

**COOPERATIVE RESEARCH CENTRE FOR COAL IN SUSTAINABLE DEVELOPMENT (CCSD)
PROGRAM P1.2: SUSTAINABILITY DIMENSIONS AND IMPACTS**

Dear CCSD Industry Partner:

What follows is an industry discussion paper that considers the development of key performance indicators for the adaptiveness approach to sustainability currently under development within programme P1.2. This is the seventh in the series of brief discussion papers specifically for industry partners. They are designed to explain the key ideas behind the approach that programme P1.2 is taking to sustainable development, discuss the consequences for coal-chain industries, and provoke dialogue and feedback.

Discussion papers 1 to 6 are available at <http://www.ccsd.biz/research/project1.2.cfm>
(See also <http://www.newcastle.edu.au/centre/casrg/research/ccsd.html> for these and for a brief overall description of the P1.2 project).

This seventh paper considers the problem of developing performance indicators for adaptiveness, particularly from the point of view of the adaptiveness of the coal industry itself, as well as the impact that it has on the adaptiveness of the Australian economy.

As for previous discussion papers, the concepts and principles involved here are often recently emerged and may be novel to your thinking. You may wish to inquire further about how these ideas may be applied. Alternatively, you may be able to provide us valuable examples of how they fit your company or industry, and/or provide welcome improvement to our understanding and application of them. On both counts we welcome your feedback.

We thank you for attending.

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SUSTAINABLE DEVELOPMENT: UNDERSTANDING & ISSUES FOR INDUSTRY
**An occasional series of brief papers designed to explain key ideas and provoke
dialogue.**

PERFORMANCE INDICATORS FOR ADAPTIVENESS

“An organization's ability to learn, and translate that learning into action rapidly, is the ultimate competitive business advantage.”

Jack Welch: Chairman and Chief Executive of General Electric

In a dynamic and uncertain world, adaptiveness is a minimum necessary condition for continued survival. Agile creatures that can intelligently learn (such as humans) to exploit new ecological niches or evolve (such as bacteria) to meet new climate and interspecies interactions will survive in the natural environment. Agile firms that can move quickly into new markets or innovate new production processes will survive in a competitive industry. Future technological and policy developments in the energy sector are both highly uncertain and potentially subject to rapid change. This requires a broad suite of economic and social adaptation options so that, across the broadest possible range of likely future developments, the sector is able to supply the energy requirements of Australian society both securely and cost-effectively.

But resources are limited, and investing in developing and maintaining options for adaptation will often compete for resources that could otherwise be dedicated to becoming more efficient at what is presently done. There is thus a trade-off between performing current activities efficiently and developing, in anticipation of future changes, the adaptive capacity to potentially perform alternative activities efficiently. So, how should relevant adaptiveness be identified and evaluated, and how much adaptiveness is sufficient?

This discussion paper addresses the question of developing indicators for adaptiveness. The main message here is that there will be no key performance indicators for adaptiveness that are completely general. Rather the particular indicators will be specific, not only to the adaptive entity, but also to the particular environmental conditions in which it is operating.

There would be no need for peaking plant to be part of the electricity supply system, providing for short term peaks in energy demand, if the demand for electricity were constant over 24 hours or if there were no commitment to meet all electricity demands.

And in the absence of a climate change threat, the carbon capture and storage retrofit readiness of a coal fired electricity plant would not be relevant. This paper therefore does not prescribe particular adaptiveness sustainability indicators for the coal industry, although it does describe a general process for generating candidate indicators, illustrating this with a number of examples.

I: Performance envelopes and adaptiveness indicators

A key concept for characterising adaptiveness with a view to developing indicators is the performance envelope. The concept originated in aerospace engineering, where it can be defined as the range of flight conditions safely realisable by a given aircraft. Generalised, it is the range of relevant behaviours realisable by a given entity. Indicators of adaptiveness of a given technology, organisation, or technological network characterise the performance space of possibilities open to it.

For example, consider a bread baker with a very efficient, though also highly specialised, bread mixing machine and oven. These supply only a limited range of products to her bakery, but do so quickly and cheaply. In fact, suppose she has only two bread products: 500g loaves and 250g rolls; and a maximum mixing capacity of 50kg per day. Even so, with this quite limited range of products there is still some flexibility in the production schedule: any combination of loaves and rolls not exceeding the maximum mixing machine capacity can be produced, for example 100 loaves and no rolls, 80 loaves and 40 rolls, or no loaves and 200 rolls. And if demand is low the equipment can be rested for the whole or part of the day so as little as nothing at all is baked.

The entire range of combinations of loaves and rolls that can be created within this bakery we might call its “performance space”, and its maximum production frontier the “performance envelope”. Depending on the choices made by the baker, any product combination within the performance space can be realised. Here the ranges of quantities of loaves and of rolls, and of their sum ($\#loaves + \#rolls$), and the ‘size’ of the performance space, are all obvious, if partial and naive, indicators of the degree of the adaptability of the bakery production. (See further below.) In sum, indicators of adaptiveness of a given technology, organisation, or technological network characterise the performance space of possibilities open to it.

Performance space adaptiveness has aspects of scope, timeliness and dependence on external contingency. It is also limited by coordination capacity. These are discussed in order.

Scope. The performance envelope of alternative technological arrangements can vary qualitatively or quantitatively. For example, consider adding an extra 25kg specialist mixing machine that is suitable for producing bread dough, but nothing else. It can easily be seen that this addition of capacity *quantitatively* increases the performance space by pushing out the performance envelope.

