks and flows systems described above are very suitable to examine 'what if' type questions surrounding alternative technology and consumption behaviour. In this sense they are analogous to flight simulators, where operators can try different strategies and compare outcomes. This mode requires other conditions of the scenario, such as economic growth, to be supplied exogenously as inputs to the simulations.

In recent advances, two separate approaches have been taken to incorporate economic settings internally within the scenario simulations. This means that economic growth is endogenous to the simulations—it is an outcome rather than an assumption of the simulation.

In the first approach, both production (primary and secondary industry output) and final demand consumption are adjusted to simultaneously maintain a target unemployment rate and a target trade balance (relative to GDP). The level of (un)employment is a result of the population size, its age profile, the participation rate, labour productivity, and the various economic activities requiring labour. If no other change is made to the ASFF inputs, then increased productivity (labour input per unit output and other efficiencies) leads to increased unemployment due to the simple fact that the same economic output can be achieved with fewer workers. With the productivity growth assumed above, mass unemployment of the order of 50% occurs after several decades.

To achieve a stable unemployment level and replicate past economic conditions, the background scenarios incorporate re-employment of displaced labour through increased economic activity. It was assumed that the trends in labour participation rates are not changed from their background settings. Consequently, in the background scenarios, final demand consumption was increased (or decreased) in order to lower (or raise) the unemployment rate. The modelling calculations allow for service workers supporting the physically productive sectors of the economy.

The other key macro-economic indicator simulated is the international trade balance (relative to gross domestic product, GDP). The net foreign debt (NFD) relative to GDP has increased over recent decades, to 52% in 2006 (Kryger, 2009). High rates of debt (and surplus) are considered to be contrary to a stable national economy. In one measure of the economy, the net foreign debt is compared with the nation's GDP in order to judge whether an economy is overstretched to pay its international debt.

The net foreign balance in the ASFF was adjusted by changes to exports and imports, and international travel (inbound visitors, and outbound Australians), and investment. It is possible to achieve the same NFD through different combinations of changes to exports, imports and investment; however, this study (to date) has not explored this sensitivity. Adjustments to exports were made by altering activity in both primary and secondary industry, after allowing for domestic requirements to be met from these industries (where Australian exports are a large fraction of Australian production). International travel and investment were adjusted by the same proportion as exports. Imports were adjusted by changing the fraction of the domestic demand for goods/commodities that is obtained from overseas. These changes also alter GDP, so that an iterative feedback calculation is necessary to achieve the specified NFD:GDP ratio.

In the second approach, a dynamic non-equilibrium financial model of the economy was used, and linked to the physical stocks and flows model. A multi-sectoral model of a dynamic monetary economy based on non-equilibrium assumptions is used to simulate economic growth (as opposed to it being an input assumption to CGE models) and to capture the inherently cyclical nature of this growth. The economic model is based on Monetary Circuit Theory (MCT) and captures the non-equilibrium dynamics of the monetary economy (loans, investment, etc.), and its interaction with the productive economy (labour, consumption, etc.) (Keen, 1995, Keen, 2009). This enables scenarios with realistic economic cycles to underpin the resource use trajectories in the biophysical model. Such an integrated approach describes different aspects of a single overall economic reality (i.e. material and monetary).

The monetary model is a dynamic simulation of the financial and physical flows that must occur in an economy, augmented by simple behavioural relationships. This is the first ever economic model to work explicitly in terms of monetary flows. Therefore, the simulation is driven by the financial sector, which is treated as an aggregate private bank that maintains bank accounts for itself and the two main classes in society, firms (or capitalists) and households (or workers). The financial sector creates credit money by crediting each firm sector with money (and simultaneously the debt of each sector is increased by the same amount). This enables firms it to invest, purchase intermediate inputs from the other sectors, and hire workers. The money supply can expand in response to firms' demands, and the level of debt grows commensurately with this increase in the money supply.

The unique monetary nature of the model means that three additional monetary behavioural functions exist: the rate of loan repayment, the rate of circulation of existing money, and the rate of creation of new money are all modelled as nonlinear functions of the rate of profit.

