Chapter 6
A Socio-economic Metabolism Approach to Sustainable Development and Climate Change Mitigation

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Abstract Humanity faces three large challenges over the coming decades: urbanisation and industrialisation in developing countries at unprecedented levels; concurrently, we need to mitigate against dangerous climate change and we need to consider finite global boundaries regarding resource depletion.

Responses to these challenges as well as models that inform strategies are fragmented. The current mainstream framework for measuring and modelling climate change mitigation focuses on the flows of energy and emissions and is insufficient for simultaneously addressing the material and infrastructure needs of development. The models' inability to adequately represent the multiple interactions between infrastructure stocks, materials, energy and emissions results in notable limitations. They are inadequate: (1) to identify physically realistic (mass balance consistent) mitigation pathways, (2) to anticipate potentially relevant co-benefits and risks and thus (3) to identify the most effective strategies for linking targets for climate change mitigation with goals for sustainable development, including poverty eradication, infrastructure investment and mitigation of resource depletion.

This chapter demonstrates that a metabolic approach has the potential to address urbanisation and infrastructure development and energy use and climate change, as well as resource use, and therefore to provide a framework for integrating climate change mitigation and sustainable development from a physical perspective. Metabolic approaches can represent the cross-sector coupling between material and energy use and waste (emissions) and also stocks in the anthroposphere (including fixed assets, public and private infrastructure). Stocks moderate the supply of services such as shelter, communication, mobility, health and safety and employment opportunities.

The development of anthropogenic stocks defines boundary conditions for industrial activity over time. By 2050 there will be an additional three billion urban

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dwellers, almost all of them in developing countries. If they are to receive the level of services converging on those currently experienced in developed nations, this will entail a massive investment in infrastructure and substantial quantities of steel, concrete and aluminium (materials that account for nearly half of industrial emissions). This scenario is confronted by the legacy of existing infrastructure and the limit of a cumulative carbon budget within which we could restrain global temperature rise to <2 °C.

A metabolic framework incorporating stock dynamics can make an explicit connection between the timing of infrastructure growth or replacement and the material and energy needs of that investment. Moreover, it provides guidance on the technical and systemic options for climate mitigation concurrent with a future of intense urban development and industrialisation.

Keywords Climate change • Cross-sector coupling • Embodied energy and emissions • Flows • Infrastructure • Metabolic framework • MFA • Socio-economic metabolism • Stocks

1 Background

There is strong consensus among scientists that climate change is upon us and that mitigation action is both worthwhile and urgent (UNFCCC 2011; IPCC 2014a). At the same time, there is widespread recognition that the poverty and inequality in the developing world is unsustainable and there are internationally agreed goals to rectify this (UN 2012). Climate change research has defined the problem: through measuring and modelling the flows of CO_2 and other greenhouse gases (GHGs), monitoring extreme weather events, acidification of oceans and other observations, the causes and consequences of climate change have been identified. We can attribute global climate change to a host of different economic activities with some degree of spatial detail (e.g. Hertwich and Peters 2009; Peters 2010). Current mainstream models for climate change mitigation (CCM) frame the problem predominantly as one of the energy systems and one that is located where energy or emissions are produced or where energy is finally consumed. They emphasise energy and emissions directly or indirectly associated with activity in different sectors of society (including land use change) – see Fig. 6.1 – but they omit (1) the linkages between energy use sectors through nonenergy resource flows, (2) the drivers of resource use (e.g. from infrastructure development) and (3) the secondary resource availability (e.g. from infrastructure retirement). Thus, the current mainstream CCM models omit the material boundary conditions of the global system and opportunities for energy and emissions saving through recycling and reuse of materials.

When we refer to solutions, we ask: ‘what can we do about climate change?’ What are the technical and behavioural responses to the challenge? Analysis of energy and emissions flows is essential but insufficient to address these questions

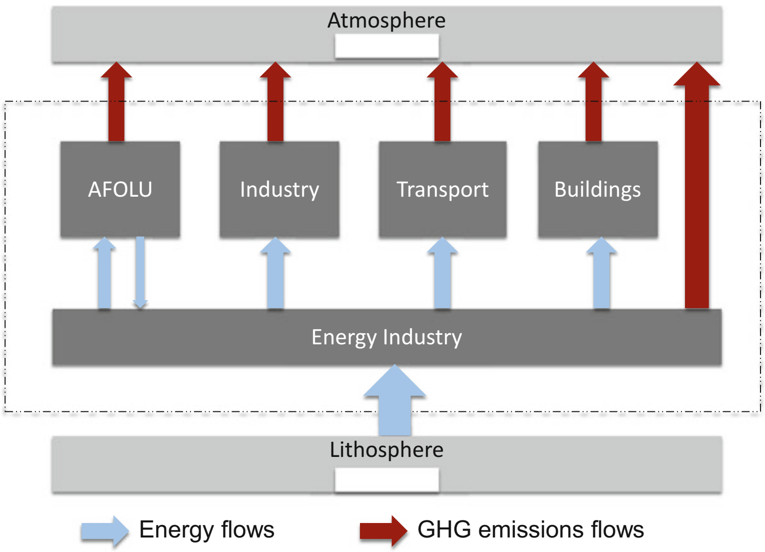

Fig. 6.1 Summary of the standard approach for emissions accounting, e.g. 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPPC 2006)

because it has only a poor representation of the capital stocks and infrastructure that are the mediators of many mitigation initiatives.