As an alternative option for expansion, consider a more expensive mixing machine that

can also produce 25kg/day of bread dough, but is also suitable for mixing the batter required to make up to 25 wedding cakes per day. To characterise the performance space of the alternative setup we can add an additional bakery output indicator: “wedding cake production”. Now the performance space has expanded qualitatively from two to three dimensions and also been quantitatively extended, because the performance envelope has been extended, e.g. to include producing 110 loaves, 40 rolls and 10 cakes. *Thus performance envelopes can be extended quantitatively, by improving the quantitative range of performance that can be achieved by one or more outputs while maintaining the others, and/or extended qualitatively, by adding an extra production dimension.*

Comparing technologies in terms of their performance envelopes allows for consideration of a fuller range of their capacities than narrowing attention to a small set of performance evaluation criteria that are universal. For instance, it simply doesn't make sense to compare spreadsheet software to digital calculators, or mobile phones to land lines, solely on the basis of cost alone. A net cost-benefit criterion identifies just a single point in the performance space: that production point (e.g. total bread quantity and mix) that is optimal according to some economic objective, ignoring the value of the alternative options expressed in the performance space. Similarly, compared with a traditional efficiency measure, which again identifies a single optimal point (the most efficient production configuration), the concept of performance possibility space is much broader in scope.

Similarly, a less extensive life-cycle analysis might investigate only a single process configuration based on actual past performance, which is a single point in the performance space. However, a full life-cycle analysis devoted to uncovering system-wide *relationships* among mass-energy flows would also cover the full performance space and thus disclose, as performance analysis does, all that is prospectively possible for the system should it prove relevant - that is, should it prove efficient in some larger context.

Correlatively, however, comparing performance envelopes will require making comparisons across qualitatively distinct criteria. This is particularly advantageous for the comparative evaluation of breakthrough technologies, since they frequently offer functions unavailable to traditional devices - qualitative changes in the performance space. There isn't any simple way of evaluating the importance of mobile phone flexibility of location of service provision or ability to take and send digital images against its requirements for regular recharging and higher service charges compared to land-line technology. However the performance space concept does at least allow these extra functional capabilities to be recognised and a wider range of values to be attached to them. Using traditional performance criteria like cost to evaluate an innovative technology in order to preserve an overly narrow sense of comparability can result in an under-appreciation of its novel capabilities. Because the capacity of truly breakthrough technologies is incommensurate with existing ones, qualitative comparison of performance spaces is a less biased starting point.

In principle then, the performance space characterises the total space of possible adaptive

performance. As the above examples demonstrate, the multi-dimensional nature of the space can very quickly become quite complicated. In practice it will be rarely possible to provide a complete characterisation of this performance space. However, as illustrated in the bakery example, the notion provides a useful conceptual tool for exploring adaptiveness performance indicators.

Timeliness. Not only can adaptiveness be improved via quantitatively or qualitatively, increasing the range of scope of performance, it could alternatively be improved by increasing the rate at which it is possible to move from one point to another. For example, if there is a lot of inertia in the bakery ingredient supply chain, it might require several day's notice to order the icing sugar required to make wedding cakes, so that wedding cake production agility is thus limited. However, an in-house stockpile of icing sugar might reduce the time for switching production schedules from a few days to a few hours. Thus timeliness is also a dimension of adaptiveness.

The scope and timeliness dimensions of performance space apply equally to energy technologies. The quantitative scope of power output for a coal fired power station corresponds to the range between its minimum and maximum output capability. The qualitative scope of the output of an integrated gasification combined cycle plant includes both electricity and syngas, since varying quantities of each can be produced. The timeliness of a peaking natural gas plant corresponds to the power ramp rate.

Scope and timeliness characterise the performance space inherent in a technological arrangement, a bakery, pulp and paper mill, and so on. Call this the production performance space. It comprises those performance conditions that are logically and physically possible given the materials available. Now we deal with two kinds of important constraints on the accessibility of the production performance space: external contingencies and internal coordination.

External contingency. Observe that performance possibilities can be made more or less dependent on the existence of particular environmental conditions that are necessary to enable those possibilities to be realised. For example, the ability to produce wedding cakes at all ultimately depends on the existence of an icing sugar supplier, along with a corresponding supplier of each other ingredient, and the characteristics of those suppliers may constrain what parts of the performance space are accessible. Most obviously, if icing cannot be supplied at all, then the wedding cake dimension of the bakery performance space is not accessible to it. But if the quantity of icing provided per unit time is limited then the performance domain beyond the corresponding maximum wedding cake production rate is inaccessible, while if there is a significant time delay between ordering icing and its supply, then the agility of ramping up wedding cake production is limited. An in-house stockpile of icing sugar can ameliorate these last two constraints to varying degrees depending on the stockpile size relative to the demand schedule. At the cost of creating it, a stockpile internalises external dependencies,¹ thereby adding to the adaptability of production.

¹ See industrial discussion paper #1, *Introducing three basic concepts: system efficiency, resiliency, adaptability*, at www.ccsd.biz.

Label the associated external contingency conditions necessary to enable the full technical performance space to be available for use, the full external operating conditions. Then the access available to the production performance space is determined by the proportion of the full external operating conditions that are satisfied. A solid fossil fuel power station requires timely supplies of coal and water, adequate water and gaseous effluent discharge channels and connection to the electrical power grid, many other contributing requirements; constraints in any of these may limit the operating regime of the power station.

