Exploring Broader Physical System Impacts of Three Alternative Electricity Generation Technology Scenarios for Victoria

West, J. [1], G. Turner [1], T. Baynes [1]

[1] CSIRO Sustainable Ecosystems Division
Email: jim.west@csiro.au

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EXTENDED ABSTRACT

A continuation of historical growth trends in the Victorian electricity generation sector, combined with the current technology mix, would soon test political constraints on sourcing cooling water, and on greenhouse gas emissions. Transitioning the current system away from the existing technological mix, however, will carry other major implications for underlying physical stocks and flows. In some scenarios, quite profound flow on effects would manifest themselves in economic sectors which are currently only tangentially linked to power generation.

The Victorian Regional Stocks and Flows Framework (VRSFF), a physical Stocks and Flows Frameworks (SFFs) implemented on the whatIf?® software platform, was used to simulate three different technological development scenarios for the Victorian electricity generation sector. The technological scenarios chosen were designed primarily to yield different GHG emissions outcomes. Secondary areas of interest included changes in direct water used in power generation, and any feedback effect that may have on ultimate electricity demand, and the degree of coupling between electricity generation and the water system generally.

The study highlighted the desirability of drawing wide system boundaries when assessing the effects of technological change in any industry characterised by large physical flows of any sort. This was exemplified by the interplay between GHGs, broad area land use change, and water availability, and climate change explored in a scenario which incorporated a significant proportion of biomass fuelled electricity generation. It was in the accommodation of sectors outside of the core electricity generating sector that the largest effects on physical flows manifest themselves, most notably as major requirements for land and water in the forestry sector. Restricting the boundaries to the electricity generation sector alone would have missed the most significant effects flowing from technological shift in that sector.

Indirect water demand ultimately attributable to electricity generation in scenarios with high biomass component, due to replacement of grasslands with plantation forests, was an order of magnitude larger than that used directly in generators. This indirect demand should be considered in the context of GHG mitigation strategies that potentially avoid reductions in water supply that might result from climate change. For example, flows in the Murray River may be diminished by about 8 % at 2050 under an aggressive technological shift scenario incorporating biomass, assuming that little or no climate change occurs i.e., that a global response to mitigate climate change is active and the Victorian biomass scenario is a local contribution. By comparison, if global temperature change of about 2 °C occurs—as is possible if current GHG emissions continue to track worse-case IPCC scenarios—then we calculate flows in the Murray may decrease by about 50 % at 2050.

In the aggressive shift scenarios incorporating biomass based electricity, the requirement for land indicated that electricity generators could become major indirect users, competing with existing broad area land users. Furthermore, shifting electricity generation from its current spatial form, concentrated on the brown coal deposits of the Latrobe valley, to a form able to utilise dispersed biomass and wind energy resources has a number of implications. These range from a need to reconfigure the distribution grid to match electricity supply with metropolitan demand, to the possibility that road networks in remote areas may need to be extended and/or upgraded to deal with significant traffic bearing heavy loads. As well as costs, there are benefits to be considered, such as regional development directly associated with building, maintaining, and operating the new power generation infrastructure, and that accompanying any new industrial capacity sited in close proximity to the new generating capacity.

1. INTRODUCTION

The scale of the materials and energy flows which underlie modern economies is such that individual sectors of the economy are coming into competition with each other for some basic resources. These resources include both those which need to be "sourced" from the environment, such as water, fuels, and other raw materials, and increasingly those which need to be "sunk" into the environment, e.g. GHG emissions. Technological mode shifts in one sector aimed at alleviating an emerging constraint can require major changes in other sectors, sometimes in sectors which are currently peripheral to the target sector. For effective analysis of the overall costs and benefits of different technological scenarios, we need tools which enable us to trace through system wide impacts.

The Victorian electricity sector is a good example of an economic sector associated with very large material and energy flows. Electricity generation accounted for 63.2 Mt of Victoria's total net GHG emissions of 121.9 Mt CO_2 equivalent in 2005 (DEWR 2005) (DEWR 2005), and used almost all of the state's output of brown coal. Brown coal in turn accounts for the majority by tonnage of all mineral production in Victoria.

Scenarios simulating technological shifts aimed at reducing GHG emissions were implemented in VRSFF. The main changes involved reducing the share of electricity generated using brown coal fired steam turbines, with some scenarios sourcing up to 80 % of electricity demand from a mix of biomass fuelled steam turbines, wind turbines, and combined cycle gas turbines.