Linkage from the MCT to the APSFF gives the latter cyclical predictions of future demand rather than smoothly growing demand from population growth, technical change and changes in living standards. This linkage is communicated via unemployment levels, using the same background assumptions of growth in labour productivity. This approach was applied to analysis of the resource use and emissions of the Asia-Pacific region, as described in the next section.

Scenario Simulations of Options and Assumptions

In this final main section of this paper, results are presented from the stocks and flows analysis that are drawn from a collection of separate studies. The approach of other recent studies dealing with transport fuel and greenhouse gas challenges is summarised and compared with the present analysis, and a summary given of critical issues that will need to be addressed if energy shocks are to be averted. The first sub-section examines the issue of GHG emissions and the potential in the energy system to reduce these. Analysis is presented at regional (Asia-Pacific), national (China, Australia) and down to sub-national levels (State of Victoria). The second sub-section looks more closely at the issue of transport fuel and transitions to alleviate dependence on oil.

System simulations of energy and GHG emissions

Results are first presented in this section from the modelling of the Asia-Pacific region using the coupled biophysical and economic models (Turner et al., 2010b).

They show the simulation results for the scenarios over 2010-2050, as well as the simulated history from 1970. Three scenarios have been constructed to illustrate future resource use possibilities and their consequences. The business-as-usual or reference scenario represents the continuation of current policies and provides a measure of the scale of some of the problems that have been anticipated to flow from them. The essential feature of the business-as-usual scenario is that major historical trends are continued.

A second scenario involves wide-spread technological progress, in the form of efficiency gains. This 'high efficiency' scenario applies to physical processes used in the extant economic structure. The amount of material, energy and water resources used per unit output is continuously decreased in compounding annual growth.

The third scenario adds to the changes in the resource efficiency scenario by also invoking structural change. This 'system innovation' scenario incorporates changes to consumption and lifestyle habits, urban form, transportation modes, energy production and economic structure. These include food consumption shifts/reversion to lower meat diets, and total food intake rates that are lower than the excessive levels of affluent developed countries. The growth in per capita consumption of material goods is also curbed. Urban form is assumed to change toward greater density housing in new developments. Where possible, allowance is made for local food production, resulting in decreased freight. Passenger transport shifts/reverts from growing dependence on the car, toward bicycle and public transit. Electricity generation comes increasingly from renewable sources such as solar and wind, which are phased in as fossil-fuel based thermal power stations are decommissioned at the end of their life.

Primary energy consumption is shown for 'Business as Usual' (BAU) and 'High Efficiency' (HE) and an intermediate scenario in Figure 2. The intermediate scenario is the outcome of moving from BAU to high resource efficiency without making any other change. A consequence is a high and growing level of unemployment because less labour is required as throughput of materials and energy is lowered. The efficiency improvements (50% less inputs per unit output by 2040 compared with recent values) are sufficient to keep primary energy use lower. (Note that the BAU scenario also employs efficiency gains, achieving 25% less inputs per unit output by 2050).

However, without any other change in the underlying economic or social conditions, very high levels of unemployment are anathema to stable societies. Therefore, in both the BAU and high resource efficiency scenarios, excessive levels of unemployment were eliminated by increasing consumption and primary production rates (using a feedback process described above). The consumption and production rates are adjusted until the biophysical model achieves the unemployment rate simulated by the dynamic economic model. Consequently, cyclic variations are evident in the resource indicators presented, clearly illustrating the linkage between the economic and biophysical models.

