Modelling longer term cross sectoral requirements of the Victorian electricity generation system in a Physical Stocks and Flows Framework.

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EXTENDED ABSTRACT

The increasing emphasis on sustainability issues in recent years has created a need for tools able to quantify the broader cross sectoral materials and energy flows associated with different industries. This requirement comes in addition to the traditional need to provide useable forecasts of product demand and direct input requirements.

Here, the example of the Victorian electricity generating sector is used to show how physical Stocks and Flows Frameworks (SFF), implemented on the whatIf?® software platform, can be used to explore the broader physical implications of following different technological paths over the long term. The technological scenarios examined were chosen to yield different CO2 emission profiles for a given primary demand for electricity. Sub-scenarios dealing with different growth rates in primary demand for basic materials and energy per capita are also simulated.

Comparisons between scenarios envisaging a major shift in generation technology (where 80% of electricity demand is met from a mix of combined cycle gas turbines, wind turbines, and biomass fired steam turbines), and scenarios where the current technological mix is continued into the future yield some interesting results when cross sectoral effects are taken into account. These include:

1. The degree to which a move to biomass could change electricity generation from modest water and minor land area consumer into a major indirect consumer of both.
2. The major spatial reconfiguration of the distribution grid required to include major contributions from biomass and wind turbines
3. The failure of any of the scenarios examined to maintain anything like 60% reductions in CO2 emissions, compared to year 2001 levels, in the absence of demand management.

The way in which the Victorian electricity generation sector is modelled in the Victorian Regional Stocks and Flows Framework (VRSFF), as part of an integrated system dealing with the production of Basic Materials and Energy (BME), is outlined in the latter part of the paper.

At the core of the BME calculations is an innovative physical Input/Output operation that allows for technological advances, substitution of production processes, and capital development. The treatment of the Victorian electricity generation sector is followed through as a detailed example. The roles of physical Input / Output tables, plant life tables, capacity factors and different plant technology shares are discussed.

1. INTRODUCTION

Constraints on materials and energy inputs to production processes, and the disposal of waste products from those processes, have begun to feature more prominently the planning developments in basic industries. The sheer size of the physical stocks and flows which underlie modern economies is such that individual sectors of the economy are coming into competition with each other for some basic resources, where previously constraints on these resources were not important.

The electricity generation sector will be strongly affected by this trend, due to the political sensitivity of some of its key inputs and outputs, (notably water and CO2), and the broad land use and infrastructure implications of some technological paths under consideration to lower the sector's CO2 emissions.

Physical Stocks and Flows Frameworks (SFFs), implemented on the whatIf?® software platform, can be used as effective tools to identify where competition for resources may occur under different development scenarios.

An outline of the underlying design of SFFs is given in section 2. The utility of SFFs in identifying any physical inconsistencies or “tensions” associated with different development scenarios across interlinked systems is demonstrated in section 3, by following through the cross sectoral implications of alternative scenarios for meeting future electricity demand.

A brief description of how basic industries are currently modelled in the VRSFF is provided in Section 4, with detail concentrating on the role of Input/Output tables, plant life tables, capacity factors, and technology shares as applied to the electricity generation sector.

2. BRIEF OUTLINE OF A PHYSICAL STOCKS AND FLOWS FRAMEWORK

An SFF consists of a simulation framework, a calibration framework, and a collection of data sets. It is designed to trace the physical aspects (tonnes, litres, joules, hectares, etc.) of a system, over an observed history, and for different simulated future scenarios over the long-term. The scope of the physical system encompassed by a specific framework can vary greatly, with existing examples ranging from nutrient input/outputs at an individual farm paddock example level, up to entire physical economies, such as the Australian Stocks and Flows Framework (ASFF) , described in (Poldy, Foran et al. 2000)

The simulation framework consists of a set of modules (calculators), each encapsulating one or more important physical processes specific to different sectors of the economy. Connections and relationships between individual calculators are established as appropriate to reflect real world linkages. For example, an increase in population in a demographics module will, ceteris paribus, flow through into an increased requirement for dwellings, in turn generating an increased operational energy requirement for dwellings. A detailed description of the sectoral linkages and information flow in a SFF with broad sectoral coverage is provided in (Poldy, Foran et al. 2000).