Drivers of emissions are seen as consumption and production, connected by primarily linear flows of materials and energy. What is important for CCM interventions and what is usually not well covered is the underlying activity, which is often associated with infrastructure growth and maintenance. For example, we attach emissions to aggregate steel production and steel consumption but frequently *not* to what the steel is used for, or for how long. If we seek to substitute for, or reduce, steel in-use ('lightweighting'), prolong its lifetime in-use or increase the intensity of use for the product containing steel, these are questions about the stocks in-use (Pauliuk and Müller 2014). Infrastructures are currently a blind spot in the framing of climate change mitigation, and they are also an essential link to sustainable development.

The sectors of buildings, transport and industry account for more than 40 % of direct GHG emissions and nearly 65 % of direct and indirect energy-related emissions (IPCC 2014a), but to enact mitigation in these sectors requires knowledge of the stocks in-use, their age structure, current and potential future efficiency and the material resources needed to create them. The same information is also needed in assessing the requirements (and speed) of future development. It is the services from capital stocks and infrastructure that are essential to improving and maintaining quality of life, whether they be productive assets that are linked to employment or roads that enable mobility or schools, hospitals and other public infrastructures that facilitate education, health and social prosperity.

Some integrated assessment models do include the population dynamics of stocks and their characteristic efficiency – for example, the TIMES (Loulou et al.

2005) and IMAGE (Stehfest et al. 2014) models – but they do not account rigorously for materials and the dynamics of flows from stocks at the end of life. The existing assessment and modelling frameworks are not lacking in scope – they include many sectors of society in detail – but often in-use stock dynamics and cross-sectoral linkages are absent (e.g. Allwood et al. (2010)). Moreover, studies of material flows and models of aggregate stocks (Davis et al. 2010) rarely couple the material flow to a capital stock that has both a direct energy efficiency characteristic in operation and an indirect energy and emissions requirement in its own construction. These issues are also addressed in Chap. 8.

In this chapter, we discuss a socio-economic metabolic framework that can represent the interlinked nature of sustainable development and climate change mitigation from a physical perspective. It incorporates stocks and flows of infrastructures, materials, energy and emissions as well as their multiple linkages through processes that are treated using mass and energy balances. This allows for a representation of feedbacks and delays in these material and energy connections through recycling and maintenance. The metabolic framework is not intended to replace the energy and emissions framework, but rather expands it in order to reconcile CCM with sustainable development, to understand the side effects of CCM (co-benefits and risks) and thereby identify effective mitigation pathways.

2 A Socio-economic Metabolism Framework

The concept of socio-economic metabolism is relatively young in the literature. Here we interpret the term in an inclusive sense that is synonymous with social (Fischer-Kowalski 1998; Fischer-Kowalski and Weisz 1999), industrial (Ayres 1989) and anthropogenic metabolism (Baccini and Brunner 1991).

Modelling methods that incorporate anthropogenic stocks and flows can trace their lineage back to the early works of Forrester (1958), but examples where social metabolism and material and energy flow accounting are united with dynamic stock analysis are rare (Baccini and Bader 1996; Müller et al. 2004; Lennox et al. 2005; Müller 2006; Baynes et al. 2009; Müller et al. 2013; Pauliuk and Müller 2014). Even within that handful, few talk of the services from stocks that are germane to our discussion on sustainable development.

There are a number of proponents of this integrated thinking and there is a natural application in urban systems. The ‘Social-Ecological-Infrastructural Systems Framework’ of Ramaswami et al. (2012) begins with questions of urban sustainability and expands to the same scope as the socio-economic metabolism framework. They specifically include services from internal and ‘trans-boundary’ infrastructures, but the key difference from the socio-economic metabolism framework lies in the dynamic treatment of stocks in-use in the latter. In the following sections, we discuss key features of the socio-economic metabolism framework (hereafter the ‘metabolic framework’ or approach) – see Fig. 6.2.