Internal coordination. A bakery without a baker to manage the process can produce nothing: its production performance space is inaccessible. And if the baker hasn't been trained to make icing (and it can't be bought in from another supplier), or is unable to imagine how a wedding cake should look, then wedding cakes are not part of the accessible performance space. An adaptive performance space needs some appropriate form of coordination capacity. And when that coordination capacity is embodied in human form, such as in a company manager and workforce teams, that coordination capacity also includes the ability and willingness to imagine possible production performance conditions and to carry them out.

Coordination capacity includes the capacities both to manage production at each point in the performance space, as well as to manage changing production settings from point to point. For example, the baker's coordination capacity requires not only the ability to make loaves, rolls and cakes, it also requires the ability to switch from - for example - the production of loaves and rolls to the production of some cakes as well.

In parallel with the external constraints, label the range of coordination conditions that need to be successfully selected and managed to enable the full production performance space to be available for use, the full internal operating conditions. Then the access available to the technical performance space is determined by the proportion of the full internal operating conditions that are satisfied. A national electrical power grid that cannot effectively coordinate supply from diverse sources to demand from diverse users will operate far inside its technical performance envelope. Coordination constraints can appear in any situation, but typically become important whenever the situation is sufficiently complex. The coordination capacity may also be hard to characterise and measure, especially when the coordination is emergently self-organising, as it is in market economies and may be in ecosystems.

The actual performance space in any situation is the common overlap between the production performance space and the external and internal operating conditions.

Context dependence. The above examples suggest that what are relevant performance indicators will depend significantly on the context. This is generally true for any performance indicator, not just indicators of adaptiveness. For instance, SO_x, NO_x and heavy metal pollutant outputs are simply not relevant indicators for wind powered electricity generation, though they are for coal-fired generation, while demand for

agricultural land and water are relevant indicators for a biomass energy process, but not for a gas-cooled natural gas generator. More broadly, the very successful South-East Queensland Healthy Waterways sustainability assessment started with a vision for the region of “A healthy ecosystem supporting the lifestyles of residents and visitors” and only later were specific performance indicators such as nitrogen nutrient pollution and duck population developed, based on the specific details of particular catchment regions.²

These considerations equally apply to the construction of adaptiveness indicators. The adaptability of the energy sector has many facets, from the suite of diverse technologies available and the suite of fuels utilisable, at the whole-sector level, all the way down in scale to the ease with which a particular power plant can respond to demand changes, be retro-fitted to reduce pollutants or accept solar boosting, or even be turned over to non-energy uses. The many adaptabilities applicable to the energy sector are not mutually independent, sometimes they go together (e.g. gas-fired generators are both adaptable load-followers and adaptable fuel acceptors through solar boosting and coal gasification) and sometimes adaptabilities partially conflict with one another (e.g. solar technologies are more adaptable to distributed generation than are fossil-fired generators but, without storage, much less adaptable to load-following). In addition, a capacity to adapt is a real physical capacity costing real resources (money, materials, skilled employees) to implement. The finite supply of resources alone ensures that cross-sectoral competition will mean that not all potential adaptabilities can be pursued, and within-sector competing efficiency considerations may further reduce the desirable suite of adaptabilities (note 1). The issue then becomes one of deciding what are the most important adaptabilities to pursue in any given situation or context.

One obvious consideration here is what conditions are externally imposed on the system because they are required for performance to be considered satisfactory or acceptable. The load-following capacity of a peaking electricity generation plant is a relevant adaptive feature only because it is deemed to be a requirement for electrical power to be available on demand. A flue gas desulfurisation retrofit alternative in a coal fired power plant is important because of the undesirability of SO_x emissions.

Relevant performance indicators for adaptiveness will also depend on the particular uncertainties and projected changes that are currently operative. For example, it is the unpredictable and rapidly changing nature of electricity demand that makes the load following capacity of a peaking plant a relevant adaptive feature to consider. It is only due to the uncertainty in the long term price and availability of oil for transport that a coal-to-liquids technological capability might be a desirable adaptive option for Australia. Uncertainties associated with drought make it important for Australian cattle farmers to have feeding options of pasture versus hay, or options to retain stock for breeding or to sell them on international or domestic markets. In the absence of those uncertainties, or changes in future conditions, the adaptive features mentioned above may

² See Dennison WC and EG Abal (1999), *Moreton Bay Study: a scientific basis for the Healthy Waterways Campaign*, SEQRWQMS, Brisbane Australia. See also Moreton Bay Waterways and Catchment Partnership (2001), *South East Queensland Regional Water Quality Management Strategy*, September (Appendix A in particular)

be of little consequence.

II: *Developing Adaptiveness Indicators*

The following outlines a procedure for generating adaptiveness indicators. The starting point is clearly identifying particular relevant adaptive capacities. For this it is necessary to specify the system that has the capacity, the kind of changes to which adaptation is being made, the overall aim in making the adaptation, the adaptive options available and, to get beyond a 'black box model', the mechanisms of adaptation – that is, respectively specify adaptability of what, to what, for what, between what, by what. Once this is done it is then possible to consider relevant adaptability indicators as a function of these features.

The first specification is that of the adaptive object being considered. For example, is it a single technology - such as a motor car, and electrical motor, or a steam turbine, an organisation - such as an electrical generating company, a school or a software firm, or a network of technologies - such as a transport system, a silicon chip fabrication plant, or an electricity supply network. This choice determines the scale of analysis. For the sake of an example, suppose that we select an electrical generation company.

The next task is to identify the relevant criteria that characterise adequate functioning and identify the key uncertainties where potential changes can affect that functioning. For an electrical generator, adequate functioning could be characterised simply as making a profit and meeting environmental and industrial regulation requirements. (A stricter condition – making a profit from the supply of electrical power - is possible, although this may overly restrict the scope of the analysis.) In the current situation, some of the key uncertainties whose change may affect future profitability include the cost of renewable energy technologies, the technical and economic feasibility of carbon capture and storage, and greenhouse gas emissions policy.

