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The OzECCO Embodied Energy Model of Australia's Physical Economy

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ABSTRACT

Within the broader context of a population-development-environment project focussed on Australia's environmental futures out to 2050, we have developed an embodied energy model (OzECCO) of the country's energy metabolism based on the ECCO approach first developed by Malcolm Slesser. The model has aggregated descriptions of the main sectors which physically transform natural resource stocks such as coal, oil, natural gas, minerals, water, agricultural soils etc. into useful goods and services for both domestic consumption and for export. The influence on national energy metabolism of a globalised economic and trading system is included with aggregated descriptions of key international trade and monetary flows as well balance of payments and international debt. This research project of two main parts sits within an environmental division of CSIRO which is a government funded national research organisation. The first is a context setting and more qualitative part where possible future options are explored through the development of scenarios which include political, social, economic, technological and environmental components. The second part is more quantitative and focused on dynamic models and analytical frameworks which analyse the larger and more important physical transformations which underpin the functioning of the national socio-economic system.

The OzECCO model is built and calibrated on the national physical and financial accounts for the period 1981 to 1993. During that period approximately 11 MJ of primary energy were transformed within the physical economy to produce one constant Australian dollar of gross domestic product. The calibration achieved produces very close agreement between real data and modelled data for all the key energy using sectors. An iterative approach has been used for model development to both achieve a more competent modelling framework as well as one that can deal with topical technological issues. The eleventh iteration is currently the operating version. Model development is guided by the PLOT approach where policy issues on **Population, Lifestyle, Organisation and Technology** can be assessed either individually (other factors being held constant) or in more complex and holistic combinations to mimic the national scenarios developed in the more qualitative part of the project.

There are four insights, important in a national context, so far developed from a wide range of OzECCO simulation studies. (1) In a post-Kyoto greenhouse context, Australia's physical economy could triple its carbon dioxide from energy use from 340 million tonnes per year currently to around 1000 mt/year by 2050. (2) The run down of Australia's domestic supplies of oil and natural gas around 2020 could, through feedbacks from the balance of payments and international debt areas, could cause a slow down in the ability of the physical economy to grow. Annual rates of growth of 3-4% could decline to 1% and this could signal a large change in political, economic and social systems that rely on growth for their *raison d'être*. (3) Transitions to renewable energy economies have been tested which stabilise and then reduce carbon dioxide emissions while maintaining national infrastructure and indices of gross domestic production. The pressure of investment also stabilises a per capita physical measure of discretionary income out to 2050. (4) The use of embodied energy analysis in a dynamic simulation model gives many counter intuitive results over the long term out to 2050. These results may challenge strongly held paradigms in science and policy circles where in-depth knowledge in focussed sectors is the norm, and where the integration of complex outcomes is usually performed qualitatively by policy experts.

INTRODUCTION

The OzECCO modelling approach described in this paper one component of a broad approach to future environmental quality in Australia within the context of population-development-environment studies. Attempts to develop quantitative studies on such a broad front are difficult for both technical and political reasons. The scientific difficulties of how to integrate, which numeriare to use and how to describe and model complex socio-economic systems are the topic of this workshop. The political difficulties are well described by Choucri (1994) in the following excerpt, 'This paradox is salient in modern societies, in which undeniable benefits are derived from applications of technology, energy in various forms, and other natural resources are increasingly balanced against consequent ecological debits. Each increment of growth and development appears to exact costs in resource depletion, pollution, and other forms of degradation. Conversely, serious efforts undertaken to protect the environment are perceived as threats to agricultural and industrial production, commercial enterprises, employment, and the general welfare as it is conventionally defined.'

This work started initially from an environmental quality perspective with a desire to contribute scientifically to Australia's national population policy. As the definition of the problem became more complex three insights developed. The first was that the problem was complex and intertwined and required a systems approach. The second revealed that precise definition of a particular problem was not particularly useful in policy terms. Instead we were required to develop a range of solutions for a complex set of nested problems. The third is that integrated analysis with a futures focus can be viewed as doubtful and dangerous science especially when if it challenges current policy paradigms.

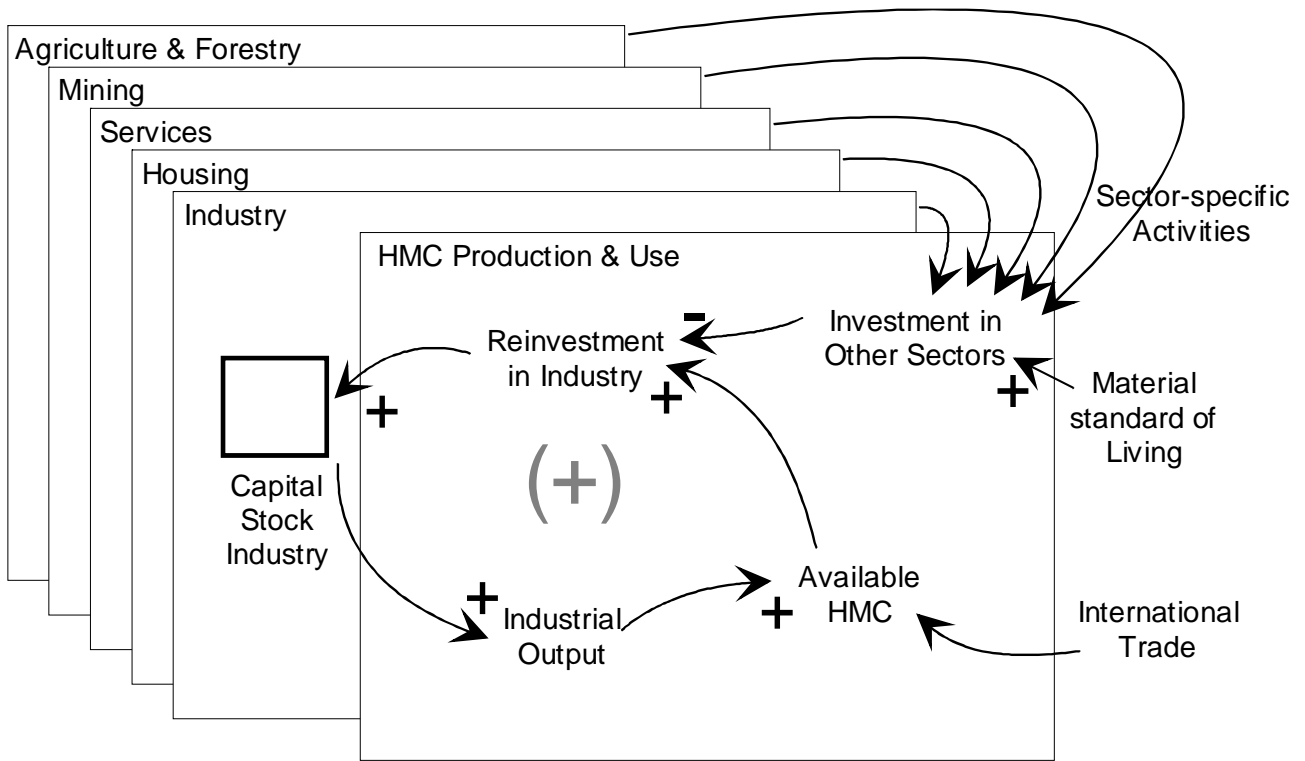
These insights led to a research program with qualitative and quantitative themes. The qualitative theme sets the context for the work by documenting a wide range of social, economic and political drivers and developing future scenarios. These can be seen as political options for Australia out to the year 2050 and beyond. The quantitative theme seeks to test the national scenarios for physical feasibility in a whole system sense. It can also test the effect of individual policies (eg renewable electricity) on the whole system. The search for analytical paradigms and approaches led to the development two 'stocks and flows' approaches. A top down approach using the ECCO paradigm of Slesser (1992, 1997; Crane, 1996; Noorman, 1995) in a system dynamics framework (Pugh Roberts, 1986) was developed by Crane (1995) into the OzECCO model of Australia's physical economy (Foran et al, 1997). A highly disaggregated bottom up approach was implemented in the *Whatif* simulation language (Robbert Associates, 1998) into the Australian Stocks and Flows Framework (Poldy and Foran, 1998). The choice of two analytical frameworks for integrated assessment of a physical economy was needed to cover the range of modelling paradigms noted by Janssen (1998) as well as the aggregated and disaggregated nature of the advice potentially required in national policy discussions. This paper describes the development of the OzECCO embodied energy model and its analytical application to a number of studies of Australia's physical economy in a futures context out to the year 2050.