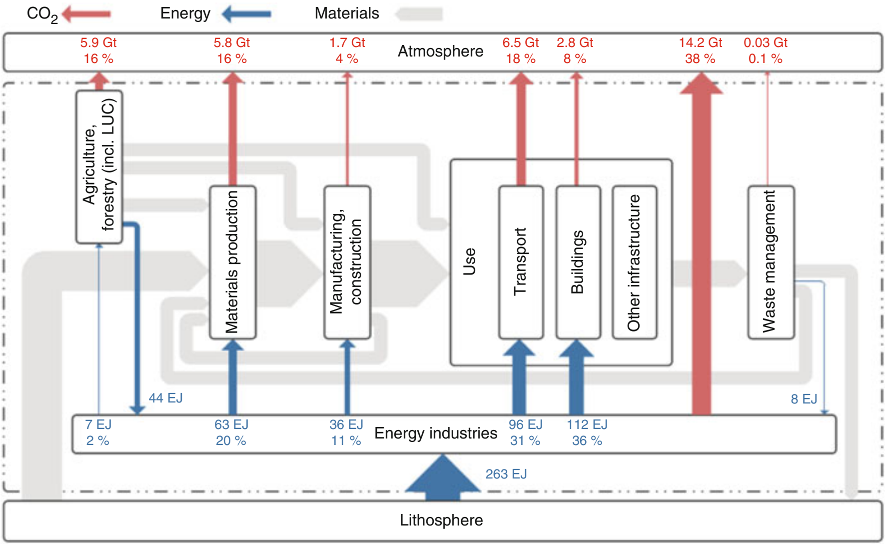

Fig. 6.2 Socio-economic metabolism framework including energy and emissions flows (as in IPCC Guidelines) and material flows. Stocks of materials and energy can occur in all segments of the diagram though in-use stocks lie within the boundary around the economic system

2.1 *Energy*

Energy and emissions flows, as calculated in the standard formulations of energy and emissions accounting (OECD/IEA and Eurostat 2005), are still essential components of the socio-economic metabolism framework. The quantity of energy required is a reliable indicator of aggregate economic activity and affluence. The way in which energy is used in society and sectors of the economy is a measure of socio-economic status and structure.

The major role of energy accounting is one of monitoring the problem: recording how much of what type of energy has been used and in which sector of the economy. This may enable assessment of excessive energy use or of overdependence on a particular fuel or an emissions-intensive means of providing energy. A socio-economic metabolism framework extends this accounting framework to have a more explanatory function by linking energy flows with in-use stocks and material cycles across sectors. From these explicit connections, we may proceed to simulations to develop possible solutions to global challenges: exploring the questions of where to effectively intervene in the system to achieve lesser impacts, greater efficiencies or other beneficial outcomes for society.

For example, about one-third of the world's population still relies on the use of animal power and non-commercial fuels. More than 1.4 billion people have no access to electricity (Global Energy Assessment 2012). If we are to redress this situation in the future, there will likely be a need for both an increase in the flow of energy and a change to the distribution of its use. This, of course, would need to be monitored, but it also begets the question of *how* this change will occur, and we are immediately drawn into the need to include the energy producing and consuming stocks in the future analysis, their interconnection and the materials that those stocks require for operation (and, in the complete picture, the energy efficiency of those stocks and the energy embodied in their constituent materials).[1]

An energy analysis is basically linear (thermodynamics prevents energy from being truly recycled in feedback loops). The energy and emissions flow emphasis of most integrated assessment models has lead analysts to view opportunities for climate change mitigation as if sectors operated separately. Energy flows into a sector; it is used in production and transformed into waste heat; and local or upstream GHG emissions are co-produced. Yet industrial materials are used in transport and building stocks, and building stocks are part of the capital stock of industry. Clearly, emission mitigation schemes in different sectors are interrelated.

The flow of materials shown in Fig. 6.2 reveals connections between sectors and shows how energy-using sectors are dependent. Furthermore, it represents physical feedbacks – material recycling – that highlight the importance of circular relations in production. Lastly, the metabolic picture reveals many more potential intervention points, within and across sectors, than in the linear conception of energy and emissions accounting in Fig. 6.1.

2.2 Materials

To record energy flows independent of materials is to mute half of the story of social metabolism. Material flows, as in the economy-wide material flow accounting EWMFA (EUROSTAT 2009) and as feedback flows in recycled material from stocks, are an essential component of the metabolic framework (see Chap. 8), and it is important to track material flows along with energy use. Materials production is an important energy user, and the production of energy technologies depends on many critical materials.

While a large portion of energy is consumed directly in providing services like thermal comfort, lighting, communication or entertainment, industry accounts for more than 32 % of global final energy use[2] (115EJ in 2005). Production of just five materials – cement, iron and steel, chemicals, pulp and paper and aluminium – accounts for more than half of industrial energy use (Global Energy Assessment 2012).

While still acknowledging the importance of energy flows in climate change mitigation, we must also recognise that energy is inextricably linked to material flows and in-use stocks. For instance, the consumption of hot clean water involves

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[1] These issues are addressed from a 'Global South' perspective in Chap. 12.

[2] This includes final electricity consumption in arc furnaces and smelters that ultimately requires a great deal more upstream primary energy.

the treatment, pumping and heating of the water, and, effectively, we consume the energy and material simultaneously whether it is in a hot shower or a hot cup of coffee. Similarly, the energy use and emissions associated with industry are linked to the movement and transformation of materials: energy may be used in a factory but the output is the material product.

It has been noted already that there is more embodied energy in household consumption of goods and services than directly consumed energy (Lenzen et al. 2004). Furthermore, as housing standards improve and operational energy use declines, there is an increasing importance of embedded emissions in the materials of dwelling construction (Giesekam et al. 2014).