The calculations performed within calculators are generally limited to reflecting the most straight forward physical relationships. The simulation framework is used to generate the data characterising future scenarios.

The calibration framework is where historical data is integrated. It has a similar high level structure to the simulation framework, but its calculators may be more complex, as they are involved in functions such as importing raw data, harmonising conflicting data sets, filling gaps in time series data, etc. A practice of maintaining the most direct link feasible to original data sets has been adopted. Where data must be cleaned or transformed, those transformations are performed openly, on the original data, *within* the framework. This ensures that those who use the framework can always establish the provenance of data, what transformations it undergoes before being used in the framework, and the rationale behind the transformations.

SFFs are structured so that the flow of information is one directional, and so generally don’t take into account any feedback loops automatically. That function is instead performed explicitly by the person creating a scenario. Where physical feedback loops are sufficiently straight forward to justify automation, tools can be created to do so, however requiring the creators of a scenario to explicitly set control variables encourages greater familiarity with any assumptions underlying that input. Behavioural or policy feedbacks in particular are never automated. This is a key purpose and strength of employing SFFs. An early and clear exposition of the rationale behind using SFFs constructed in this role is contained in (Gault 1987).

3. AN EXAMPLE OF THE CONCEPTION, DEVELOPMENT, AND USE OF A SFF

The particular SFF explored in this paper is the Victorian Regional Stocks and Flows Framework (VRSFF). It was originally conceived to help land use planners follow through the less obvious cross sectoral effects their development decisions may have. Whilst the nature of the individual cross sectoral linkages is generally quite simple, there may be many of them. The relatively poor ability of humans to simultaneously track more than a few linkages in causal chains, and the negative implications of that for long term planning (Lempert 2003), indicated that a SFF could serve a useful role as a planning support tool.

VRSFF’s subsequent development illustrates the flexibility of SFFs. The original focus on land use planning and demography regimes for Melbourne was extended spatially, to cover the whole of Victoria, and sectorally to include electricity generation and a general treatment of basic industries. A separate but linked framework, VRSFF Water, was developed in parallel to provide detailed accounting for water requirement and supply in Victoria under different development scenarios.

Integrating a detailed treatment of the Victorian electricity generation sector became a priority due to the growing political concerns around GHG emissions, and a perception that power generation was an particularly water intensive activity. The expanded VRSFF was then used to implement a series of scenarios based on alternative development patterns for Victoria, in collaboration with the Victorian Department of Sustainability and Environment (DSE), out to the year 2100.

The focus in this paper is on modelling material and energy flows associated with electricity generation, so the scenarios explored here are all based on the same underlying population growth, settlement pattern, and household formation rates. Six scenarios were formed from two different consumption scenarios underlying three different electricity generation technology scenarios. The assumptions and rationale underlying each is given in **Table 1**.

Consumption growth trend scenarios
high growth - continuation of a linear trend in growing intensity of materials and energy used per capita, derived from electricity use data for 1974 – 2004.
low growth - compounding rate of growth in materials and energy used per capita. A rate of 0.7% used as this leads to an outcome compatible with both the Victorian DSE's "Victoria in Future" population projections and ABARE's energy use projections for Victoria in 2030.
Generation technology scenarios
current mix - Continuation of the current mix of generation technologies into the future.
moderate shift - drying of brown coal, (25% fuel efficiency improvement), 15% combined cycle gas turbines, 15% renewables (wind turbines and biomass fired steam turbines). Reflects a combination of current policy and relatively easily implemented GHG reduction strategies.
aggressive shift - Drying of brown coal, 40% combined cycle gas turbines, and 40% renewables (wind turbines and biomass fired steam turbines). Major structural change aimed at large GHG reduction.