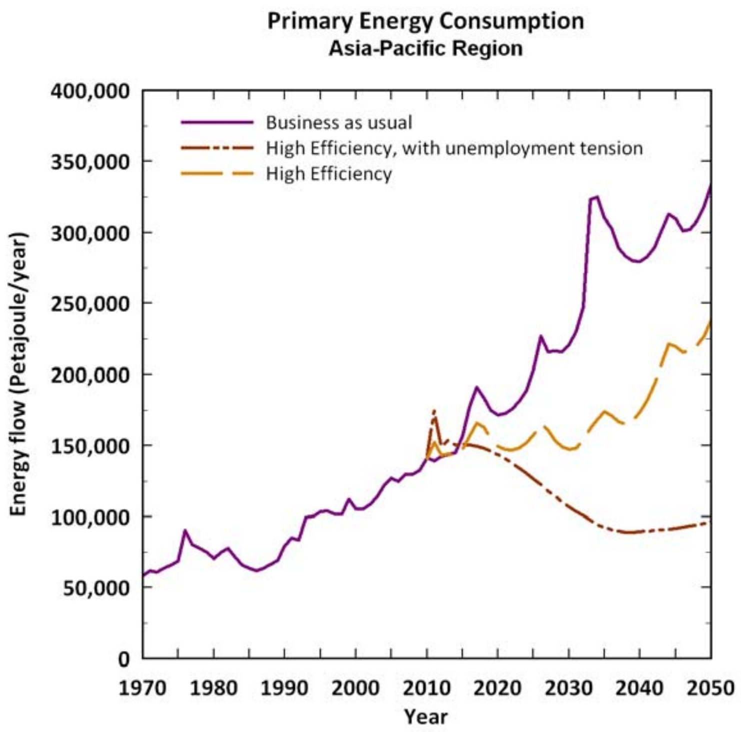

Figure 2. Primary energy consumption for the Asia-Pacific region, for two scenarios (and an intermediate one). Results have been aggregated over countries, activities and fuel types.

Beside the cyclic variations, substantial increase in throughput of materials and energy occurs, even when high resource efficiency is employed. Primary energy consumption doubles over the scenario period. The fact that strong growth in resource use and emissions occurs even with high resource efficiency follows from the rebound effect caused by economic growth required to keep unemployment low.

The corresponding GHG emissions, which include the effects of fuel combustion, are shown in Figure 3. In both business-as-usual and high-efficiency scenarios there are substantial increases in emissions, though the latter scenario achieves some stabilisation at contemporary levels for about two decades before growth in the economic activity (and population) drives emissions higher. As a result, emissions in both scenarios are substantially higher than levels suggested to avoid dangerous climate change.

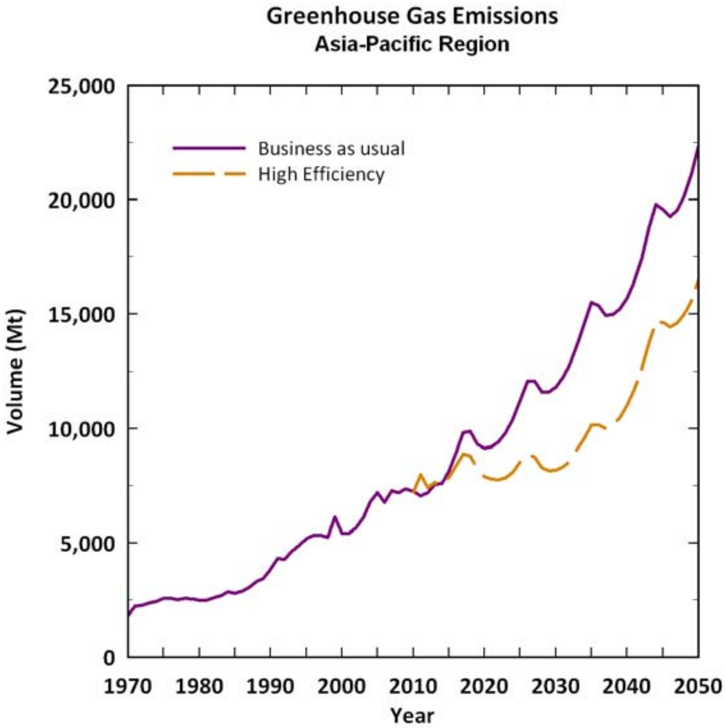

Figure 3. Greenhouse gas emissions for the Asia-Pacific region, for two scenarios.

The corresponding scenario trends for individual nations are somewhat different, as shown for China (general increase for some years, followed by a decrease for more than a decade, then a sustained increase) - Figure 4. Additionally, a substantially different alternative is presented in the 'System Innovation' scenario. In contrast with the other scenarios, substantial emission reductions do occur in the System Innovation scenario. But even so suggested targets of 60–90% reduction relative to 1990 levels are not achieved. As described above, this scenario not only employs high resource efficiency but combines this with structural changes such as shifts in modes of transport. Additionally, the System Innovation scenario also seeks to avoid the rebound affect by not employing displaced labour in traditional jobs. The important social question concerning the role or occupation of the population not otherwise employed is not explored in this analysis. There are several different ways that lower employment might be absorbed within society, such as general reduction in working hours. The scale of the change is illustrated in the biophysical model by the about a 50% decrease in labour participation rates by mid-century from current levels, in order to eliminate the excess unemployment level.