Lastly, and relevant to the next section, materials exhibit dynamic path dependency. Material flows enter and stay in the system as stocks and leave, or are recycled, at a future date. Most energy embedded in products is not recoverable, but an interesting and useful feature of material stocks in-use is their latent ability to contribute to material and energy saving through recycling in the future.

2.3 The Importance of Representing Stocks

Operational efficiency and embodied energy are not simply properties of the aggregated material stock but of individual items making up infrastructure and other artefacts (appliances, durable goods, etc.). These stocks contain a great deal of material, but they also have discrete lifetimes and often interact across sectors to supply services to society. This key point has been made by Fischer-Kowalski and Weisz (1999): ‘physical infrastructure (buildings, machines, artefacts in-use and livestock)’ is ‘core to our understanding of the society-nature interrelation.’ In-use stocks represent large monetary investments and determine the long-term dynamics of social metabolism. Through their long lifetime in-use, they are responsible for lock-ins of lifestyles and emission pathways.

Urban in-use stocks also relate to the density and accessibility of urban spaces and the capacity and utility of urban systems such as public transport or water supply systems. A study of global cities over 10 years (Angel et al. 2010) revealed that recent trends are away from denser cities, and the implications in both the industrialised and developing world are for cities to take up yet more space and for more infrastructure to be needed to fill and connect that space.

Stocks and flows play different roles over different time scales. Over the short-term (less than 5 years), physical and economic flows can change with the vicissitudes of markets, income (GDP), prices and events. Over the long-term, deeper structural changes related to population dynamics, urbanisation and infrastructure development, long-run economic policy, cumulative savings, resource depletion and institutional arrangements are more connected to the development of stocks. Thus, long-term change is recorded in the quantity and quality of in-use stocks, and existing stocks and systems of stocks influence the long-term future. This is valid from both the metabolic and the wealth and income perspectives (Piketty 2013).

Stocks and flows are certainly interrelated. Flows are the 'material income' to a system, and any net addition to stocks (NAS) is limited through the conservation of mass by direct material input (DMI) minus domestic processed outputs (DPO) minus exports. Yet, the use of stocks by society determines the resource flows needed to operate, maintain or expand the physical stock. The services from stocks of infrastructure, machines and durable goods are closest to the interests of society; the socio-economic metabolic framework is driven first by stocks. Flows of resource inputs and waste outputs are driven by the need for services provided by stocks rather than the demand for the flows themselves (Müller et al. 2004; Pauliuk and Müller 2014). For example, travel by automobile requires a flow of energy, but it is the stock (the automobile) that enables the conversion of energy into the service of mobility determines the amount and type of fuel used and resulting emissions.

Stocks in-use record the cumulative resource flows – materials and energy – embedded in the infrastructure and artefacts of the socio-economic system. Through their role in production, the age and efficiency of stocks are key factors in the operational consumption of resource flows in the economy and related GHG emissions. At the same time, the services from stocks are key for social and material development.

3 Problem Shifting

An important issue in responding to global challenges is the danger of 'problem shifting': the potential for an intervention that alleviates one challenge to exacerbate the response to another. Without an integrated approach that encompasses stocks and flows of materials and energy, such a trade-off is underestimated or even invisible. What follows is an example from Müller et al. (2013) using an indicator for the carbon footprint of infrastructure stocks, the 'carbon replacement value' (CRV) of the stocks, which is defined as the carbon emissions required to replace an existing infrastructure stock or to build a new infrastructure stock using currently available technologies. Müller et al. (2013) based their CRV on upstream carbon emissions starting with primary production, CRV_P. This indicator is used to estimate the carbon emissions caused by developing nations if they were to converge on the level of service provided in industrialised nations. The CRV_P for scenarios of infrastructure development was calculated using a metabolic approach that incorporates stock dynamics.

3.1 Sustainable Development and the Carbon Budget

Emissions from the operation of infrastructure are generally considered to be the main concern in the standard energy and emissions approach to GHG accounting: the models used, such as Davis et al. (2010), represent infrastructure stocks as energy users and GHG emitters but omit the energy and emissions embodied in the stocks. However, for the developing world to converge on the quality of life enjoyed in the industrialised world by 2050, there will need to be a significant increase in the material and monetary quantity of infrastructure stocks. If we are to use current energy sources and technology to construct them, this must lead to a large carbon impost.

To estimate the GHG emissions from the materials needed in such a development scenario, Müller et al. (2013) used data on the key materials of steel, aluminium and cement (other materials having either less associated emissions or less importance in infrastructure stocks). They found that current $\mathrm{CRV_P}$ is similar for most industrialised countries at a level of about 50 t CO_2 per capita. Assuming a population growth from currently 6.8 to 9.3 billion, the direct material requirement for infrastructure and other assets needed to maintain or improve human welfare would involve an indirect carbon footprint $CRV_P = 350$ Gt CO_2 (see Fig. 6.3). The cumulative emissions during the 2000–2050 time period cannot exceed 1000–1440 Gt CO_2, if we are to have a 75 % or 50 % probability of limiting warming to less than 2 °C, respectively (Meinshausen et al. 2009). About 420 Gt of this amount has already been emitted between 2000 and 2011 (IPCC2014a) which leaves an emissions budget of approximately 600–1000 Gt CO_2 for the period from 2012 to 2050. Just the emissions embedded in the stock yet to be built therefore constitute 35–60 % of the remaining carbon budget, provided developing countries invest in built environment stocks similar to industrialised countries and use currently available technology. This leaves precious little in the carbon budget for using the stock and emissions beyond 2050.