Table 1 Consumption growth and electricity generation technology scenarios.

The population scenario used was based on setting fertility, death, and immigration rates to yield total population matching the projections for Victoria in 2030 in (DSE 2004), and maintaining those settings for the remainder of the simulation, out to 2100. The population curve produced passes through 6.2, 6.7, and 7.3 million persons in 2030, 2050, and 2100 respectively

The electricity production required in each scenario is given in **Figure 1**, with the CO2 emissions profiles corresponding to each in **Figure 2**.

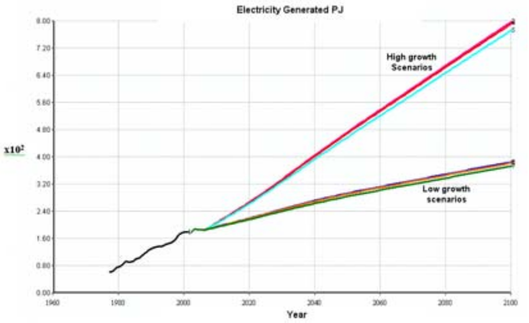


Figure 1. Comparison of high and low growth electricity production scenarios.

In **Figure 1**, the slight divergence in curves between scenarios with identical underlying assumptions on population growth and material and energy intensity per capita arise from the different electricity requirements involved in building, operating, and maintaining different types of generation plant, detailed further in section 4.

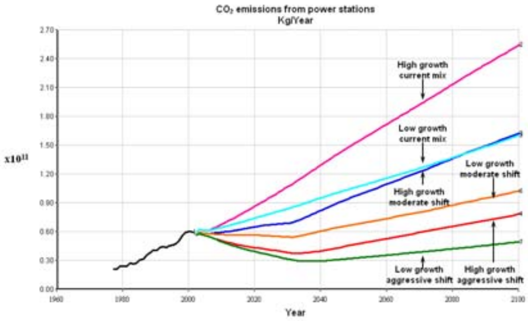


Figure 2. CO2 emissions associated with electricity generation for the six different scenarios

In **Figure 2**, the pronounced break upwards in slope in the four scenarios reflecting technological mode shift reflects the end of the gains made by the progressive introduction of brown coal drying over a 25 year period. The effect is further enhanced by the decreasing rate of technological mode shift as the share of brown coal power stations approaches the long term targets (70% in the moderate shift scenarios, and 20% in the aggressive shift scenarios).

Interestingly, none of the scenarios reach 60% reductions over year 2000 levels, and all except one exceed year 2000 levels again before the end of the simulation. The trajectories of all indicate that the technological paths tested would not yield cuts in GHG emissions over the longer term in the absence of simultaneous demand management.

There are also large differences between the different technological paths in terms of direct water use. The water used in the *high growth – current mix* scenario of 376,409ML is over four times that used in the *low growth – aggressive shift* scenario. .

This is a very large relative difference in direct water used by electricity generators between the different technological options. However, seen in the context of overall water use in Victoria, the difference between the highest and lowest scenarios by the end of the simulation amounts to less than 9% of the 3,281,389ML consumed by Victorian agriculture in 2004/5 (ABS 2006).

The resolution of cross sectoral tensions between requirements and supply, integral to the SFF approach, leads us to then consider where other sectors may be impacted by technological shift in the electricity sector. The *low growth – aggressive shift* scenario has the lowest direct water usage of all scenarios, however in meeting 20% of overall electricity demand from biomass (wood) fired generation, it generates a demand for raw logs and bolts over 20MT p.a. greater than that in the *high growth – current mix* scenario.