The following step involves identifying the alternative options available to ameliorate the consequences of the uncertain contingencies that threaten satisfactory functioning, along with the mechanisms for carrying out the adaptation processes. This is less straightforward and, like the preceding tasks, requires a reasonable degree of familiarity with the situation.

For our example case-study we begin by specifying two broad categories of options, the installation of alternative electricity generation technologies or changing the business model from focussing solely on the generation and sale of electricity. It is within these categories of adaptation options that adaptive performance will be specified more precisely. Just how difficult and costly any specific option would be to implement will depend in part on its inherent costs and in part on the change planning and management processes in place in the company, that is, on the cost structure of its coordination performance space. For the sake of simplicity we do not pursue these latter details further here, but readers will appreciate that, poorly realised, they can prove very disruptive and costly.

It is now possible to be more specific about the particular adaptive options that ought to be considered more closely within the broad categories. For alternative electricity generation technologies, candidates might include coal driving high temperature (supercritical) steam cycles, natural gas, and hybridisation of coal with solar thermal or biomass. Changing the business model might involve selling hydrocarbon based chemicals as well as electricity with the acquisition of integrated gasification technology, or integration with a retailer seeking opportunities to market thermal energy and/or energy efficiency measures. It might involve trading in carbon credits and associated activities such as afforestation or the promotion of low emissions technology measures both internationally and domestically.

In this step it is important to identify only those alternatives that either already are, or have a reasonable prospect of becoming, a realistic possibility. In principle, nuclear fusion generation is “possible”, generously understood, but the other technologies mentioned above are much more realistic candidates and have higher priority for consideration. Similarly, changing the business model to become a motor vehicle manufacturer is “possible”, but unrealistic.

For the identification of key performance indicators, it now remains to select relevant measures of the adequacy, given the uncertainties, of the range of possible adaptive options identified. Adequacy measures may include measures of the quantitative and/ or qualitative scope of the options, the timing and/or cost of realising them, and the extent to which they are contingent on external factors.

Scope. A company that has enough capital to install an advanced supercritical coal plant of 1000MW has a greater quantitative scope than one that could install only 400MW. A company that can profitably install as little as 10MW of wind turbines (because it already has 40MW and experienced personnel to operate them) has a greater quantitative scope than one that requires a minimum scale of 50MW installation in order to justify the investment economically. A company that could realistically operate either a coal-fired power plant, a solar thermal plant hybridised with coal, or a stand alone solar thermal plant has greater qualitative scope than if it were only capable of operating a coal-fired plant.

Timing. A company that could realistically expect to have the technical capability of storing carbon underground within eight years has superior adaptiveness along the timing dimension than if this prospect were twelve years away. A proxy indicator for the timing of a technology would be how advanced it is on its technological development pathway – whether it is at the laboratory demonstration stage, is a pilot plant, fully commercialised or is a mature technology.

Cost. If a generating company develops customised solar thermal technology that enables lower cost hybridisation with its particular existing stock of fossil generated power plants, then its adaptiveness has improved (quantitatively) along the cost dimension.

External contingency. A compressed air or hydroelectric pumped storage capability associated with a wind turbine farm enables the meeting of electricity demand to be less contingent upon the timing of the wind regime and the ability of the rest of the generating network to balance the load.

Which particular type of adaptiveness measure might be the most relevant will again depend on the particular strategic circumstances – the scope, timing and significance of the uncertainties that are being faced. A technical capacity to install and operate an integrated gasification combined cycle generator within two years is not required at the current stage in that technology's development – a ten to fifteen year commercialisation time scale should be sufficient. Once the key dimensions of the adaptive response have been selected – for our generator company, for instance, it might be the range of renewable hybridisation technologies accessible to it and the speed with which it can take these up – then measures for these same features form the leading or key performance indicators in that situation. Other features of the options – for instance, how costly a specific hybrid option is to install, or how dependent it is on local weather – might then form secondary performance indicators in the situation.³

III: *Is the performance space adequate?*

The concept of performance space has the merit of making necessary a clear conceptual distinction between a system's *capacity* (the performance envelope), and any performance or task *requirements*. Requirements are often better conceived of as being imposed externally due to the characteristics of the environment.

For example, let us suppose that an energy generating company has a performance requirement imposed on it to profitably make a reasonable return on invested capital. This depends not only upon the inherent performance space of the company, but also upon external constraints of the economic environment which are beyond the company's direct control - conditions such as the continued availability of resource inputs at sufficiently low cost and a market for its products at sufficiently high prices. A sufficient condition for the adaptiveness of the company to be adequate to the profitability requirement is that its performance space meet or exceed the profitability requirements imposed by the external economic conditions, over a range of feasible conditions. That is, it must be that for each feasible economic market condition in the uncertainty range, there is somewhere within the production performance space where profit performance is satisfactory (that is, the production performance envelope must be adequate). Furthermore the company management must be able to select that location in the production performance space contingently upon the particular actual market conditions (that is, the coordination performance space must also be adequate).