There is a premise to these calculations that should be acknowledged that achieving Western-style infrastructure stock is a desirable endpoint of sustainable development and that obtaining the same level of services from infrastructure and in-use stocks involves the same intensity of resource use as seen currently in the developed world. The former assumption is certainly debateable in terms of environmental sustainability, and the latter is not necessarily the case as, quite apart from probable technical improvements, it is possible to realise a better quality of life without the need for a high-income, high impact society. As a model for this, there is a group of countries in the so-called Goldemberg corner that have relatively high income and long average life expectancy with low-carbon lifestyles (Steinberger et al. 2012).

The salient point, however, is the significant trade-off between the aims of sustainable development and climate change mitigation. The very poor access to basic infrastructure in developing nations is untenable. If we are to alleviate this situation, then industrial development and urbanisation in these countries will dominate growth in infrastructure construction for several decades; this will increase global material demand and thereby produce GHG emissions.

Problem shifting is not limited to the issues of developing nations. While attempting to depress the carbon intensity of production and consumption, we face increasing material demands, sometimes for critical materials. Hence, it is important in any scenario analysis of climate change mitigation to include materials and anticipated large-scale in-use stocks of materials.

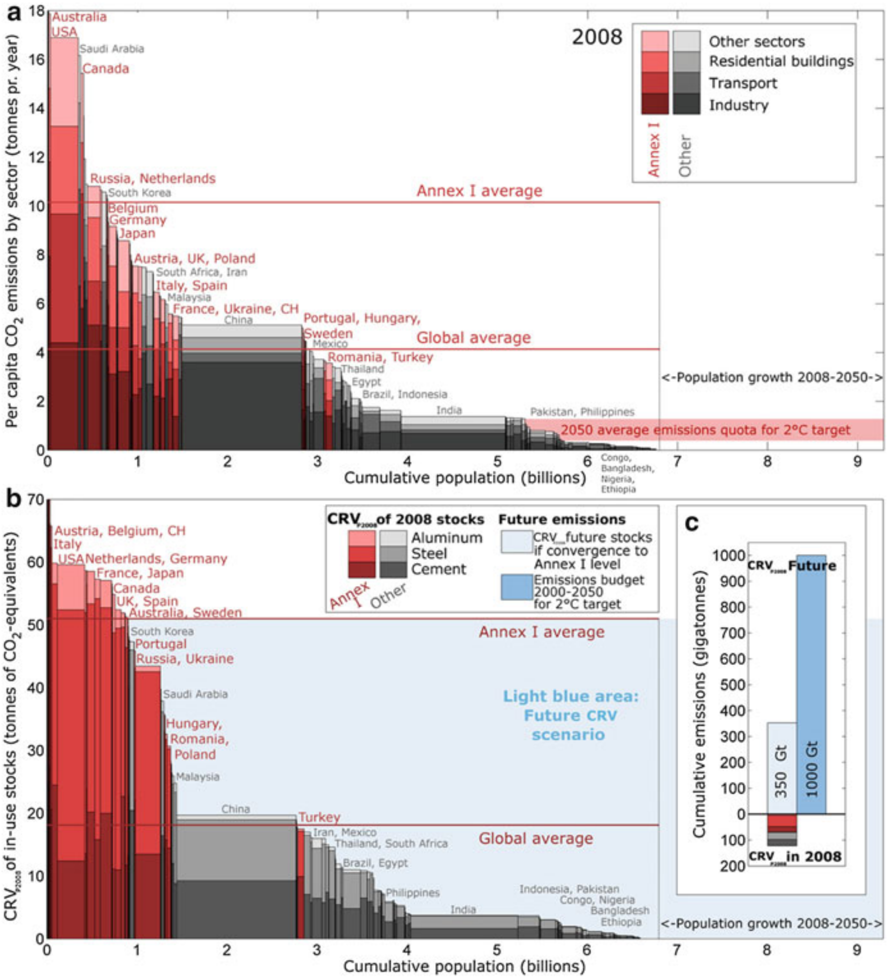

Fig. 6.3 (**a**) Total fuel-related per-capita CO_2 emissions by country (*red and grey bars*) compared to the global per-capita emission level in 2050 to remain within the 2 °C target with a 50–75 % probability (*red horizontal bar*); (**b**) CRV_P at 2008 per capita of existing stocks by country (*red and grey*) and of as-yet unbuilt stocks if developing countries converge on the current average Annex I level (*light blue*); (**c**) comparison with emission budget for the period 2000–2050 to reach the 2 °C target with a 75 % probability. Of this emission budget (1000 Gt CO_2), approximately 420 Gt CO_2 was already emitted during the period from 2000 to 2011 (Graphic reproduced from Müller et al. 2013)