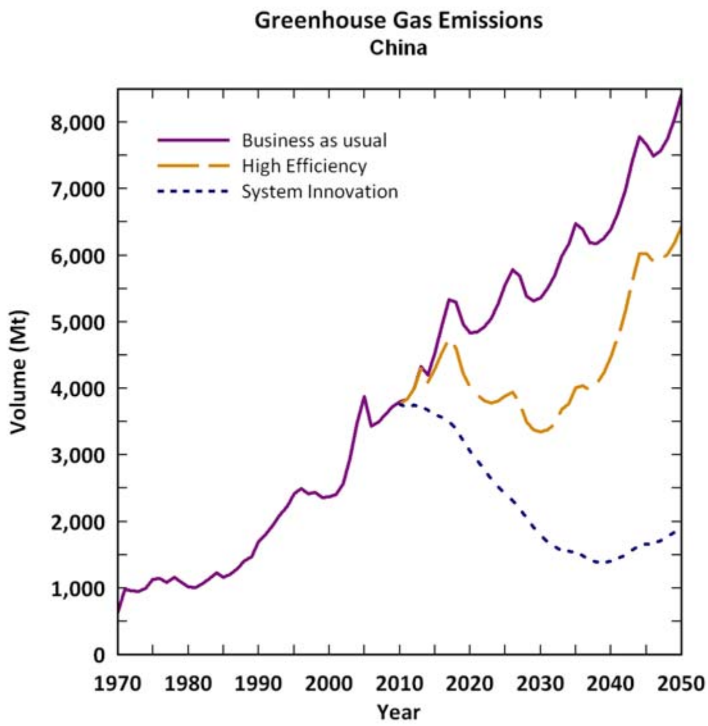

Figure 4. Greenhouse gas emissions for China, for three scenarios.

In separate, earlier modelling, the "dematerialisation" potential of the Australian economy (Schandl and Turner, 2009, Hatfield-Dodds et al., 2008) was simulated using the Australian Stocks and Flows Framework. In this, the ASFF was used to model large-scale changes to material and emission intensive sectors, including construction and housing, electricity generation, and transport and mobility. Average energy use intensity of all housing was halved (assuming retrofit and adoption of simple solar passive technology), new dwellings were of lighter construction and the trends for increasing floor area reversed; electricity generation was transformed by 2050 to a mix of wind, solar and gas as aging coal-based power plants were decommissioned; and commuting by car was reduced from 85% to 60%, with commuting distances reduced 30% to reflect improved urban design, and modal share of long distance travel switched from air to bus.

These and other changes managed to stabilise aggregate energy consumption and greenhouse gas emissions for about two decades (see Figure 5). Subsequently though, overall economic growth offset the environmental gains and led to emissions higher than contemporary levels, albeit some 30% lower than if no transformations had been attempted. The Australian 'dematerialisation' scenario and the 'system innovation' scenario for the Asia-Pacific shared a similar mechanism for dealing with growing unemployment that results from ongoing efficiency gains, whereby displaced labour was assumed to be engaged in "service" activities that do not result in physical activity in the economy.