For example, assume that it is possible to guarantee that the market environment will be such that the price of carbon will range up to \$40/tonne of CO₂ over the next ten years

³ Under some circumstances all performance indicators might be treated as variables in an encompassing 'adaptation production function' which is to be maximized. That would allow, and mandate, specific kinds of trade-offs among performance indicator values, rendering any key/non-key distinction moot.

and range up to \$80/tonne afterwards, that electricity demand growth will be between 1% and 3% per annum for the next fifteen years, but that it is unknown whether carbon capture and storage will be possible. What range of technological options does a company need to be able to possibly bring on-line, and at what rates, in order to ensure ongoing survival? Will it be sufficient to rely on developing a small amount of expertise in carbon capture and storage and wind generating technology alone? Or would it be also required to have expertise in biomass and solar thermal generation options as well, in order to maximise the likelihood of ongoing profitability. These questions cannot be answered without detailed knowledge of the specific siting opportunities and technical expertise available to each firm.

For the purposes of this thought experiment, assume that some hypothetical energy company is currently operating several large coal-fired power stations, and is fortunate enough for one of them to be sited near a suitable location for carbon storage. Technical assessments show that the additional cost of capture and storage at this site will be between \$20 and \$35 per tonne, depending on whether infrastructure costs can be shared with other industry players. The company also has a small number of experimental wind turbines, and an option to purchase a number of sites for larger scale development of its wind generating capacity.

Due to its continued access to low cost fuel (coal) and the expectation that there will be no CO₂ restrictions for the next six years, the company is confident of remaining profitable for that period of time. In fact, the existing portfolio of coal generators will remain profitable up to \$40/tonne of CO₂ (noting that the wholesale price of electricity increases with the carbon penalty). Fortunately, one of the wind sites becomes profitable at \$30/tonne and the remainder are profitable at \$50/tonne, assuming the availability of adequately trained personnel. Thus, the following adaptive strategy is decided upon. Plans to develop the most likely wind site will be drawn up and a sufficient number of personnel to operate that site will be given experience with the currently existing experimental turbines. Meanwhile, plans to install carbon storage infrastructure at the suitable site can also be drawn up.

If a carbon penalty remains low or zero over the next decade, then neither plan is implemented. If it creeps up to the level at which carbon capture and storage becomes cost effective, and its technical feasibility has been demonstrated, then those plans can be realised. At higher carbon penalty rates the most attractive wind site can be developed, with further personnel trained on that operating site if the carbon price looks to remain elevated - with a view to developing the remaining sites and mothballing the existing coal plants. On the other hand, if the carbon penalty rate remains moderate, then only the one wind site would be developed in addition to the continued operation of the existing plant.

The above scenario makes explicit that in order to achieve satisfactory performance, a certain degree of adaptiveness of the surrounding (economic) environment is required. In particular the industrial environment has to be sufficiently adaptive to be able to provide (or not provide) suitable carbon capture and storage plant, and wind turbines at sufficient rates to keep the existing workforce occupied and maintain enough revenue for the

company to survive the transition. This may not be the case if the demand for such developments increases simultaneously all over the globe.

Performance indicators for adaptiveness in these circumstances will be highly situation specific. What percentage of the workforce is trained to operate the prospective alternative technologies (wind and carbon capture) relative to potential requirements? How quickly could the wind site be developed? What is the prospective cost of carbon storage? What range of technological options is under serious consideration (in the above example, there are only the two)?

We can then see reasonably intuitively how research & development can result in increasing the range of satisfactory performance. On the one hand, research & development can improve the performance space of a new technology directly, or indirectly by reducing its cost or construction time. On the other hand, research and development can reduce the range of uncertainty due to ignorance associated with the environmental conditions. For an example of the former, the development of compressed air energy storage for wind turbines will expand the range of energy demand profiles that can be met, thereby extending the performance space of the wind farm. As an example of the latter, research identifying that the carbon price will be within the range of \$20-\$40/tonne over the next twenty years narrows the range of uncertainties that must be dealt with.

IV: Some examples: adaptiveness indicators for the coal industry

The following describes the development of some adaptiveness performance indicators for the coal and energy industries, at varying scales of analysis: from individual technologies, to processes composed of technological networks, to entire organisations, to industries (coal - including steel and electricity and/ or energy - including transport), to national and global economies.

The operational performance space of a coal boiler, an individual technology, can be expressed in terms of its thermal power and temperature output, range of acceptable fuel inputs (coal – or other fuel such as biomass and oil – type, and particle size) as well as pollutant outputs (for example, lower NO_x might be achievable at lower temperatures). The scope of this space will be described in kW and degrees for power and temperature, specific identification for fuel type, and for pollutants, mass density and flow rate. Timeliness will be described in terms of how quickly its power output can be raised or lowered to meet demand requirements, or how quickly the switching of fuel can be achieved. And it is not simply the technical feasibility of the performance that matters. In order to achieve its full range within the technical performance space the boiler requires a regulator, whether that takes the form of automatic control equipment, skilled operators, or a combination of both. Only those performance conditions that the plant personnel are confident to operate in can be achieved.

A technological process network, such as an integrated gasification combined cycle process, has both an operational performance space and a process development

performance space. Analogously to the operational performance space of an individual technology, this can be expressed in terms of its range (quantitative upper and lower capacity bounds and type) of output products - without further chemical processing plant to convert the syngas into other hydrocarbons the range of product types includes electricity, thermal energy, hydrogen, CO and CO₂ in varying ratios. The performance space will also include a range of acceptable input fuels (various acceptable combinations of coal, syngas, and natural gas). Operational timeliness will describe how quickly the operating point can be changed.

The process development performance space describes the range of possible capital improvement retrofit options that are available – such as carbon capture equipment, or further chemical processing plant suitable for the production of synthetic fuels such as hydrogen, methanol or diesel. Each possible retrofit option will be associated with its own individual operational performance space. Process development timeliness will describe how quickly such capital improvement retrofit (and necessary associated operator training) can be implemented. In order to achieve the full range within the process development performance space, skilled design engineers, who have an understanding of how to optimise the process design, are required. The process development “coordination performance space” will characterise how well the design engineers understand the process development possibilities.