One problem is that many renewable energy technologies are reliant on critical minerals, for example, neodymium in wind turbines and indium in thin film solar cells. Scenarios based on widespread implementation of wind, solar and other alternative means of generating electricity shift the problem of decarbonising the energy sector to one of material criticality. Material criticality is not to be confused with material scarcity. Material criticality may be measured using two orthogonal dimensions: the quantity or importance of a material in an activity and the risk of supply interruption. Criticality can be represented in a matrix format using these measures, as shown in Fig. 6.4. This analysis identifies a few mineral elements that are at high risk for supply disruption in the United States, including the rare earth elements neodymium and dysprosium used extensively in permanent magnets that enable a number of lightweight electronics and ‘green’ energy technology.

Despite their name, ‘rare earth metals’ are not as limited in supply as, for comparison, platinum or palladium. Criticality can be a complex function of factors such as geographical distribution of reserves and stability of government in the nation owning those reserves (Dawson et al. 2014; Roelich et al. 2014). Although rare earth elements are often found in other metal ores, e.g. zinc, 95 % of the world’s current rare earth metal supply comes from China and 72 % of the known geological reserves of dysprosium are also in China. Criticality is sensitive to such a monopoly and one uncertainty is the speed at which new mines can be opened outside of China, but another part of the supply issue is the limited opportunities for recycling before 2050 due to the long lifetimes of end-use products. These issues are not limited to critical materials; see, for example, Kushnir and Sandén (2012) on lithium supply. Roelich et al. (2014) examined electricity system transitions in the United Kingdom in this light, with a focus on neodymium. While supply disruption was anticipated to decrease by almost 30 % by 2050, the criticality of low-carbon electricity production increases ninefold because of an increasing demand for neodymium across a range of technologies.

Economists could argue that more demand will raise prices and thereby make it economic to exploit more reserves. Whether or not this is valid, and whether or not production is sufficiently responsive to changes in demand, the challenge remains: over the next human generation, large infrastructure investment decisions will be made in developing nations, and unless they have affordable greener options, they will revisit an industrial history in a way that the available carbon budget does not permit.

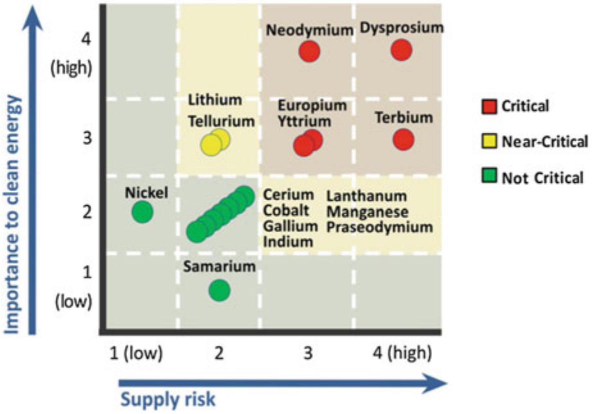

Fig. 6.4 Medium-term (5–15 years) relation of supply risk to the importance in clean energy technologies (From Fig. 8.2 in the US Department of Energy *Critical Materials Strategy* (USDOE 2011))

4 Effective Policymaking: The Case of the Aluminium Sector

The preceding sections expanded on the challenges of climate change mitigation and the physical aspects of sustainable development. Effective policy that enacts responsible management of energy, emissions and materials needs to consider:

- Increased future demand for services from infrastructure and other fixed capital – such as carbon capture and storage (CCS), water treatment plant, roads and renewable energy technology – nearly a billion new dwellings globally
- The boundaries imposed by emissions reduction targets
- Material resource use and availability

In contrast to some adaptive strategies that aim for resilience through flexibility and reversibility in investments and even reducing the lifetime of investments (Hallegatte 2009), climate change mitigation is about commitment to long-term change: setting in place the economic, institutional and physical structures to enable a sustained transition to a low-carbon future. The first priority is *effective* interventions to limit climate change (UNFCCC 2011), followed by the question of whether a response is efficient in terms of cost or resources required.

What are the options for effective climate change mitigation policy and how does the metabolic framework generate answers or enable assessment? We use the global aluminium sector to illustrate a range of policy actions addressing technical and behavioural change. The energy intensity of producing new aluminium makes it a major contributor to GHG emissions, and there is also the need for aluminium in the future infrastructure stocks of both the industrialised and developing world.

Stabilising global average temperature at 2 °C above pre-industrial levels by 2050 has been translated into a general reduction of global GHG emissions of 50–85 % below levels in 2000 (IPCC 2007). Reducing the emissions from the aluminium sector by 50 % would entail a reduction in emissions *intensity* of nearly 85 % because of the expected threefold increase in global demand for aluminium by 2050 (IEA 2009).