METHODOLOGY

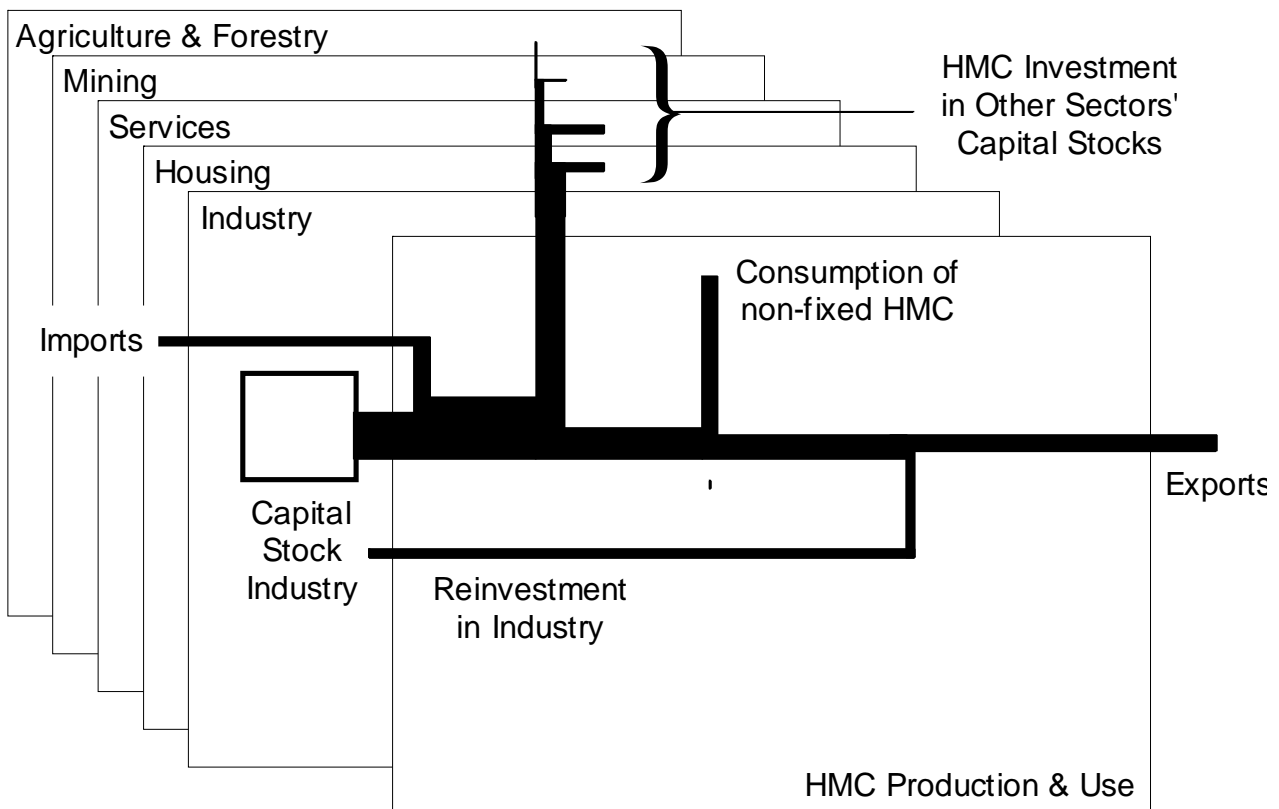
Design and Operation

The OzECCO model is designed to integrate the driving forces of population, lifestyle, organisation and technology and explore their possible impacts on the environment within the context of Australia's physical and economic structure. It is a systems dynamics representation of Australia's national function based on the philosophy of embodied energy analysis. The structure of the national economy and the energy accounts have been integrated so that capital stocks are expressed in terms of petajoules of embodied energy. The activities within the economy have been expressed

as energy flows, again in petajoules. In this way economic activity has been converted to physical activity which is consistent with the first and second law of thermodynamics. All economic transactions are represented by the physical transformations which underpin them. This representation is consistent with the long term physical processes which are central to the functioning of any modern economy.



(a) Primary Influences on human-made capital creation and use



(b) Primary flows of human-made capital

Fig 1 A diagram of the central growth-determining loop in the *OzEcco* model, with the aggregated industrial sector depicted here as the core resource on which growth depends. The processes of fixed- or human made capital (HMC) are depicted as (a) an influence diagram, illustrating the main causative features represented in the model (b) a flow diagram illustrating the sources and sinks of HMC. (Black lines indicate HMC flows into, out of and through the economy, with flow rate being represented by line thickness. The total HMC available is the sum of imports and native production. The ordering of flows from left to right here does not imply any temporal ordering of events).

Conceptually the model has five broad components: natural resource stocks, the transformation sectors, consumption activities, pollution generation and whole system indicators. The core modelling concept is that access to, and transformation of energy (typically stocks of fossil fuel) are the determinants of physical growth in a modern industrial economy. Thus all goods and services are seen in terms of their embodied energy content. Some sectors such as domestic housing act as long term accumulators of fixed capital (expressed in embodied energy terms), whereas personal consumption for example, dissipates embodied energy quickly. The concept is shown in Figure 1a and 1b. The capital stock of industry is a node which creates human capital through its contribution to other sectors such as agriculture (fertiliser, machines), domestic housing (bricks, carpets, stoves) and so on.