It is similarly possible to describe the performance space of the organisation that owns and operates such engineering processes. It will also have both operational and process development performance spaces corresponding to the aggregation of those of its constituent technologies and technological process networks. Its operational performance space represents immediately available, typically inexpensive, options for changing the production schedule and might be characterised by fuel resources and other materials used, labour required and energy services delivered. Its process development performance space represents more significant alternatives for process augmentation and other modifications, though ones that retain essentially the same character of process. These might include options such as boiler modification to accommodate an integrated drying process with brown coal fuel, the upgrade of sulfur control equipment, retrofitting a coal boiler with the injection of oxygen enriched air, or adding a solar thermal process that preheats recondensed steam before the heating cycle is completed in the boiler.

As the process modifications become more and more significant, they eventually encompass the possibility of entirely different technological processes and/or business models. Such possibilities have been discussed above, and can also be described in terms of scope and timeliness. Is it a realistic possibility for the organisation to invest in modern supercritical generation, or in solar thermal plant? How quickly could this be achieved, taking into account the requirement for regulatory approval, financing, workforce training and construction? Is there a realistic possibility for the organisation to invest in sequestration activities or perhaps to focus business activity around expertise in emissions reductions? One possible indicator of organisational innovativeness might be the number and significance of new technical processes (or business models) introduced in the last five years.

At the scale of the wider energy sector, the adaptiveness performance space includes new industries and products that are synergistic with existing technological capacities and personnel skills (that is, qualitative scope) as well as export market potential (quantitative scope). Both the coal and uranium mining industries have high export market potential (uranium arguably more so than coal in a carbon constrained global economy). However coal-based electricity generation technologies can be hybridised synergistically with solar thermal, which also has export potential. If wind turbines are manufactured locally, this will enhance Australia's technical capacity to make small-scale electrical generators and drives. A biofuels industry represents an opportunity to take advantage of existing agricultural capacity. This observation emphasises that energy supply technologies should not be evaluated solely in terms of their cost, but also in terms of the industrial development possibilities that are enabled by the technical skills that they support.

Consideration of timing as an indicator is necessary because some technologies, such as nuclear for example, require decades of advance planning, in this case to establish appropriate regulatory institutional arrangements and technically trained personnel. Hence at the scale of the energy sector of the national economy, performance indicators might include, for example, the extent (and diversity) of economic exchanges with other sectors, the skill levels (as well as quantity) of employment promoted (the coal industry does well here), or the extent to which the technology could be part of an Australian export industry (concentrating solar thermal does well here).

Thus adaptiveness indicators will provide answers to questions like the following. *Timeliness*: How quickly would it be possible to replace less thermally efficient power plants with more efficient higher temperature versions? Improvements will be obtained if this installation time can be shortened through clever retro-fitting designs. How long would it take to develop an export industry in concentrating solar thermal technology? Improvements will be obtained if this time can be shortened through domestic industrial involvement in demonstration projects. *Quantitative scope*: What is the present capacity for biomass cofiring with coal? How stringent is the requirement that energy is generated simultaneously to demand, that is, what is the potential storage capacity of the energy system? Improvements will be obtained if these capacities can be increased. *Qualitative scope*: What is the range of responses available to Australia in response to the doubling of the price of oil? Improvements will be obtained if extra potential responses can be developed (preferably without too much redundancy).

Thus there are many potential indicators of the scope and timeliness of the performance space of coal industry related technologies and organisations. Which are the most relevant for any particular case will depend on the scale of analysis, the characterisation of acceptable outcomes, and the most significant uncertainties. For the energy industry the most obvious significant uncertainties include the potential impact of carbon constraints on energy policy and economics, the technical and political feasibility of carbon capture and storage, the availability and security of oil and natural gas supplies (both domestically and internationally) and the economics of ongoing developments in a wide array of energy technologies. Corresponding relevant adaptive options will include

the capacity to reduce carbon emissions quickly and cost-effectively if necessary, including options for capture and storage, the options to lower demand - or produce substitutes - for oil, low cost options to use - or not use - natural gas depending on availability, and the ability to quickly exploit new supply technologies as they become cost-effective.

Note that some adaptive capacities of an aggregated system of components will depend on the corresponding adaptive capacities of the components. For example the total quantitative range of energy supply capacity of an energy network will be composed of the corresponding supply ranges for each of its existing component supply technologies. More significant adaptive capacities include the ability to remove, add, or modify component subsystems - for example the ability for the energy industry to decommission generating plant, retrofit new advanced processes (such as oxy-PF, post-combustion capture, coal dewatering pretreatment), or commission new plant (such as advanced thermal coal, integrated gasification, wind, concentrating solar thermal).

V: Industrial networks and adaptiveness

Industrial and technological networks operate at scales between firm and sector (though in some cases may cross industry sectoral boundaries) and are here discussed in some detail focusing on the different ways in which the performance space is affected by the elaboration of network linkages. Indeed, the concept of performance space permits a more precise description of how industrial networks can impact on adaptiveness.

For example, when BHP sources hydrochloric acid for cleaning steel from the waste by-product of Orica's production of ferric chloride (for the removal of phosphorus in wastewater) and ferrite (for pigment), and recycles the spent acid back through Orica (note 1), the external contingency requirements of the performance spaces of both organisations are reduced. In particular, neither process now relies exclusively on an external supply of raw materials, but has a choice of whether or not to source it from their network partner as an alternative. However, performance space analysis also reveals that sufficient buffer storage capacity for both the raw and spent hydrochloric acid is required in order that there is mutually independent flexibility in production rates of the two network partners.