Assuming a density for green wood of around 1.1 tonnes/m3, this is more than two thirds of total current production from all Australian forests of around 25.7 Million m^3 p.a. (DAFF 2007), implying a major expansion in forestry activity in Victoria. Using the Australian plantations average of 9.52 m3 of wood/ha/pa, satisfying the additional demand for wood would require an additional 1.9 million hectares of plantations. The new plantations must be sited at the expense of some existing land use in VRSFF, and the linked VRSFF Water framework have its runoff coefficients for the affected land adjusted. To do this we choose to locate the new plantations on current grasslands, and apply the mean annual water yield curves derived for the Goulburn-Broken catchments in (Zhang , Dowling et al. 2003). They indicate that replacing grassland with forests in areas of receiving of 500-1500mm p.a. rainfall decrease catchment yields by 60-45%. If these factors are more broadly applicable to Victoria, growing the indicated biomass could decrease catchment yields overall by 1,000,000 – 6,000,000 ML. This greatly outweighs the initial savings in direct water used of around 300,000ML for the *low growth – aggressive shift* scenario.

The water required for biomass production then needs to be explicitly sourced from somewhere within the VRSFF Water framework. Where there is insufficient water available with the current settings, it needs to be taken from a competing land use, or supply increased by some other means e.g. desalination.

The large land requirement for biomass production, and the desirability of favourable wind conditions for wind turbines, would also have a strong effect on the distribution of electricity generation Vs. electricity demand over time in the *low growth – aggressive shift* scenario. **Figure 3** shows the change in the distribution of electricity generated surplus to residential demand, by LGA, from 2007 to 2100.

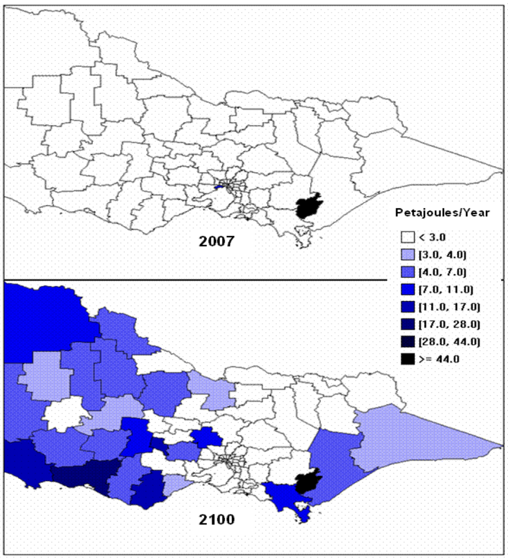


Figure 3. Change in distribution of electricity surplus between LGAs for the low growth – aggressive shift scenario. Darker = higher surplus.

Assumptions on the siting of new generating capacity are that biomass generation is distributed proportional to current agricultural land, wind turbines proportional to existing and planned capacity in 2006, combined cycle gas turbines proportional to population (this latter for convenience, it would probably be different in practice), and brown coal fired plants according their distribution in 2006. Shifts of the size indicated are likely to have major implications for the end form of the distribution grid. Similar maps for the *high growth – current mix* scenario predictably show very little change in the distribution over time, only varying in magnitude.

A well thought out and structured SFF will lead an analyst through important linkages between different sectors in this manner. It invites them to explore various ways of resolving any tensions which occur, and in turn follow the consequences of those adjustments across sectors, and indicate where further inter-sectoral competition for resources occur.

4. MODELLING BASIC INDUSTRIES IN VRSFF.

The preceding two sections gave a higher level view some interaction between different modules within frameworks. Here, a more detailed description of key variables and operations of the Material and Energy Transformations (matEnrTran) module of VRSFF is given. Particular attention is given a core procedure within matEnrTran (procedure 5), and how key variables where configured to reflect the Victorian Electricity generation sector.

The main purpose of the matEnrTran module is to calculate the physical inputs and outputs associated with a given requirement for production from domestic basic industries. Basic industries are defined here as those which produce the secondary materials and energy (Basic Materials and Energy, or BME), required by the rest of the economy, from primary materials

The main set of information inputs to matEnrTran come from sector specific calculators upstream, which calculate the BME requirements necessary to service domestic operations and production at the levels indicated in a scenario. A total of 20 different calculators specific to different economic sectors feed data for 28 different demand flows into the matEnrTran calculator at present. There are 15 different energy demand flows e.g. operational energy for buildings, energy for goods production, etc. which are aggregated and mapped onto nine different “secondary energy types”, which can be thought of as final use fuel forms plus electricity.