The rate at which industry can grow is limited by its contributions to other sectors and the consumption activities of the population at large (both negative feedbacks). The effects of international finance can be both positive and negative. Exports are negative in that they reduce the amount of physical capital (embodied energy) that can be applied nationally. Imports and capital inflows are positive in that they increase a nations ability to perform physical work. All of these factors are linked in a systems dynamics framework and the system is set to grow as fast as is physically feasible (the first and second laws of thermodynamics) in a physical economy which is constrained by the availability of energy, the requirement to maintain national infrastructure and personal consumption activities. Global monetary flows (eg balance of payments, international debt etc.) can override the capacity of the physical economy in the short term.

Validation and Model Testing

The OzECCO model is designed and calibrated on the structure and data for the Australian physical system for the period 1981 to 1993. In assessing whether the model functions in a plausible and valid manner (ie the validation and model testing process) we have used a range of quantitative criteria to judge its validity. This judgement on the relative accuracy and validity must always be linked back to the design objective of the model ie it is structured to test technological and policy options for the physical functioning of the Australian system out to the year 2050.

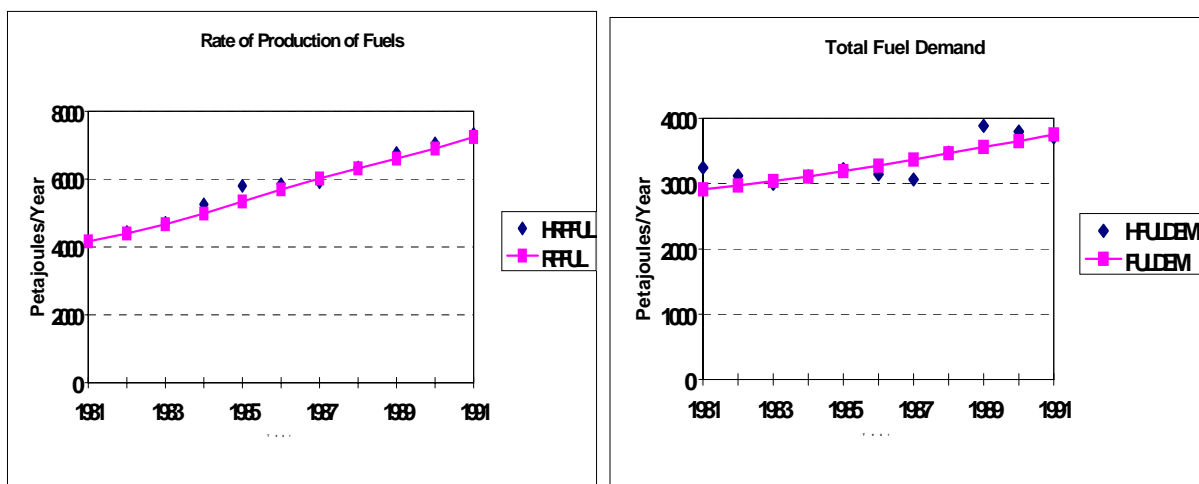


Fig 2. A comparison of historic and modelled data for rate of production of fuels (HRPFUL, RPFUL), total fuel demand (HFULDEM, FULDEM). Points are historic data and lines are modelled data.

Within those criteria, the design and calibration process has produced good results ie the model is judged to have validity. Over the period 1981 to 1993, the modelled data agree well with the historic data in the important energy using sectors (Fig 2). Growth in capital stocks is maintained at close to historic values (Fig 3) and the overall energy use and fuel mix of the economy agrees well with published data. The modelled emissions of carbon dioxide concur with greenhouse gas accounting data (Fig. 4). In addition the function of the model is believable when policy or technological variables are set within reasonable bounds. The model is not “fail safe” in cases where some policy options force large changes in the structure of the economy. While it is always possible to suggest that many sectors of the model can be developed to more detail and disaggregation, the current model version is judged to be a valid one for exploration of Australia’s physical future. This statement rests within the belief that the paradigm of a physical world is important, along with the concept of embodied energy flows and accumulation of embodied energy stocks which underlie the functioning of any modern economy.

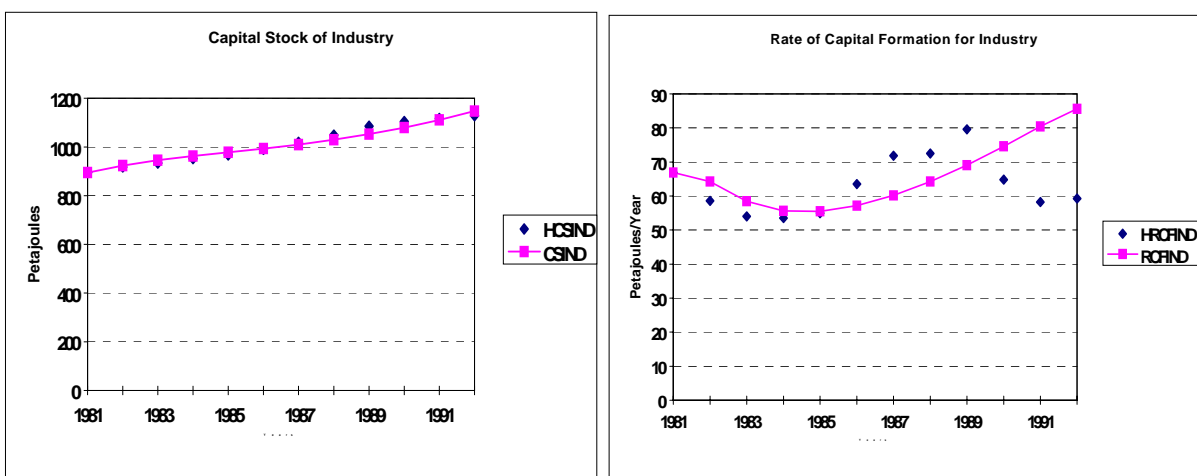


Fig 3. A comparison of historic and modelled data for capital stock of industry (HCSIND, CSIND) and rate of reinvestment in industry (HRCFIND, RCFIND). Points are historic data and lines are modelled data.