The focus of this paper is on examining some of the significant cross-sectoral effects resulting from those changes, by following through linkages in VRSFF. Thus only a very brief description of what SFFs are and how they are implemented is given in section 2. A detailed description of how the electricity sector is modelled in VRSFF is available in (West et al. 2007), with detail of the water accounting framework for Victoria in (Turner et al. 2007b)and for a SFF with very broad sectoral coverage, the Australian Stocks and Flows Framework (ASFF) in (Poldy et al. 2000)

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 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 will flow through into an increased requirement for dwellings, which in turn generates an increased operational energy requirement for dwellings. Calculations performed within modules are generally limited to reflecting the most straight forward physical relationships.

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. A detailed example of the calibration of an SFF is contained in (Baynes et al. 2007).

SFFs are typically structured so that the flow of information is one directional, and so generally don't take into account any behavioural feedback loops automatically. That function is instead performed explicitly by the person creating a scenario. Where the settings of a scenario lead to physical inconsistencies, or "tensions", it is incumbent upon the scenario creator to resolve those tensions by changing control variables. For example, if a given level of electricity production combined with the generator technologies chosen indicate that 10 Mt of wood fuel will be required, yet the settings in the forestry module would lead to the production of only 5 Mt, then adjustments should be made which either reduce the demand for wood or increase its production, until a physically feasible scenario is achieved. Requiring the creator of a scenario to explicitly set control variables and solve tensions encourages greater familiarity both with the wider system, and with any assumptions underlying a particular input. 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 et al. 1987).

The Victorian Regional Stocks and Flows Framework (VRSFF) used in this study was originally conceived to help land use planners follow through the less obvious cross-sectoral effects their development decisions may have. The original focus on land use planning and demography regimes for Melbourne was subsequently 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.

3. SCENARIO SETTINGS

The integration of a detailed treatment of the Victorian electricity sector into VRSFF enabled it to deal with questions around GHG emissions, connections between the energy and water sectors, and the impact of different electricity generation technological scenarios on broad area land use. The expanded VRSFF was used to construct 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. Results of that project are contained in (Turner et al. 2007a). The current work retains most scenario settings used in that earlier project, such as population growth assumptions and technological efficiency factors for industrial processes, however the growth rates assumed for material and energy consumption per capita assumptions have changed. The most important additional work presented here is in following through on the cross-sectoral effects on broad area land use and indirect water consumption associated with different electricity generation technology scenarios. As the focus here is on the cross-sectoral effects associated with electricity generation, all scenarios explored here are all based on the same underlying population growth, settlement pattern, and household formation rates.

Six scenarios were formed by combining two consumption sub-scenarios with three electricity generation technology sub-scenarios. The assumptions and rationale underlying each is given in **Table 1**.

Consumption growth trend sub-scenarios
High growth - continuation of a linear trend (adding 2.33 % of 2004 values per year) 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 sub-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 sub-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. Other scenarios presented in (Turner et al. 2007a) explore the implications of compounding 2 % growth in per capita consumption of materials and energy that are in keeping with long-term consumption patterns. The 2.33 % linear trend used as the high growth scenario in **Table 1** assumes that changes to the Victorian economy are projected into the future, such as: diminishing economic growth; or decoupling of energy use and economic growth through, for example, structural change to a service economy and energy/GHG generation outside the Victorian border.

4. ANALYSIS OF SCENARIO OUTCOMES

The electricity production required in each of the six each scenario is given 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. For a detailed account on how basic industries (e.g. electricity, metals, and chemicals production) are modelled in ASFF refer to (Lennox et al. 2005).

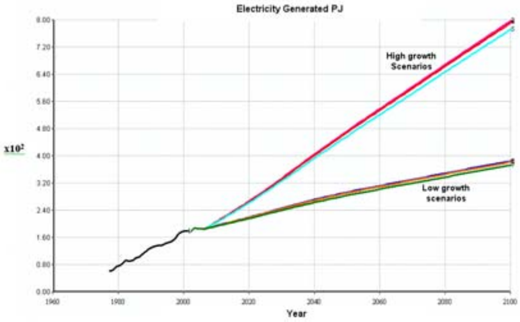

Figure 1. Comparison of high and low growth electricity production scenarios.

The trajectories of GHG emissions attributable to electricity production in each scenario are shown in **Figure 2**. The pronounced break upwards in slope of the four "technological shift" scenarios around 2035 reflects the end of 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).