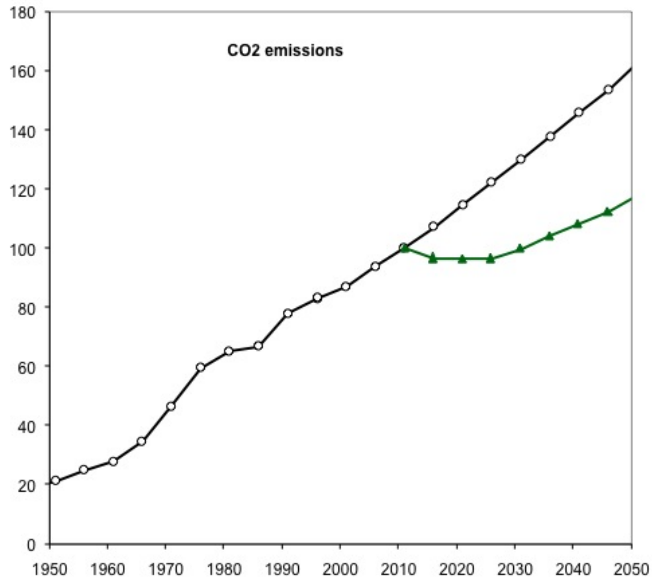

Figure 5. Comparison of greenhouse gas emissions (from fuel combustion) for Australia under BAU and Dematerialisation scenarios. Emissions are indexed (100 at 2010).

In a third study, the potential for reducing GHG emissions was also examined for the electricity generation sector in the State of Victoria (West and Turner, 2010). This identified the importance of considering the timing or rate at which change may be required, particularly when associated with long-lived infrastructure. Analysis of the turnover of power plant under different electricity consumption growth rates indicates that plant introduced after 2011–2018 must be capable of near-zero GHG emissions in 2050 if proposed reduction targets (in the range 60–90% of 1990 levels) are to be achieved. It is necessary to have in place in the near-term plant technology that is prepared for carbon capture, even though it may not be employed initially, because a significant fraction of old plant may be operating in 2050.

System simulations of transport fuel transitions

From the Asia-Pacific simulations and scenarios described above, dependency on oil can also be illustrated. Figure 6 shows the strong growth in Chinese oil consumption that could be expected under BAU. Rapidly implementing fuel consumption efficiency could stabilise consumption for about two decades. However, only ‘system innovation’ results in lower rates of oil consumption. Whether this is sufficient to avoid tensions with potential rates of decline in supply (assuming earlier realisation of peak oil) has not been investigated.

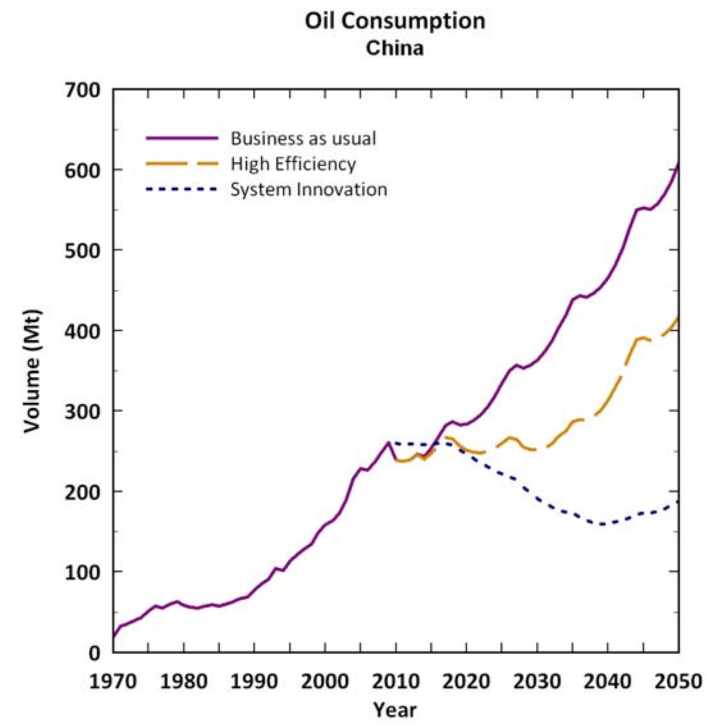

Figure 6. Total consumption of oil in China, for three scenarios.

The situation for Australia was examined separately using the ASFF and specific scenario settings developed for review of transport fuel options. The background scenario incorporates key population and economic conditions; in summary: 36 million in 2050; 5% unemployment; and net foreign debt:GDP ratio of ~52%. Average fuel consumption efficiency of the private vehicle fleet is assumed to increase over a couple of decades to equal good hybrid performance. However, since overall per capita consumption rates grow in order to maintain unemployment at a steady level, car ownership and travel distances increase.