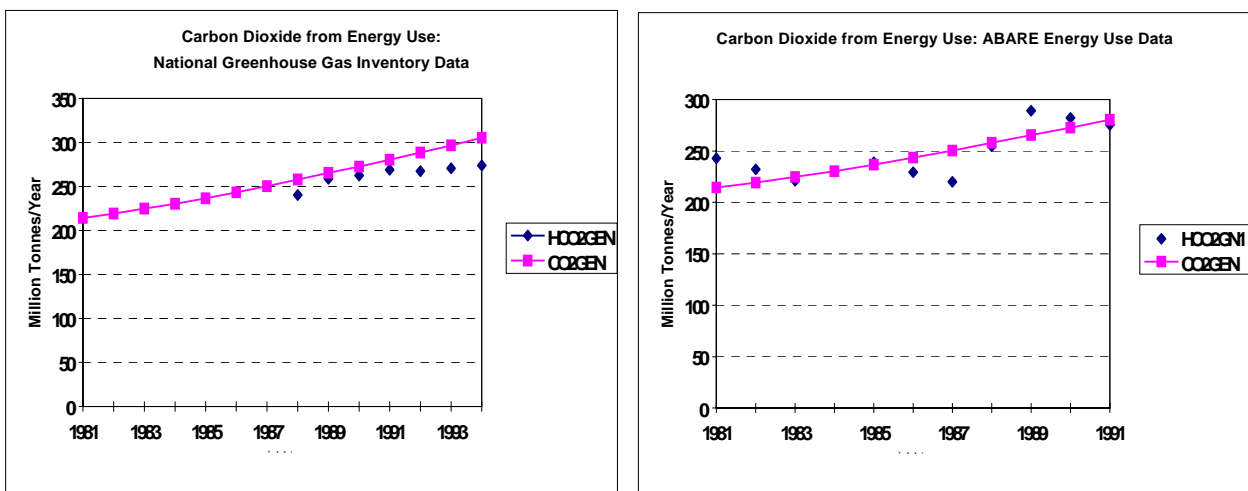


Fig 4. A comparison of historic data from greenhouse gas accounts and energy accounts (HCO2GEN, HCO2GN1) and modelled carbon dioxide (CO2GEN). Points are historic data and lines are modelled data.

SELECTED RESULTS

Three Scenarios

Within the context of global greenhouse gas policies and the agreement at Kyoto by developed economies to limit emissions, OzECCO was used to examine options for altering future production of greenhouse gas from energy use. Three scenarios were developed, the base case or ‘Business As

Usual', a 'High Tech Transition' to renewable electricity and 'Another Australia' which actively reduced consumption in sympathy with the Factor 4 concept (von Weisacker et al, 1997). In order to implement these, a range of control variables were altered over the simulation period from 1995 to 2050. A number of these are shown in Table 1. The 'Business As Usual' scenario simulates the physical economy as it is structured in the calibration period. There are a wide range of modest technological improvements out to the year 2050, but current industries and industrial growth are maintained, personal consumption grows and there is no large change in the nation's international financial arrangements.

Table 1. A selection of policy instruments (= model control variables) used to implement three scenarios for Australia's physical economy to 2050.

Control Variable	Business as Usual or the 'base case'	High-Tech Transition	Another Australia
Oil discovery	All 'potential' oil discovered to 50% probability level	Same as BAU	Same as BAU
Gas Discovery	Same as oil	Same as BAU	Same as BAU
Gas Exports	Grows linearly	Cease by the year 2000	Cease by year 2000
Efficiency of thermal electricity plant	34% over the total fuel cycle out to 2050	Increase to 46% by 2050	Increase to 46% by 2050
Population	Grows to 26 million by 2050	Same as BAU	Same as BAU
Renewable electricity	Hydro and biomass are maintained at present level. Minimal solar and wind	6000 MW of solar and wind renewables installed per year.	Increase from 2000 MW per year in year 2000, to 5000 MW by year 2050
Transport	Personal vehicles saturate at 500 per 1000 of population. Vehicles for industry grow in line with capital stocks	Saturate personal vehicles at 400 per 1000 people, all new vehicles powered by natural gas	Same as BAU except that slow down in the economy slows down personal and industrial vehicle use
Forestry plantations	Expand to 4 million ha by 2050	Expand to 38 million ha by 2050	Expand to 30 million ha by 2050
Repayment of debt	Interest only at 6% per annum	From 2000 repay outstanding balance at 15% per year	Same as BAU
International borrowings	Maintained at \$12bn out to 2050	Same as BAU	Cease all international borrowings in year 2000 and thereafter

By contrast the 'High-Tech Transition' seeks to maintain national productivity in GDP terms, but radically transform Australia's electricity production system, replacing coal fired thermal plant with solar and wind renewables. Trade and international financial arrangements are altered, there is massive reforestation and transport use is capped. The 'Another Australia' scenario seeks to lower the throughput of the physical economy by reducing industrial output, changing trade and finance and taking a moderate investment approach to renewable electricity. It does not seek to maintain national productivity in GDP terms and opts for a slower growing physical economy which in terms is a slower moving target for the infusion of new technologies. The results of the three simulation experiments are shown below.

The ‘business as usual’ scenario

A look ahead to 2050 for Australia under a ‘business as usual’ scenario has a mixture of good and not so good news. The good news centres on an economy that is strong in a physical sense, a strength that is underpinned by abundant coal and less abundant hydrocarbon reserves. Most modern economies rely for their growth on transforming fossil energy into useful goods and services. Thus the Australian economy can continue to grow to 2050 and beyond. The gross domestic product could multiply two and a half times by 2050, and physical output by similar amounts (Figure 5). The less good news also involves energy. Carbon dioxide emissions from energy use may grow from 340 million tonnes currently to over 950 million tonnes per year by 2050, and per capita emissions may rise from 17 to 37 tonnes. A rundown in hydrocarbon stocks around 2030 could increase the import bill for oil. Together, a number of factors such as hydrocarbon imports, interest on international debt and maintenance of national infrastructure could constrain the economic and the physical economy. Per capita physical affluence could start to decline. Anticipations of this nature, more often than not, produce a policy and management response long before they come to pass. These anticipations may therefore be assumed to be fragile from the start, or their final effect to be at least muted. In CO₂ emissions terms they represent a possibility rather than a prediction.