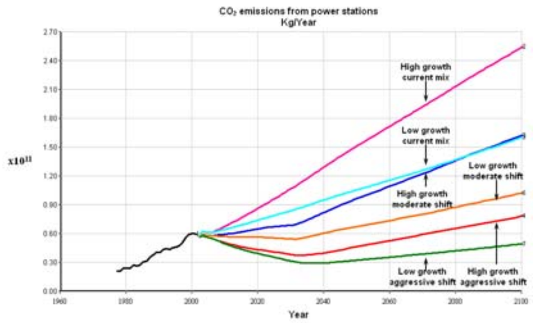

Figure 2. CO2 emissions associated with electricity generation for the six different scenarios

Interestingly, none of the scenarios reach 60 % reductions over year 1990 levels at any point, and all exceed 1990 levels again before the end of the simulation, most of them before 2050. The trajectories of all indicate that the technological scenarios 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 scenarios in terms of direct water use, shown in **Figure 3**. The water used in the *high growth – current mix* scenario of 376GL/year is over four times that used in the *low growth – aggressive shift* scenario.

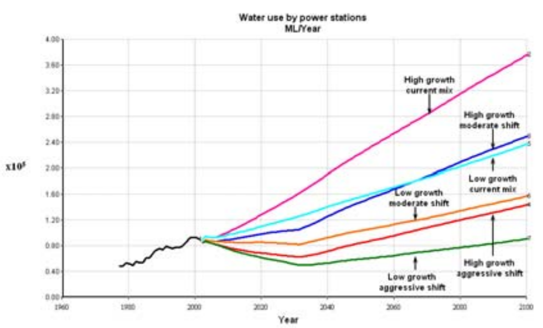

Figure 3. Direct water use associated with electricity generation for the six different scenarios

For the remainder of this section we restrict ourselves to the consideration of two scenarios, *low growth – aggressive shift* and *low growth – current mix*, as they represent end members taking technology shift alone into account. Water used directly in electricity generation is 91 GL/year for the *low growth – aggressive shift* and 237 GL for *low growth – current mix.*

Whilst this is a large relative difference, the resolution of cross-sectoral tensions between requirements and supply, integral to the SFF approach, leads us to 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 of over 30 Mt p.a. greater than that in the *low growth – current mix* scenario, by 2100. This assumes a conversion rate of 2:1 for tonnes of logs to dry wood fuel. Using a density for green wood of 1.1 tonnes/m3, and the Australian average plantations average of 9.52 m^3 of wood/ha/pa derived from (DAFF 2007), satisfying the additional demand for wood would require around additional 3.0 million hectares of plantations.

The new forest plantations must be sited at the expense of some existing land use in VRSFF, and in the linked VRSFF Water framework., otherwise a tension will exist between total land allocated to mutually exclusive land uses, and the amount of land physically available. For this exercise we chose to locate the new plantations on current grasslands, and then applied the mean annual water yield curves derived for the Goulburn-Broken catchments in (Zhang et al. 2003). The yields at 500mm, 1000mm, and 1500mm annual rainfall are given in **Table 2**.

Rainfall(mm/year	**Catchment Yield (mm/year**	
	Grassland	**Forest**
500	90	30
1000	380	160
1500	760	420
Rainfall(mm/year	**Decrease in Catchment Yield from converting grassland to forest (ML/ha/year**	
500	0.6	
1000	2.2	
1500	3.4	

Table 2. Changes in catchment yields from converting grassland to forest. Applying curves from (Zhang et al. 2003).

Three maps comparing the distribution of water demand attributable to electricity generation under *low growth – current mix* and *low growth – aggressive shift* scenarios are given in **Figure 4.** Biomass generation capacity and plantations have been distributed proportional to current agricultural land in each Local Government Area (LGA), wind turbines sited proportional to existing and planned capacity in 2006, combined cycle gas turbines proportional to population (for convenience, it would probably be different in practice), and brown coal fired plants according their distribution in 2006.

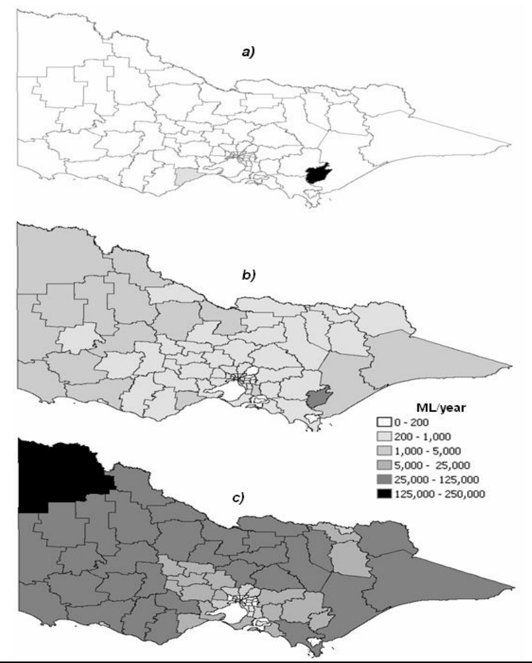

Figure 4. Water used, by LGA, attributable to electricity production in Victoria in 2100. a) *Low growth – current mix, direct.* b) *Low growth – aggressive shift*, direct. c) *Low growth – aggressive shift*, indirect (biomass).