This results in increasing total required oil volume (for domestic consumption and export) as shown in Figure 7. The gap between domestic production and this demand grows rapidly over the coming 1–2 decades. Production is taken from Geoscience Australia forecasts (at 50% probability). Consequently, Australia would soon be 100% reliant on imported oil, assuming it is available at economically feasible prices on the international market. This is not necessarily the case, as recent economic modelling has indicated (Graham, 2008, Graham et al., 2008). The economic modelling incorporated some elements of biophysical assessment, such as land use change for biofuels, but not other aspects e.g., water resource implications of the changed land uses, or constraints in the ultimate gas resource.

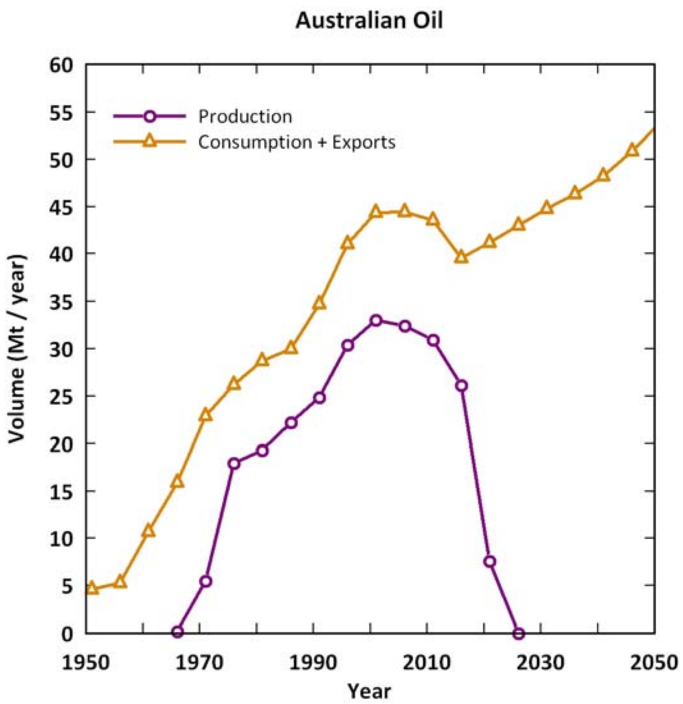

Figure 7. Comparison between Australian domestic production of oil (and condensate), and the total of domestic consumption and export, for a business-as-usual type scenario. The gap between the two curves is implied import of oil.

Therefore there is an important role for subsequent scenario analysis to investigate the potential for transition to other fuels within the system-wide biophysical capability of the economy. From the review above of potential transport alternatives, a suitable option for early substitution is the use of natural gas. This has been partially simulated in the ASFF, and shows that Australian domestic transport requirements could be met for several decades from domestic production of natural gas (Figure 8). The simulation includes the recent 3–4 fold increase in economically demonstrated resources of gas (Cuevas-Cubria et al., 2010). Exports are assumed to increase in proportion with the domestic demand for gas.

Production of domestic gas can meet the export and domestic consumption with strong increases in volume, until about 2040. At this time, a rapid fall in production occurs. There are likely to be uncertainties around this timing—potential further discoveries could extend the peak year, although extraction rates may slow somewhat as the fields deplete (this is less prevalent in gas resources, than in oil fields) and advance the peak year. Nevertheless, continual growth in demand would reduce the range in which peaking occurs. Consequently, in Australia domestic gas could play a role as a transition fuel for some three decades, before another transport fuel system is required (or fuels imported). The oil-to-gas simulation has not investigated the details of infrastructure turnover required, such as new refuelling outlets, pipelines and compression facilities.