There is a similar consolidation of 13 sectoral requirement flows for materials, which are mapped onto 39 material types. These consolidated domestic demands for materials and energy are key inputs to the calculation of domestic production of BME.

As some production from domestic BME industries may be exported rather than used locally, and some domestic demand for BME may be met from imports rather than domestic production, imports and exports of these materials are also inputs to the calculation.

A further modifier of the requirement for production of new basic materials is the flow of materials derived from domestic recycling activity.

The total primary demand for BME is thus:
BME required for domestic production and operations + exports of BME – imports of BME – Basic Materials from Recycling.

The consolidation of the different supply and demand flows into one primary requirement for (new) BME is performed in the first four procedures of matEnrTran.

This primary requirement for BME is not the final demand however. There is an additional demand for BME generated by building, maintaining, and operating the necessary plant capacity. This calculation is performed in procedure 5. This is the only part of the current VRSFF framework which allows automatic feedback, the scope of which is limited to the BME industries. Procedure 5 implements a dynamic physical input-output model of material and energy flows to simulate the operation of basic industries. At the core of this process is a series of Input/Output tables. A thorough description of the methodology behind a structurally identical matEnrTran module, used in a SFF of the whole of the Australian economy, is provided in (Lennox, Turner et al. 2005).

A table of the energy related inputs and outputs for procedure 5 is given in **Table 2**. There are generally materials related counterparts for each, and some other reporting variables which give a total of 19 inputs and 13 outputs to procedure 5. They have been omitted here as the focus here is on the variables and processes of most direct relevance to the electricity sector..

4.1 Description of energy related inputs used in procedure 5 of matEnrTran.

Domestic energy production is the primary demand for energy determined as outlined previously. *Base energy plant capacity* is the existing stock of energy plant in the year immediately preceding the first year of simulation (base year).

Plant life table parameters reflect the expected service life of all BME plant. This variable sets two parameters for each year of the simulation, for each type of BME plant considered. These parameters, Inflection point (I) and Width (W), give shape to a series of S-curves, which determine the rate at which capacity commissioned in different years is decommissioned.

Energy Related Inputs
Domestic energy produced

Base energy plant capacity
Plant life table parameters
Capacity factor
New energy plant shares
Energy capacity use priority
Energy throughput ratio
Plant material composition
Secondary energy use per unit energy plant used
Material use per unit energy plant used
Energy import share
Energy Related Outputs
Energy plant capacity
Energy plant discards
Energy plant capacity used
Intermediate energy domestic production
Intermediate energy production imported

Table 2. Energy related inputs and outputs to matEnrTran procedure 5.

Table XX Energy related inputs and outputs to matEnrTran procedure 5.

Capacity factor is the fraction of installed nominal capacity which is used in any year.

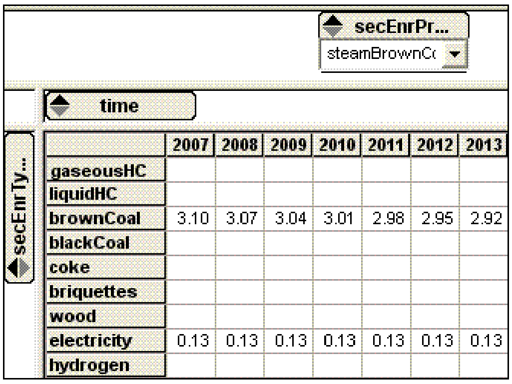
Where there is insufficient extant capacity to meet energy demand in any year, *new energy plant share* determines the share of the excess demand to be met by new plant of specific technologies.

Energy capacity use priority determines the order in which plants of different technologies are brought online where there is excess capacity.

Energy throughput ratio determines the quantity of energy output which can be generated each year per tonne of plant capacity. It is used in conjunction with the *plant material composition* variable to determine the materials required to build and maintain in commission a certain level of energy plant capacity.