In **Figure 4a** the dominance of direct demand for water used in cooling brown coal fired capacity in the Latrobe valley is evident, accounting for around 231 GL/year out of a total of 237GL/year for the scenario. **Figure 4b** shows a much more even distribution of direct water demand, with Latrobe's power plants using only 43 GL/year from an overall total direct demand of 91 GL/year. Of the other LGAs, 16 use 1 – 2.5 GL/year. The much reduced direct demand in the *low growth – aggressive shift* scenario comes from all of the technologies employed having lower to much lower direct demand for water in comparison to the undried brown coal fired steam turbines. **Figure 4c** illustrates how the situation changes if we take into account the additional water used in forestry activities, notionally a separate sector to electricity generation, but functionally linked where that activity is to grow wood as fuel for generators.

Here we have taken an additional 2GL/year, at the lower end of the range estimated above, and distributed to LGAs proportional to the biomass generation capacity sited there. With indirect water use taken into account, the highest demand for water associated with electricity production is now 136GL/year in the Mildura LGA, out of a total of 2091GL/year. Some 20 LGAs incur water demands greater than the 43GL/year direct demand in Latrobe, with demand in Latrobe itself increasing to around 59GL/year.

Other indirect water demands can be tracked through the framework, but tend to be dwarfed by that implied by any substantial changes to broad area land uses. One partial exception to this is the water consumed in brown coal mining. Using the water intensity of 0.29L/kg for brown coal mining activities applied in ASFF (water use in mining is not currently integrated in VRSFF), the difference attributable to changed coal mining activity between the two scenarios is around 39GL, with that demand concentrated in Latrobe. More typical is the 1.6GL/year difference between the two scenarios resulting from the change in basic materials required to build the two different technology mixes. A detailed treatment of how basic industries are simulated in ASFF, which holds for VRSFF in this regard, is given in (Lennox et al. 2005).

A table for direct comparison of the key water use components linked to electricity generation under the *low growth - aggressive shift* and *low growth – current mix* scenarios is given in **Table 3.** A move to biomass for electricity generation in Victoria appears likely to have a negative impact on outcomes in the water sector, unless climate change impacts are also considered (see **Table 4**).

Water use Component	aggressive shift GL/year	current mix GL/year
Direct Operational	90.6	237.2
Brown Coal Mining	10.2	49.0
Biomass Fuel Production	2000.0	0.0
Total	**2100.8**	**286.2**

Table 3. Key water use components associated with electricity production in two low growth scenarios.

Scenario	Relative reduction in river flow
Reference case (low climate change, BAU electricity generation)	n/a
Low climate change, aggressive shift for electricity generation including biomass	8 %
High climate change, BAU electricity generation	50 %

Table 4. Effects on Murray River flow in 2050 due to comparative scenarios.

The biomass option is taken as part of a possible strategy to mitigate GHG emissions, which only makes sense if it is part of a global obligation to lower GHG emissions. Assuming this to be the case, river flow reductions (in the Murray River entering SA) are less under the mitigation scenario than scenarios involving medium or high climate change (1.5 and 2.2 °C change at 2050 in global average temperature respectively—the latter is possible if current GHG emissions continue to track worse-case IPCC scenarios).

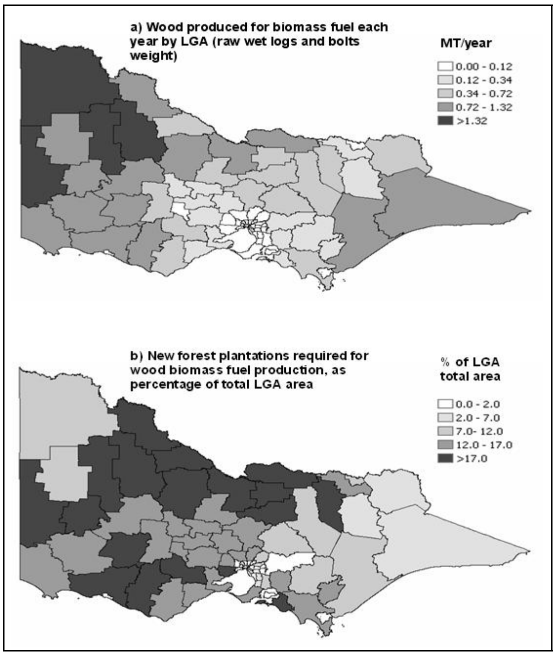

Figure 5. a) Wood fuel production and b) land area required for new forests for the low growth - aggressive shift scenario in 2100.