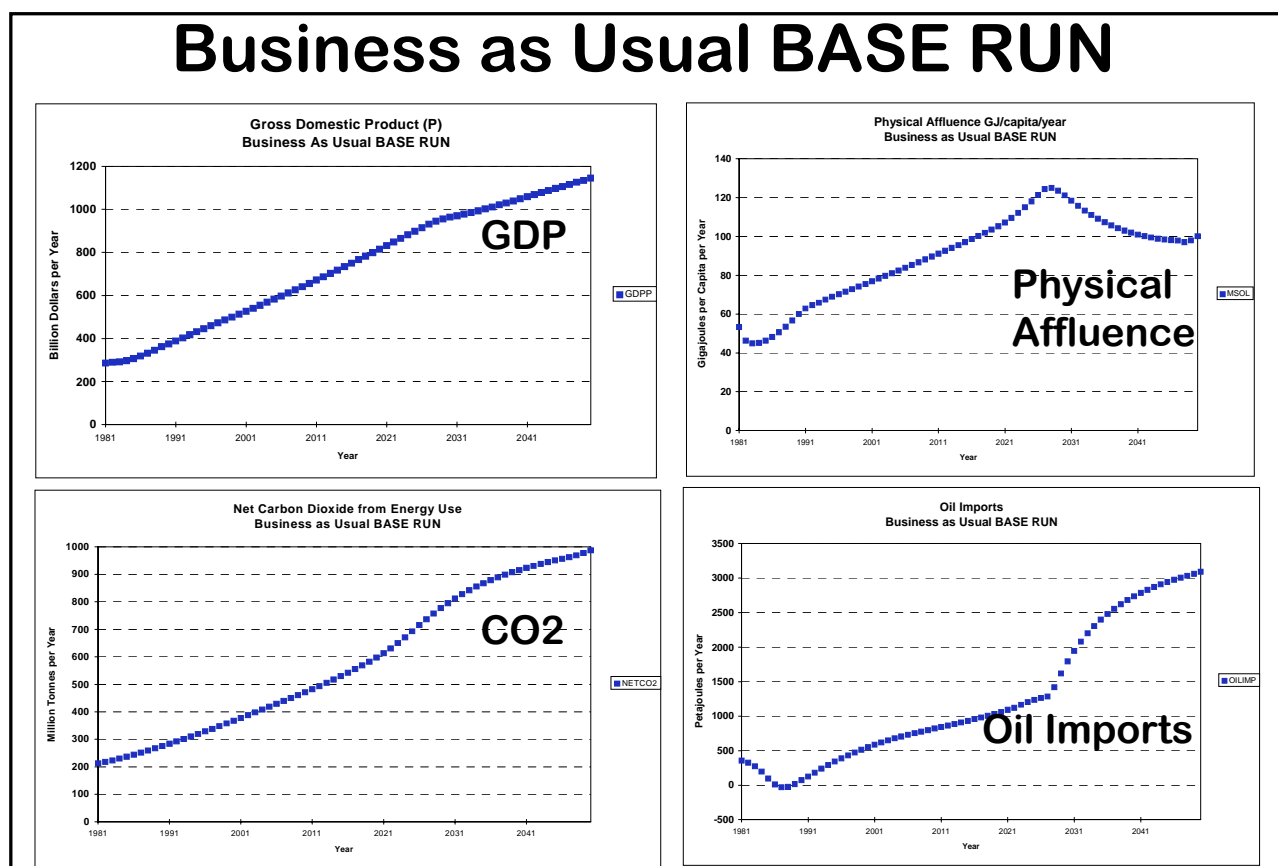


Fig. 5. The report card for the ‘Business As Usual’ scenario to 2050. This portrays GDP in constant 1989/90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in million tonnes per year and oil imports in petajoules per year.

The ‘high-tech transition’ scenario

A transition to a renewable electricity economy was tested and found to be feasible within the assumptions and constraints of the OzECCO embodied energy model. In order to manage this complex transition, it required that at least six sets of policy insights from other detailed simulations be integrated over time (Table 1). Investment into renewable electricity generation took place at 6000 megawatts per year with an assumed cost of \$4 per installed watt in constant 1989/90

Australian dollars. Thermal electricity production decreased its usage of coal to zero by 2020 and used natural gas in coal's place. Over the transition period, thermal efficiency was gradually increased to average 46% by 2050. International borrowings were stopped, and from the year 2000, international debt was repaid at the rate of 15% of debt per year. Vehicle usage was capped and all new cars from the year 2000 were powered by compressed natural gas. Carbon scrubbing technology was applied to all thermal electricity plant from the year 2020. Plantation forestry at the rate of one million hectares per year was established for 40 years to stimulate the forestry industry, repair inland hydrology and sequester carbon.

These policies together allowed the stabilisation of carbon dioxide emissions from energy use at 300 million tonnes per year until 2030, and then a decline to 200 million tonnes per year by 2050 (Fig. 6). By comparison, the 'business as usual' scenario produced over 950 million tonnes per year of carbon dioxide from energy use by 2050. In the mid period of the transition, the pressure of this investment decreased a surrogate measure of GDP by up to 7% (900 vs 963 billion dollars in 2030), but by 2050 the situation had reversed. A measure of per capita physical affluence was stabilised for 40 years during the transition, compared to the business as usual scenario where it continued to rise until 2030 and then declined gradually. While this transition is judged to be physically feasible, it needs to be further tested in other arenas for its feasibility in meeting Australia's medium and long term social, political and economic goals.

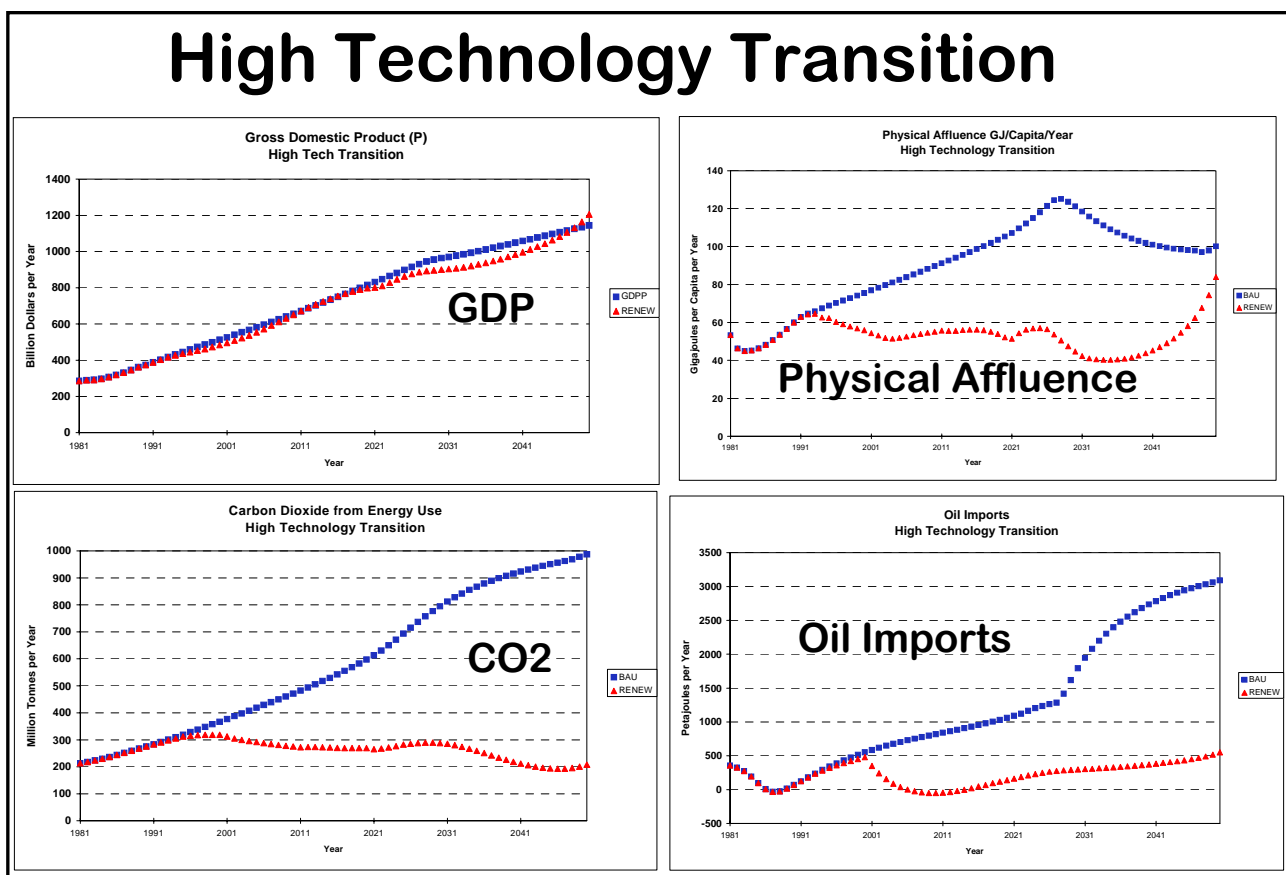


Fig. 6. The report card for the 'High-Tech Transition' compared to the 'Business as Usual' scenario to 2050. This portrays GDP in constant 1989/90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in million tonnes per year and oil imports in petajoules per year. The 'High-Tech Transition' is the lower graph in all cases.