Under these targets, Liu et al. (2013) analysed mitigation options for the aluminium industry through estimating demand in current and future in-use stocks. Their dynamic stock-driven model captured global flows of aluminium from reserves to post-consumer scrap (shown in Fig. 6.5) and calculated direct and indirect (energy-related) emissions arising from each process (not shown). A 50 % reduction in emissions compared to 2000 levels at 2050 was found to be only feasible with a combination of optimistic assumptions about rates of recycling, uptake of new technology, including CCS, and low levels of aluminium in stocks needed per person (200 kg/person or roughly double the current global average). The latter assumption implies a significant contraction in access to aluminium stocks per capita in developed countries.

If developing nations were to attain the 200–600 kg/person allocation of aluminium in stocks currently observed in developed nations, the aluminium industry would not be able to contribute proportionally to the 2 °C target. These results indi-

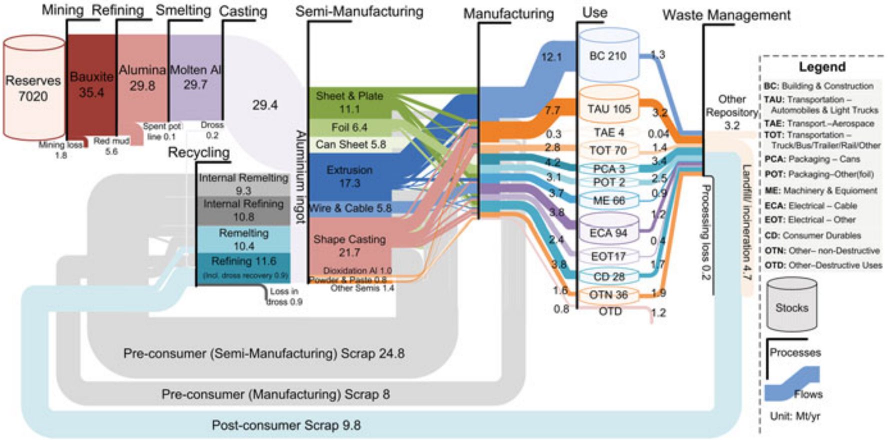

Fig. 6.5 The global aluminium material cycle (Graphic reproduced from Liu et al. 2013)

cate the magnitude of the problem at the largest scale and underline the importance of coupling mitigation strategies with material efficiency strategies. The following sections expand on a selection of strategies, again relating to aluminium stocks and their use in society.

4.1 Reducing Resource Use in the Product

Currently, global aluminium recycling is dominated by pre-consumer scrap (32.8 Mt). This is useful for reducing energy demand per unit of production by substituting for energy-intensive virgin aluminium. However, for every ton of aluminium finally consumed, approximately half a ton goes through various production processes, consuming energy and producing emissions but without ever forming a final product. These yield losses can be as high as 90 % in aircraft manufacture, and there is certainly room for improvement in reducing losses in production and using less material by design in the end product (e.g. 'lightweighting'). Allwood and Cullen (2012) have a number of other practical suggestions about reducing material and energy wasted in production in general, including diverting scrap 'blanks' to making smaller components prior to recycling and reusing components rather than recycling, e.g. steel I beams in construction can readily be recovered from demolition for direct use in new building construction.

Post-consumer aluminium scrap recycling has the potential to significantly lower total energy use and emissions, reducing energy intensity by 90 % (IEA 2009), but at present post-consumer scrap (9.8 Mt) is available mainly in the form of used beverage cans and end-of-life vehicles with 45 % of post-consumer aluminium going to waste or other repositories.

4.2 Changing the Demand for Stocks in Providing Services

Ultimately, in-use stocks provide a service and the question here is: can we use fewer stocks by using them more to obtain the same level of service? Answering this has less to do with the consumption of a particular material, like aluminium, and more to do with the characteristics and lifetime of the stock in-use. We may also seek to change behaviours in the use of stocks.

We look at the example of the stock of US automobiles in which aluminium is increasingly a material component (Ducker Worldwide 2008). Even with optimistic improvements in the efficiency of aluminium production, embodied energy in automotive parts is likely to increase (Cheah et al. 2009), but there are options for changing the way auto stocks are used.

For example, collective consumption in the form of car sharing reduces the need for people to own vehicles in exchange for the inconvenience of not having a private vehicle on demand. An analysis of the US car sharing market found members of carshare schemes reduced their number of cars per household, and on aggregate, every carshare vehicle took between 9 and 13 private vehicles off the road (Martin et al. 2010). Pauliuk and Müller (2014) also found that reducing vehicle ownership by a third, reducing vehicle use by 20 % and shifting to smaller vehicles could reduce emissions in the Chinese passenger vehicle fleet by more than 40 % at 2050 (an effect that would be greater than doubling fuel efficiency in the same period).

Another way to provide services from less stock is to have longer lived stocks and infrastructure that are more intensely used. This is counter to the current practice of planned obsolescence but is compatible with business models using adaptable design (Allwood and Cullen 2012) and more radical approaches (Chap. 8). It is sometimes argued that newer technology introduces greater operational efficiencies and so faster stock turnover is an effective mitigation strategy. However, this needs to be considered in conjunction with the emissions embodied in the stocks. Kagawa et al. (2011) demonstrated that, even based on technology from the 1990s and even when considering the longevity of less efficient vehicles, extending vehicle lifetimes in Japan has a net benefit in terms of reducing GHG emissions. Further examples are discussed in Chap. 8.