In addition to the net benefits for the water system, the tonnages of wood required and land area required to grow it are significant overall. **Error! Reference source not found.** gives an indication of where the biomass requirements may impact most on the transport infrastructure, compete with existing broad area land uses for land, and change the landscape character of specific LGAs. In Error! Reference source not found.**a**, the distribution of wood production required in the *low growth – aggressive shift* scenario is mapped to LGAs. The highest individual allocation, to Mildura, is over 2Mt/year, with a further seven LGAs required to produce over 1Mt/year. No attempt is made here to quantify what this means in terms of the transport task beyond noting that it indicates a likely requirement for a transport network able to simultaneously access a spatially dispersed resource, cope with several thousand tonnes of material movement per day, and maintain a reasonable energy profit. Indeed, if biomass plantations on the scale necessary were established, the final transport impact could vary widely from that indicated here, as the possibilities of using some or all of the biomass for other forms of energy replacement e.g. liquid transport fuels, came under consideration (Foran 1999).

The percentage of each LGA which would need to be devoted to new forests for wood biomass under the *low growth – aggressive shift* scenario is shown in **Error! Reference source not found.b**. The large combined area of LGAs requiring 17 % or more of their total area for new plantation forests is perhaps the most interesting aspect. This implies landscape changes on a scale which could be expected to have quite major impacts in areas like biodiversity, bushfire management regimes, and tourism/conservation values. The land areas involved also give a rough idea of how significant a competitor the new plantations could become to existing broad area land uses. As the wood biomass requirement of 31.9 Mt/year is of the same order as total current wood production for all of Australia's forestry industry of 25.7 million m^3 (DAFF 2007), it is perhaps not surprising that concentrating equivalent extra forestry activity in the state of Victoria alone would have a marked effect on the existing landscape.

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.

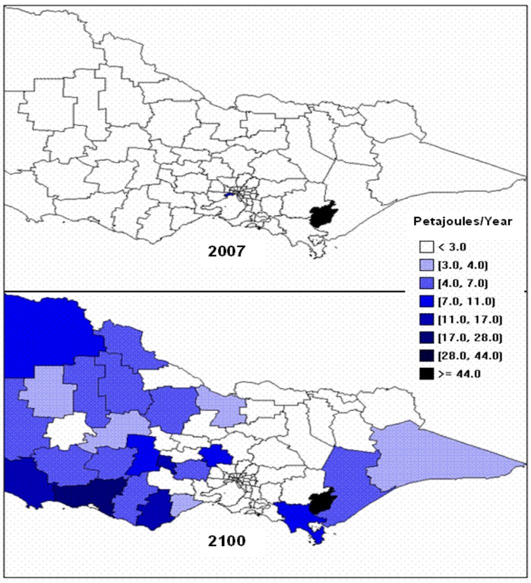

Figure 6. Change in distribution of electricity surplus over time for the *low growth – aggressive shift* scenario.

Changes in the distribution of electricity generated surplus to residential demand by LGA from 2007 to 2100 are mapped in **Error! Reference source not found.**. 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.

5. CONCLUSIONS

Where analysing the potential effects of major technological shift in an industry characterised by large physical flows, it is desirable to draw the system boundaries as wide as practicable. Failure to do so risks missing some of the most important physical impacts, simply because they occur in sectors outside of the immediate system being studied.

Technology specific linkages to sectors where the industry is not currently a major user of resources can prove crucial when technological trajectories change. In the example explored in most detail here, that of a major move away from brown coal fired electricity generation, it was the 20 % biomass component that was responsible for the most profound impacts on broad area land use sectors. It also contributed the largest component to water demands via reduced runoff, however when considered with increased use of wind turbines and combined cycle gas turbines as part of a global GHG mitigation strategy, actually yielded a net benefit for river health

A well thought out SFF provides a useful tool with which such important cross-sectoral effects can be analysed in a transparent and structured manner. Without such analysis, it is easy to overlook important components in the overall material and energy flow outcomes of any chosen development scenario.

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