The 'another Australia' scenario

A transition in this scenario aims to substantially decrease the physical transactions underpinning the economy. It is found to be physically feasible within the assumptions of the OzECCO model (Fig 7). This simulation is successful in stabilising carbon dioxide emissions from energy use at

about 300 million tonnes per year for 30 years and then decreasing them to 175 million tonnes per year by 2050. This emission loading is 80% lower than those for the ‘business as usual’ scenario at the end of the simulation. Electricity demand and supply is stabilised at around 300,000 gigawatt hours per year and by 2050 all of this comes from renewable sources. The use of natural gas is stabilised at around 500 petajoules per year, and with a policy of retaining gas stocks for use in Australia, this provides natural gas supplies sufficient to last to the year 2100. A lighter economy of physical transactions gives embodied energy outputs of both the industrial and services sectors that are approximately equal by 2050.

There are some negative aspects to this scenario. The surrogate measure of gross domestic product is 34% lower than in ‘business as usual’ in constant dollar terms by 2050. By 2050 the per capita physical affluence, a measure of the energy embodied in the goods and services purchased with discretionary income, is at 40 gigajoules per capita per year in this scenario compared to 100 gigajoules for ‘business as usual’. With 100 constant dollars equating to one gigajoule of embodied energy within the modelling calibration, this is the difference between 4,000 and 10,000 constant dollars worth of personal consumption per year. These results portray a very uni-dimensional view of the system changes needed to implement a radical approach to sustainable energy usage. Nevertheless there is a considerable intellectual development already published by other authors to suggest that similar views to this, of a vastly different Australia in both physical and social terms, are worth further investigation.

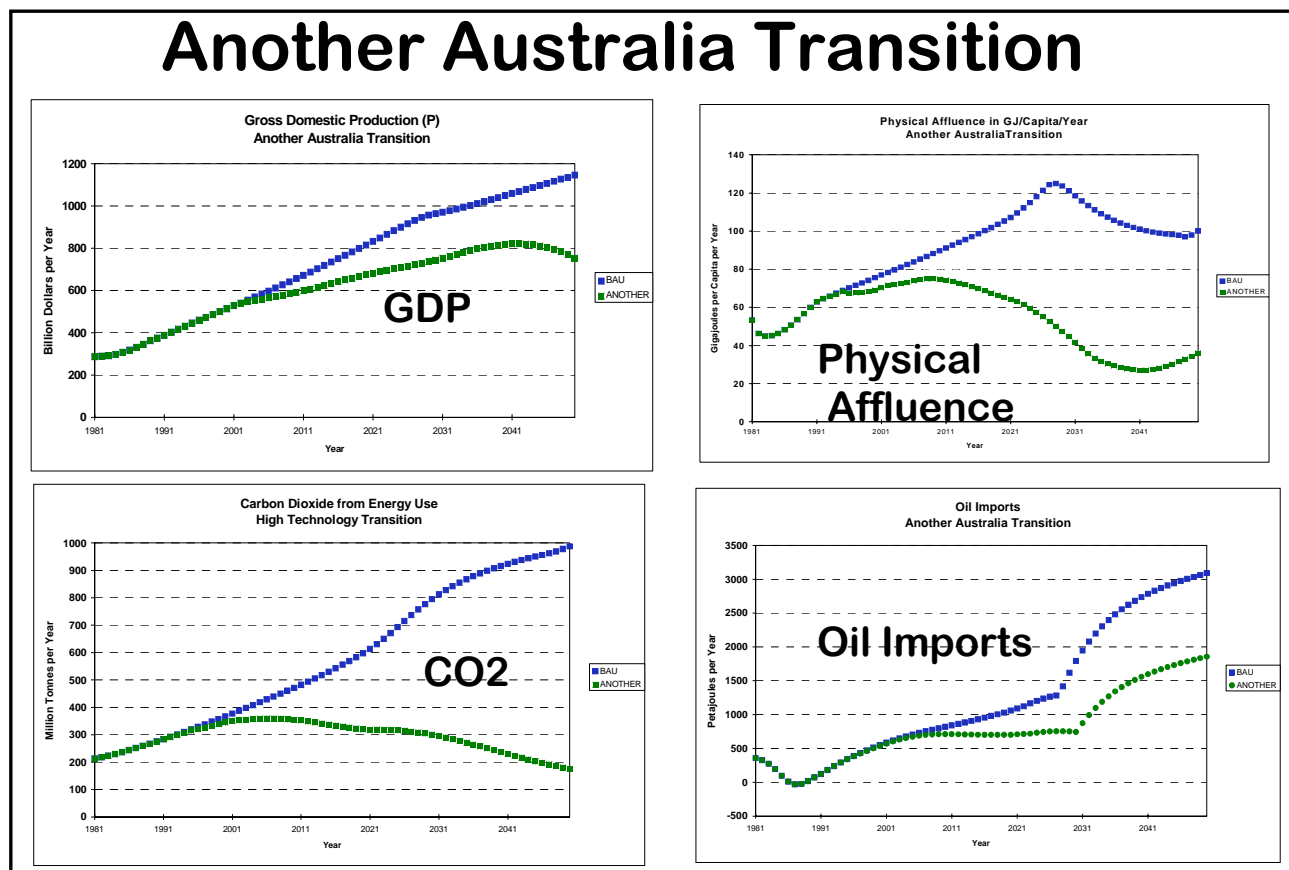


Fig. 7. The report card for the ‘Another Australia’ scenario compared to the ‘Business as Usual’ scenario to 2050. This portrays GDP in constant 1989/90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in million tonnes per year and oil imports in petajoules per year. The ‘Another Australia’ scenario is the lower graph in all cases.

PETROLEUM RESOURCES

Previous simulations using the ‘business as usual’ scenario highlighted a potential slowdown in the physical economy after 2020 caused by a number of factors, but particularly by a rundown in the stocks of domestic oil and gas (Foran et al., 1997). While both industry and the community acknowledges that oil stocks have peaked, there is little published long term policy evaluation of the flowon effects. There is an expectation that rising oil prices will spur technological innovation and make non traditional hydrocarbon sources such oil shale or coal bed methane economically competitive. Simulation results indicating that gas stocks might run down earlier than expected have been greeted with disbelief which may represent a static view by policy evaluation.