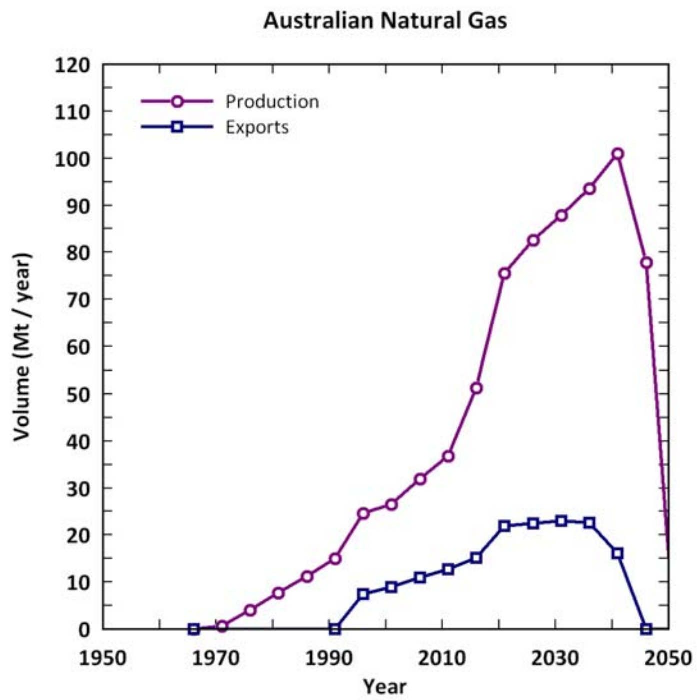

Figure 8. Comparison of Australian domestic production of and export of gas resources, in a scenario that assumes a transition from oil to gas as transport fuel. Domestic consumption is the gap between the two curves.

Current research using the ASFF to investigate food supply security is examining the impact of biofuel production in Australia. Simulations to-date indicate that first-generation biofuel options (e.g., converting crops such as wheat and canola to ethanol and biodiesel (Stucley, 2010)) could substitute for about 10% of future domestic oil requirements (which is comparable with other estimates (Deborah, 2007)), and invert Australia's trade position to that of net importer before 2040.

Other studies

In recent years there have been increasing numbers of studies into national and global energy systems, examining the potential to reduced GHG emissions and achieve energy security. A summary of these studies is given in Table 3. Though it is beyond the scope of this paper to comprehensively review these, a brief comparison with the analysis presented above follows.

Table 3. Characteristics of recent studies into potential reductions of GHG emissions and achieving transport fuel security.

Proposal	**Approach**	**Technologies/sectors considered**	**Potential limitations**	**Reference**
Zero Carbon Australia 2020 Stationary Energy Plan	Detailed supply-demand grid modelling; Separate ad-hoc analysis	Wind; Solar Thermal; Biomass; Electrified transportation	Employment of non-electricity sectors effectively held constant	(anon, 2010b) (Beyond Zero Emissions)
Zero Carbon Britain 2030	Separate technology assessments?	to be reviewed	No rebound effect considered	(Kemp and Wexler, 2010)
IEA Energy Technology Perspective	Separate technology assessments?; Scenarios	Fossil fuels; Nuclear; Renewables; Transmission; Buildings; Transport; Efficiency; CCS	to be reviewed	(Taylor, 2010)
Low Carbon Growth Plan for Australia	Economics – cost benefit (cost curves)	Fossil fuels; Renewables; Buildings; Transport; Efficiency; CCS; Agriculture; Forestry	No physical assessment of technological options; No rebound effect considered	(anon, 2010a) (Climate Works)
The Economics of Climate Change – The Stern Review	Economics – Integrated Assessment Modelling; Scenarios	to be reviewed	Assumes a higher rate of GHG emissions in 2050; No physical assessment of technological options;	(Stern, 2006)
The Garnaut Climate Change Review	Economic modelling	to be reviewed	to be reviewed	(Garnaut, 2008)
Fuels focus				
A Roadmap for Alternative Fuels in Australia	Separate biophysical analysis	Efficiency; fossil fuels; biofuels; electrical; fuel cells	No physical assessment of technological options; No rebound effect considered	(Diesendorf et al., 2008)
Powerful Choices– Transition to a biofuel economy in Australia	Embedded energy analysis, with macro-economic factors included; Scenarios	Biofuels	Controls rebound effect using a “futures fund”; No physical assessment of technological options beyond energy implications	(Foran, 2009)
Fuel for Thought – The role of transport fuels: challenges and opportunities	Parital equilibrium economic modelling, with sectoral biophysical modelling	Fossil fuels; Electricity; Biofuels	Limited physical assessment of technological options; No rebound effect considered?	(Graham, 2008, Graham et al., 2008)

From the review of other studies and proposals, it appears that the technical likelihood for implementing alternative energy options is not a key issue. These analyses find that it is possible to achieve large reductions in GHG emissions or to establish alternative transport fuel systems. The options explored are generally deemed technically feasible, and often illustrated by graphs showing parallel ‘wedges’ of technological change over the coming half-century enabling the desired change.