In the absence of such storage capacity, the rates of the two processes would be mutually coupled and thus mutually constraining. The performance space of the coupled network is smaller without the buffer storage than with it. On site storage also improves the timing responsiveness of the production processes. The mutual trading of wastes for resources provides an example of a purely quantitative modification to the performance space scope of the two production processes. The types of product and resource input requirements remain the same, only the range of quantities supplied and demanded is altered.

Note that if, as a result of the new network interconnection, the relationships with the original resource suppliers are permitted to atrophy, then the external contingency requirements that are assumed to be operative no longer hold. Making a fair adaptiveness

comparison between the original case (external supplier links but no interconnection) and this alternative (network interconnection but poor external links) requires the relevantly distinct components of the external environment (that is, the supplier links) to be brought within the boundary of analysis. In other words, fair comparison requires analysis of the performance space of network partners *plus* suppliers. This illustrates an important general lesson about choice of relevant system for proper adaptiveness comparisons.

The elaboration of the Werribee sewage treatment works network⁴, on the other hand, where sewage cascades through a sequence of fields marked by extracting useful products from its contents, represents an extension of the qualitative scope of the performance space. Adding methane, grass and cattle to the range of products that formerly included only treated sewage adds extra dimensions to the space. Feeding back the produced methane to reduce the electricity requirements of the treatment works also makes a quantitative modification to the resource input demand of the original performance space. Export of clean effluent for the irrigation of market gardens and recognition of the bird habitat function of the wetlands may also be regarded as qualitative extensions of performance space scope. Here we have an example of an extension of qualitative scope of performance space due to the addition of qualitatively distinct technological components in the network.⁵

However, qualitatively distinct options need not be mutually technically interconnected or have wider network effects. Consider a case where the energy industry had access to a portfolio of independent electricity generation technologies (eg: wind, biomass, advanced supercritical coal, integrated gasification, natural gas and nuclear) that could each *potentially* be deployed over reasonably short time periods (say 7 years or less), the actual deployment of any one technology acting as a substitute for the deployment of the others. Here, the development performance space is composed of qualitatively distinct elements that are essentially simply redundant on one another. The redundancy confers an adaptive capacity (the choice among the technologies as circumstances dictate), but not network interconnectedness.

On the other hand there can be significant interdependencies among suites of energy technologies⁶ which mean that their contingent opportunities for adaptive deployment must be considered together. For example, the development of a market for coal derived synthetic liquid hydrocarbons for transport fuel requires modification both to the motor vehicle fleet so that it is more adaptable to alternative fuel sources, and to the fuel distribution network so that it is more adaptable in the range of products it can supply. But such a development towards multi-fuelling will also provide a market for biofuels such as methanol, ethanol and bio-diesel. Thus the potential adaptive capacity of both a biofuels and synthetic liquid hydrocarbons industry depends on the composition of the

⁴ See industrial discussion paper #6, *Industrial networks - an important framework tool for sustainable policy and planning*, at www.ccsd.biz.

⁵ Note that due to the interconnected and dynamic nature of the relationships among the effluent cleansing, methane producing, grass growing and cattle grazing processes, the quantitative performance space of this network may not be simple to describe completely.

⁶ See industrial discussion paper #3, *Adaptiveness evaluation of Coal21 report*, at www.ccsd.biz.

motor vehicle fleet, which in turn depends on the reliable and cost-effective availability of alternative fuels. In contrast to the development of a domestic oil field producing standard fuels, both synthetic liquid hydrocarbon and biofuels technology have a qualitatively distinct impact on the adaptive possibilities for the development of the transport fuels industry. Either technological suite could synergistically open up the adaptive options for development of the other. The scope and range of the input fuel performance space of the domestic motor vehicle fleet and the scope and range of the fuel distribution performance space of the fuel distribution network might be a useful adaptiveness indicator in this case.

Similarly, concentrating solar thermal plant can be hybridised with thermal coal in the provision of base-load generation. A combination of coal and solar thermal plant with heat storage could provide a load-following capability that matches demand more closely than a single-technology generation portfolio of either option.⁷ The deployment of concentrating solar thermal generating capacity in hybridised form will develop Australian operating capability in the technology. It may lead to Australian manufacturing capacity and will, due to encouragement for technological development in the area, also enhance the economic feasibility of the technology as a non-hybridised, stand-alone plant, and for export in both forms. The qualitative and quantitative scope of domestic operations and manufacturing capability for energy technology might be useful performance indicators in this case.

In sum, enhancing network linkages can result in extending the quantitative, but not qualitative, scope of the performance space (BHP-Orica example) and/or in extending the qualitative scope of the performance space (Werribee example). However, if the adaptive options are mutually independent redundancies no network linkages are formed. Nevertheless, there are a number of energy technologies that are technologically interdependent either via network effects involving modifications to the wider supply chain, or due to the potential for hybridisation producing novel capabilities not realisable by single technologies alone. In all these cases the features of the resulting performance space suggest the choice of adaptability indicators.

Finally we are reminded of the substantial cost consequences of maintaining real adaptive options. Retrospectively, preceding investment in adaptive capability will appear to have been wasted. However, this will not be the case because it will have been impossible to know in advance which particular capabilities will prove valuable, and the preparedness to respond as the occasion demands will have its own (real option) value.⁸

VI: *Performance Space and Ecological Systems*

The concept of performance space provides an understanding of why, within an

⁷ Coal can provide twenty-four hour base load generation while solar provides an extra power boost during daylight hours when demand is greater. Heat storage capacity provides flexibility to modify the generation profile in order to follow demand even more closely.