In an attempt to place uncertainty bounds around these possible events, this simulation examines different levels of exploration success from the high probability level (95% sure but lower stocks), to average probability (50% sure) and low probability (5% sure but higher stocks) (Figures 8 and 9). On the demand side, oil requirements may range from 5,000 to 5,800 petajoules per year for the high (95%) and low probability (5%) finds at 2050, while domestic gas demand may stabilise around 3000 PJ/year in the same year. Gas exports could reach around 2000 PJ/year before declining rapidly in the face of domestic demand and low stock levels. The length of cover for domestic gas stocks may be interpreted as low as 30 years because both domestic and export demand will expand in a growing economy. Under the 5% (higher stocks) probability, indicators of national activity such as industrial productivity, gross domestic product and carbon dioxide emissions may be 8 to 10% higher than the 50% probability. Under the 95% (lower stocks) probability, the measures could be 4-6% lower.

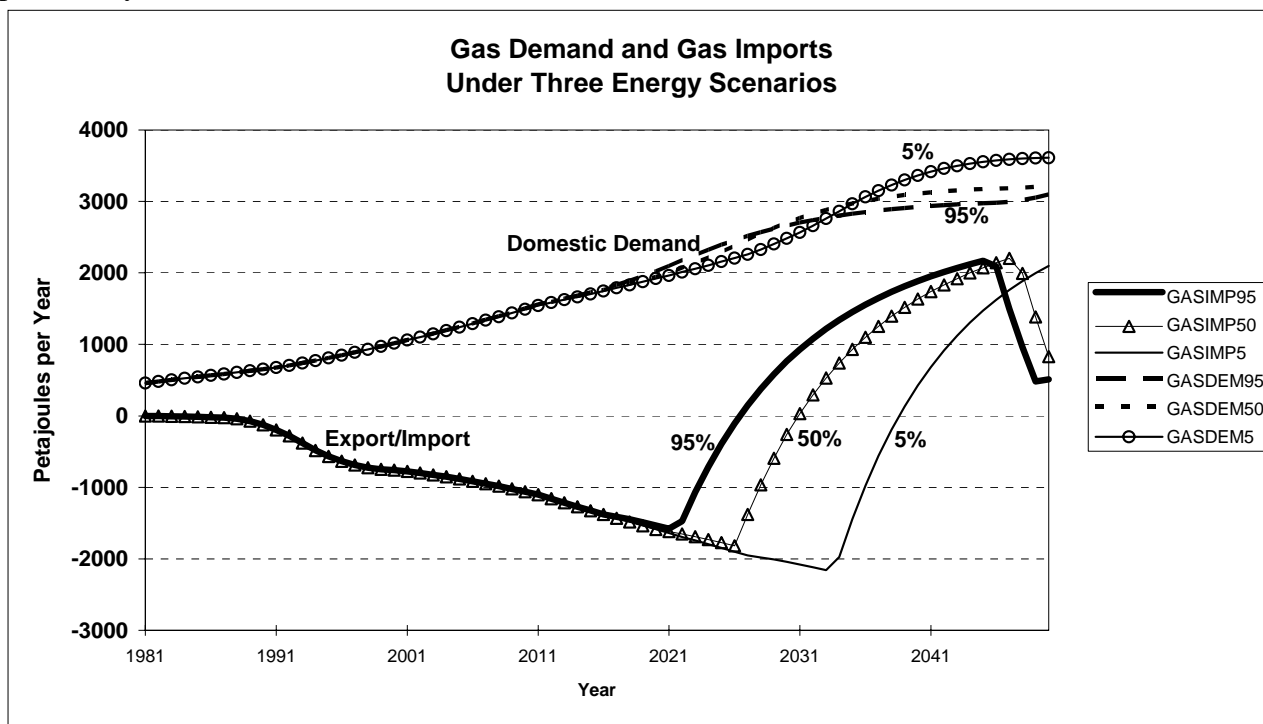


Fig. 8 Simulated domestic and export demand for natural gas and liquid petroleum gas out to 2050 under three scenarios of oil and gas discovery rates. Units are petajoules per year. Exports are represented as negative values and imports as positive values.

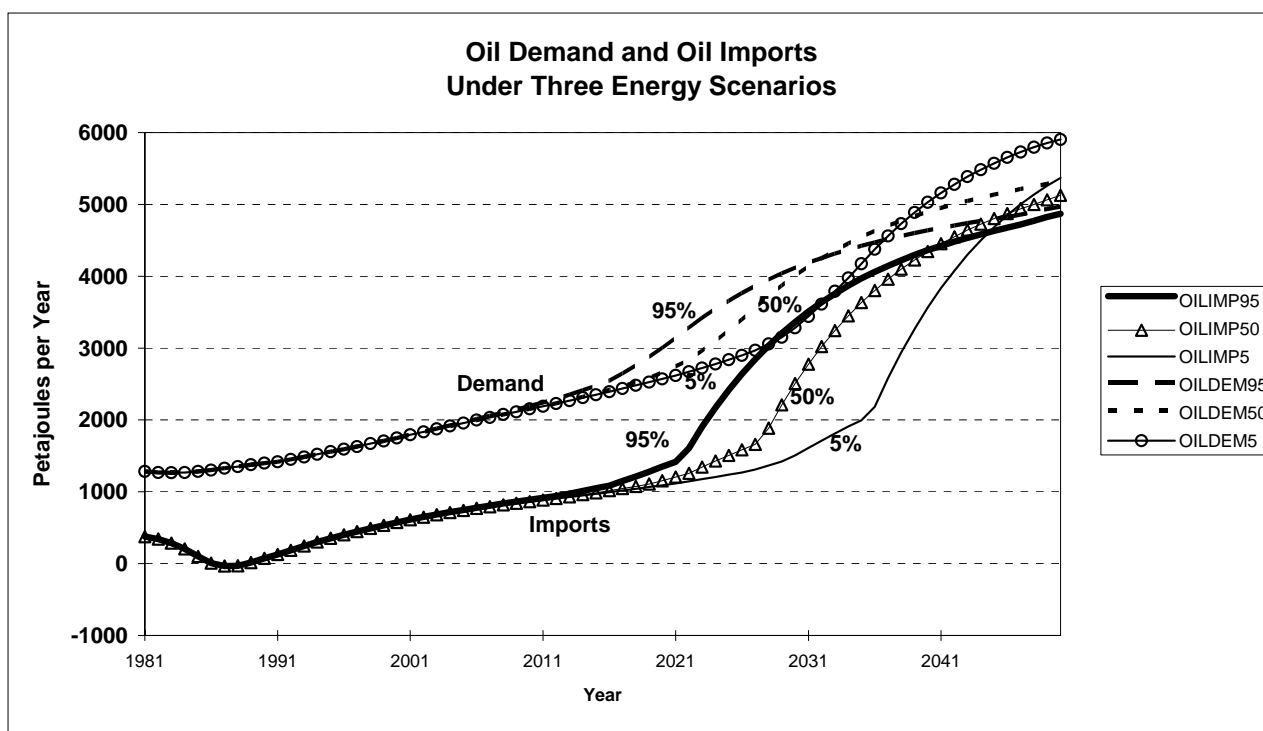


Fig. 9. Simulated domestic demand and requirements for imports for oil and condensate out to 2050 under three scenarios of oil and gas discovery rates. Units are petajoules per year.