However, in general there are several key aspects that are not well addressed or recognised in these studies, including:

- rate of change
  - about the same as past growth rates, but in the opposite direction;
  - many simultaneous changes required;
  - stranded assets are likely;
- physical implications
  - cross-sector impacts potentially increase environmental pressures;
  - impact of lower net energy gains;
- socio-economic conditions
  - employment and rebound ignored;
  - financial investment and servicing debt;
  - institutional arrangements and governance.

While the changes proposed appear feasible within the context of the technologies and sectors analsysed, the size or rate of change is dramatically different to what has been experienced in the past. In some cases, this is likely to require the early retirement of power plant and other infrastructure, despite the economic incentive of owners to obtain revenues for longer. Infrastructure inertia is compounded by the general proposal from these studies for multiple new technologies to be implemented virtually simultaneously, in some contrast with previous experience and the general objective of seeking simplicity and market dominance. Other elements of technological optimism are evident in estimates of the readiness of new technologies to be deployed. In contrast, even with mature technologies, some 10–20 years are likely to be required to enable development of infrastructure and systems. This all suggests a radical transformation is needed in the way economies operate and society is engaged, and on a scale that would arguably match a world-war footing.

Since the focus of these studies has been on energy, other environmental and resource implications tend to be neglected. While it is not uncommon to see land area recognised, other resources such as water, fertilisers and scarce minerals, food competition, forestry and biodiversity are not systematically considered in these other studies. Additionally, a full system assessment would incorporate ‘net energy’ in the analysis, to allow for the higher use of energy that is required to produce alternative forms of energy (both for transport and electricity) (Heinberg, 2009). Net energy for oil was originally very high when oil was first extracted, but has dropped as fields have been depleted or more difficult oil accessed. Most other energy sources have even lower net energy, and there are conjectures that modern economies are predicated on the “free energy gift” of oil and coal. In particular, it is not clear if these studies have considered the overall energy that is required to put the new technologies in place. Further, if energy and oil alternatives are to be implemented then these changes must occur before the supply of oil is seriously constrained, otherwise there may not be the transport services (and the wide range of economic functions) that are needed to facilitate the change.

Another common aspect missing from other studies or dealt with poorly are the socio-economic conditions typically required in modern economies. Importantly, employment and the rebound effect do not figure highly, if at all. Typically, as labour is displaced by technological progress, higher consumption and economic growth provides an opportunity to re-employ the displaced labour. This results in further resource use and emissions, that offset (or even surpass) the anticipated gains from the technological progress.

While economic analyses typically indicate the level of investment required in the proposals and scenarios put forward, the issue of being able to raise the financial investment required is not raised (the IEA's ETP is a notable exception). With investment equivalent to trillions of dollars, and the effects of the global financial crisis still unresolved, there is concern that the large, numerous and challenging projects will not be able to find sufficient financial support.

Conclusions

This paper has focused on transport fuel security and implications of GHG emission reductions as two key shocks potentially facing national and global energy systems. A plethora of alternative technology options are often put forward for dealing with or averting these shocks. System-wide biophysical analysis using 'stocks and flows framework' simulations suggests that technological alternatives are more limited in systemic sense than generally anticipated. This appears to contrast somewhat with a range of other studies, which generally propose a multitude of technological actions. The likelihood of energy shocks being averted by these technological actions must incorporate a realistic assessment of the many factors that are involved, not least:

- the substantial rate of change and multiplicity of actions required, compared with inertia associated with infrastructure and institutions;
- the transfer of environmental impacts and other resource constraints due to cross-sectoral dependencies;
- the impost of increasing energy inputs underlying each unit of energy delivered;
- the un-employment implications of moving to economic systems with drastically reduced throughput of commodities; and
- the substantial financial investment that would be required in economies already laden with debt.

System-based analysis undertaken to-date with these factors incorporated points toward the unlikely outcome that energy shocks will be averted.

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