Energy import share is used both further back in matEnrTran to calculate primary demand, and within procedure 5 to modify the ultimate requirement for domestic production of energy.

Secondary energy use per unit energy plant used is effectively a partial Input/Output table, specifying the quantity of secondary energy required to produce one unit of output of an energy production process. **Table 3** shows settings for this variable, for electricity production via the brown coal fired steam turbine process. In this scenario, the process efficiency is improving by 1% p.a., simulating the introduction of coal drying technology over a 25 year period. The electricity value relates to losses in generation and transmission. VRSFF currently deals with 15 different electricity generation processes.



	2007	2008	2009	2010	2011	2012	2013
gaseousHC							
liquidHC							
brownCoal	3.10	3.07	3.04	3.01	2.98	2.95	2.92
blackCoal							
coke							
briquettes							
wood							
electricity	0.13	0.13	0.13	0.13	0.13	0.13	0.13
hydrogen							

Table 3. Secondary energy used per unit of electricity generated via brown coal steam turbines.

Material use per unit energy plant used performs the same I/O table role for material inputs to material and energy processes as s*econdary energy use per unit energy plant used* does for energy inputs. VRSFF currently uses 39 different materials.

During calibration of the framework, input values are set to reflect known values for the history period. For the electricity sector, the most important sources of information for calibrating electricity generation in were ESAA publications, notably (ESAA 2005). Technical parameters were sourced on an ad hoc basis where ESAA data was insufficient e.g. current water efficiencies of Victorian brown coal steam turbines from (LYP 2004), current gas turbine and combined cycle thermal efficiencies from (ACIL-Tasman 2005).

4.2 Determination of outputs from matEnrTran procedure 5.

Energy plant capacity includes all electricity generation capacity in place for each year of a scenario. It also includes other non-electricity related plant, thus the name “energy plant” rather than “electricity plant”. This is not discussed further here but detail of these other energy processes are available in (Lennox, Turner et al. 2005). Plant capacities are evolved for each time step by first applying the life tables to plant stock extant at the beginning of a time interval, and subtracting the plant due for decommissioning. The decommissioned capacity is output to the *energy plant discards*.

If sufficient capacity remains to meet the primary energy demand for BME, existing plant is operated in accordance with the priorities set in *energy capacity use priority*. Energy production disaggregated by technology and location is reported in *energy plant capacity used.*

If there is insufficient extant capacity after discards, new capacity is built with technology shares determined by *new energy plant share* and *capacity factor*. Applying e*nergy throughput ratio* to the new capacity yields an additional demand for new BME products (recall that while we are only following through energy related components here, procedure 5 has materials counterparts for most). This additional demand is added back into the primary demands for BME, and the required capacity recalculated. This is an iterative process which proceeds until convergence is reached in *energy plant capacity used.*

Intermediate energy domestic production, and *intermediate energy imported* report how “intermediate” energy is sourced. The ratios are determined by *energy import share.* Intermediate energy refers to energy used within the BME industries to satisfy primary demand, and is an additional requirement, over and above primary demand. It is derived by subtracting d*omestic energy produced* from *energy plant capacity used.*

For electricity, the majority of the *energy plant capacity used* will be accounted for in the primary demand from households, processing and assembly etc, with a smaller portion under the *intermediate energy* categories capturing that used in aluminium production, losses in generation, etc. In contrast, energy derived directly from burning brown coal is not generally used outside of the BME industries, where it is mainly used in steam turbines. Thus nearly all of the energy sourced from brown is captured in *intermediate energy domestic production.*

5. CONCLUSION

Significant technological shifts in economic sectors underlain by large primary physical flows are likely have significant cross sectoral physical impacts. Electricity generation fits into this category.

A well structured physical Stocks and Flows Frameworks, implemented on the whatIf?® software platform, with broad sectoral coverage provides an effective and transparent way to forecast where competition for resources may result from such technology shifts, and so provide an effective tool for longer term planning.

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