There are some interesting dynamics portrayed by these OzECCO simulations as petroleum stocks decline. As oil and gas stocks decline, capital is released from the oil and gas exploration and production sector. This may cause an increase in growth of the physical economy, even as oil and gas imports are increasing. After ten years, the pressure of petroleum imports cause a number of constraints on what is effectively a ‘business as usual’ physical economy. These constraints might suggest a physical economy that cannot grow as developed economies have been used to doing under readily available and relatively cheap oil supplies. Rather than been seen as a prediction, the physical insights offered by these simulations of future petroleum stocks should be interpreted as some early warning signs for policy deliberations. Without complementary analyses from longer term economic and social studies, this restricted physical view of the future may miss a number of key innovations that lie outside the physical economy. Technological and marketplace innovations are obvious examples of these. It is however difficult to ignore some of the physical realities imposed by the rundown in domestic oil and natural gas stocks, especially in a country as large as Australia. If the domestic and export transportation structure is to remain functional into the future, then policy responses may have to accommodate the possibility of less oil, higher prices and a substantial change to the physical nature of transport infrastructure.

DISCUSSION

The OzEcco Model

Acceptance

For a number of reasons, acceptance of the OzECCO approach by both the science and the policy community has not been assured. The use of a numeriare such as embodied energy is difficult for most scientists to accept and perhaps comes from the ‘summing apples and oranges’ problem. However recent news reveals that another energy research group in our organisation will now collaborate with us in developing energy supply and demand scenarios for a 10 year Kyoto protocol period and a 100 year period out to 2100. This follows a difficult year in which the environmental,

climate change and industrial groups in a large government research organisation have found it difficult to come to some agreement, or even speak the same language around a topic entitled 'sustainable energy policy'. National policy fora are likewise becoming more sensitised to the concept of a physical economy and the different analytical paradigms which are becoming available. While OzECCO was not able to contribute to national policy discussions in the pre-Kyoto period, some of the policy advice resulting from econometric approaches to energy integration were found wanting. The post-Kyoto period might provide an opportunity for physical modelling to complement these econometric approaches which will remain the dominant method for national integration and policy advice in most developed countries.

Further development

A recent review of the research project of which the OzECCO model is part, suggested that the model development be stabilised and effort be spent on developing client led analyses. As part of the completion of this development and testing phase, we have decided to introduce nuclear power plants, nuclear fuel reprocessing and the production of liquid transportation fuels from biomass. Given recent developments in our research organisation, further work might stress a more rigorous description of the fossil fuel cycle and prospective new technologies therein. There is always a temptation to include more disaggregation of population cohorts, vehicle fleets, building types and the industrial sector. However as noted in the introduction, the OzECCO model has been deliberately developed with a more aggregated view to examine behaviour of the whole physical economy in a more macro manner. The bottom-up Australian Stocks and Flows Framework (Poldy and Foran, 1998) is well disaggregated and is able to provide those detailed analytical insights.

There are a number of improvements which could be made to the simulation environment in the OzECCO model. The design and testing of any individual technology or a fully integrated scenario as discussed above, inevitably involves many sequences of simulation runs until physically feasible solutions are found which minimise some system indicators (eg carbon dioxide emissions) and maintain others (eg per capita physical affluence). At one level this involves considerable learning on the part of the operator particularly around the dynamics of a complex physical economy. However there may also be need for automated searching and simulation which may reveal some policy settings and sequences previously unrecognized because they lie outside conventional knowledge. In addition there is scope to infuse the concepts of adaptation, learning and agent based modelling (Janssen, 1998; Epstein and Axtell, 1996) into the simulation experiments.

WHOLE SYSTEM PROPERTIES

Initial use of the OzECCO model (Foran et al., 1997) involved eight simulation experiments, four of which have been reported briefly in this paper. While the individual experiments are interesting there are also diffuse properties of the system, perhaps hypotheses of system behaviour, which are becoming evident. When these are tested, distilled and refined then they may form the rules of thumb which energy analysis might take back to the policy table. Some insights are presented below:

- An economy may be on a trajectory that could lead to some future problem arising (eg fossil fuel use leads to depletion of stocks and increasing CO₂ emissions). Where this is the case, the rate at which it consumes resources is not particularly important since the problem will be encountered sooner or later in a 50 year timeframe. The key question is the timeliness of the response strategy, e.g. bridging strategies to other trajectories developed well in advance; trust in technological progress or preparing to manage the crisis when it happens.
- The stabilisation (or reduction) of physical affluence on a per capita basis, may be a central part of the complex transitions so far simulated for the physical economy. The implications of this in a growth based economy could be challenging to conventional economic thinking and the current organisations of markets.

- Inefficiency in energy use can be viewed as not a complete 'bad' as it retards the capacity of the system to accelerate growth in physical transactions. Large and rapid increases in energy efficiency release resources to the consumption sector which in turn re-stimulate all of the primary resource sectors. Resource use and emissions may then increase over the long term in 'free' market situations. Simply put 'increased energy efficiency stimulates physical growth and physical throughput'.

ENERGY ANALYSIS: THE WAY AHEAD

The ECCO approach to energy modelling has proven resilient through time and is beginning to gain acceptance in some policy circles. In this application it uses national data bases and those central to economic theory and policy. The concept of converting monetary stocks and flows to embodied energy stocks and flows is a difficult one to conceptualise and this is one of the challenges of the discipline. Much of the analysis underlying the global greenhouse concerns is couched in the same language and analytical paradigms that underlie the ECCO approach. This is cause for optimism.

The concept of eMergy has intuitive appeal and the bridge between embodied energy and eMergy must be built. Long term sustainability issues are better based in ecosystem theory and functional reality with the eMergy concept. In policy terms however eMergy may face tougher barriers of acceptability than does embodied energy which is well accepted in the 'life cycle analysis' and 'industrial ecology' areas. However, since eMergy collapses geological and human timescales into a single accounting framework and bypasses the intricacies of a dynamic analysis, it may be well-suited to the policy table in providing an essentially static view for policy makers.

Finally to complex adaptive systems. The paper by Giampietro and Mayumi (this conference) is timely in the challenge it poses to the energy analysis discipline. The OzECCO model is a complex systems model and it portrays a number of behavioural characteristics which are sometimes difficult to explain and more difficult to control. The chief of these is the 'intersectoral rebound effect' or Jevons' paradox. However the model cannot yet be called a 'complex adaptive systems' model as there is no facility for learning and adaptation similar to those used by Janssen (1998) in his 'battles of the perspectives'. Being able to explain and defend the results of simulation analyses to a policy fora is the first step in changing policy. The formulation and development of complex adaptive models of national energy systems is a large enough challenge. A bigger challenge will be to find ways in which these can be explained and understood by harried and focused policy experts.

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