⁸ See industrial discussion paper #2, *Introducing adaptive sustainable development - a framework for policy and planning*, at www.ccsd.biz.

ecosystem, a range of functionally redundant species with a diversity of responses to environmental disturbances can result in functional resilience of the ecosystem. The performance space of an ecosystem corresponds to the range of possible species distributions, contingent externally on climate variables and internally on biochemical signalling and other coordinating variables. Interaction among species transforms the ecology into a production network. It is on the network dynamics that much of the characteristics of an ecology, including its resilience to change, depend.⁹

If there are no interactions among species then this can be regarded as a simply redundant ecosystem structurally analogous to having available a range of independent technological options, e.g. Australian inland dry grasslands. An ecosystem with few species has a performance space that is qualitatively limited in scope and relatively narrow in the range of environmental conditions within which relevant functions are preserved. On the other hand, an ecosystem with many species often has accessible to it a much wider range of species distributions, and shows more resilience to perturbations. Though often very complex and not well understood, both effects are largely due to the ways that species serve to support each other directly through food webs and indirectly through their contributions to such shared resources as soil conservation, water retention and humic content in soils. These network interdependencies both support larger species numbers and population sizes, and resilience, through complex feedback loops that stabilise ecosystem functioning in the face of perturbations (such as fire or disease).

Though not identical, these ecosystem network features have analogues in the ways that a primary energy technology (such as coal) becomes embedded in a complex economic network of industries (see V above), with financial and production feedback interdependencies that will largely stabilise macro-economic functioning against even substantial changes in energy sources (cf. change in photosynthetic sources in food webs).

Conclusion

An unpredictably changing world requires a broad suite of relevant adaptive options to meet a broad range of possible contingencies. That suite of adaptive options realises a multi-dimensional performance space of performance possibilities. A narrow performance space will be risky if only a narrow range of possible contingencies can be acceptably accommodated. While developing a broader performance space will divert resources away from being highly efficient (narrowly conceived), it will also result in a more moderate strategic risk profile. Sustainability – of any valued condition – whether it is the ability for human technical and economic development to meet human needs, or whether it is the integrity of natural ecosystems, requires a minimum sufficient degree of adaptive capacity.

⁹ See, e.g., Gunderson L.H. and C.S. Holling (eds. 2002), *Panarchy: Understanding Transformations in Human and Natural Systems*, Island Press, Washington; Walker B., et al. (2002), “Resilience Management in Social-ecological Systems: a working hypothesis for a participatory approach”, *Conservation Ecology*, 6:1:14ff.

Future technological and policy developments in the energy sector are highly uncertain and also potentially subject to rapid change. By the above argument, this requires a broad suite of economic and social potential adaptations to ensure that the energy sector not only continues to securely and cost-effectively supply the energy requirements of Australian society across the broadest possible range of likely future developments, but also supports the industrial basis of the economy via the maintenance and development of innovative and productive technical skills. What is the currently accessible performance space of the Australian energy industry - or that of particular energy organisations? On what key external contingencies and internal coordination is its functionality dependent? Does the energy industry realistically have only a small number of technological options and business models that it could genuinely move towards within a reasonably short period of time - or is it actually capable of realising a broader range of technological futures if the opportunities were to arise? What is the performance space of industrial development opportunities in other economic sectors that is supported by its current mix of skills and technical capacities?

Indicators for a performance space will be measures of its scope, the timeliness of the ability to move quickly within the space, or the stringency of external conditions and internal coordination that must hold for the performance space to be accessible. Improvements in adaptiveness will be recognised when the performance space scope is extended (quantitatively or qualitatively), when the time that would be required to reach various points in the space is reduced, or when the achievement of the performance possibilities is made less dependent upon external conditions. Internal coordination capacity becomes especially important when, as in the current energy technology circumstances, resilient response calls for a coherent sector capacity to experiment, learn and grow adaptive options nationally in the face of recent industry fragmentation in the pursuit of increased market competitiveness. However, constructing relevant adaptiveness indicators requires an appreciation of the wider external context - the most significant uncertainties and the key criteria for judging the adequacy of outcome. Furthermore, there will rarely be a definitive answer to the question of how much adaptiveness is sufficient – this will ultimately depend on wise judgment based on the relative costs of acquiring a relevant portfolio of adaptive capacities and an appreciation of the plausibility of scenarios in the recognised uncertainty range.

We have noted that developing suitable network interlinkages can extend the performance space of the wider interlinked system - improving adaptiveness quantitatively and/or qualitatively. Furthermore, the realisation of some technological options (such as fossil derived synthetic fuels) can synergistically improve the adaptive capacity of the economy to realise other technological opportunities (such as biomass derived synthetic fuels) via its impact on the wider industrial network. Thus not all adaptive capacities relevant to new technologies will be inherent within them - their adoption can have spillover effects, contributing to the adaptive capacity of the wider industrial or economic network.

The complexity of natural and human cultural and economic dynamics means that it will always be somewhat uncertain whether or which specific ecological and socio-economic

conditions are absolutely necessary for the sustainability of continued functioning. In such circumstances it is prudent to seek to expand the range of relevant options available and to shorten their potential realization time, and to avoid either eliminating options or allowing preparedness for their timely realization to lapse. The space spanned by the performance realized by the set of available options then represents the adaptive capacity that should be preserved or enhanced for adaptive sustainability – in technologies, industries, economies, ecologies and in our societies and culture.