4.3 Timing

The current impacts of climate change and the prospect of yet higher global temperatures and more extreme weather should already instil urgency in policymakers to institute climate adaptation and mitigation measures. There are also long-term benefits of early action that interact with large-scale urbanisation and infrastructure growth. For example, implementing more stringent building codes now that anticipate and avoid the impacts of future climate events can have a net economic benefit over the long term (Baynes et al. 2013; Wang et al. 2015). This raises the importance of timing in effective policymaking.

Delaying mitigation action can have long-lived consequences. Retaining or augmenting carbon- or energy-intensive technology stocks locks in their emissions intensity for at least the life of those assets (IPCC 2014a). Where stocks operate in a system, e.g. roads and private transport, the inertia against change can be even greater. In many sectors, the technology to achieve cuts in emissions is already available (Pacala and Socolow 2004; IPCC 2014b), which undermines the contrary view that it may be better to wait for yet more efficient technology and hold off investment until that is available.

Returning to the example of the aluminium industry, Liu et al. (2013) explored four options to reduce resource use in products: scrap collection, minimising losses, efficiency improvement and decoupling emissions from electricity supply. They also considered three high-level scenarios of reducing the demand for stocks by assuming different saturation levels for global in-use aluminium per capita. They found that the effectiveness of mitigation options depended heavily on the stock dynamics and the timing of stock creation and scrap availability. Among the options they simulated for reducing emissions in aluminium production was CCS in decarbonising electricity. Introducing efficiency measures and CCS early (before 2030) had a greater effect because emissions related to aluminium in new building, transport and communication infrastructure were reduced. Conversely, later in the century, maximising scrap collection had an increasing benefit as earlier cohorts of stock came to the end of their lifetime.

5 The Socio-economic Metabolism Framework and Wealth

Building up the infrastructure capacity, as an essential component of wealth, also involves energy and emissions. A dynamic metabolic analysis properly represents both physical wealth in in-use stocks and the material and energy flows needed to create and maintain those stocks. Economic or physical flow measures may represent growth and development, but they are insufficient to understand long-term change and the lasting effect of wealth creation. On the basis of environmental and economic flows alone, developing nations appear highly materialised compared with industrialised countries and have lower productivity, but a more balanced assessment, taking into account physical stocks and infrastructure, can provide information on their relative socio-economic situation. In reporting and modelling sustainable development, physical in-use stocks are an essential complement to the current information on flows in the system of environmental and economic accounting.

There are conceptual parallels between the economic and environmental accounting systems even if their valuation and methodology differ. In the UN system of national accounting (European Commission et al. 2009), economists measure income as separate from wealth. Although the income measure of GDP is commonly misperceived as a measure of wealth, there is a separate ledger of assets and liabilities from which ‘net worth’ is calculated. This is entirely a calculation on values of capital stocks that has not been fully translated into the environmental extensions of national accounts. There is a substantial literature on the valuation of natural and anthropogenic capital, but there is a strong tendency to use a common denominator of monetary value or utility. Important physical information is then lost. For example, there is a world of difference between having a small amount of high quality, recently built road, and a much larger quantity of ageing, highly depreciated road that will soon be due for repair or replacement; the way capital value is determined means these two situations could be equivalent in net worth but they are very different in the services they provide and in their long-term material and energy requirements.

Concentrating on the flow measure of GDP is rightly criticised as a false measure of human well-being, which might be better defined by the accumulation of capacity to provide employment, food, education, safety and security, an approach explored in Chap. 8. That capacity corresponds more with the quantity and quality of infrastructure, productive and non-productive capital stocks. Stocks are not merely the accounting residuals of the net difference in bulk material flows. Through the services they provide, stocks are indicators of physical wealth, and our ability (through flows) to maintain and sustain that wealth is equally an important dimension of reporting and modelling the physical aspect of human well-being.

Just as seeking greater wealth by increasing GDP can produce perverse outcomes (Costanza et al. 2014), appraising environmental performance through flow measures alone is insufficient. For example, the metric of domestic material consumption (DMC) is used widely as a macroeconomic indicator of material requirements. Developing countries will always have a relatively high DMC until they attain sufficient infrastructure and capital stock to satisfy the physical demands of their socio-economic aspirations. Evidence for this comes from growth in DMC of developing nations in the Asia-Pacific region (UNEP and CSIRO 2013); for example, the DMC per capita of China has increased by 640 % over the last 40 years.

Most developed countries have achieved relative material decoupling (lower DMC/GDP) over the last 30 years (Giljum et al. 2014). Müller et al. (2006) and Wiedmann et al. (2013) have both suggested that industrialised nations have lower DMC because they have already established their major infrastructure and their population has grown more slowly than developing countries or has even saturated. However, the interpretation may not be so simple. Matthews et al. (2000) calculated NAS as the residual between input and output flows for a sample of developed nations with established infrastructure and concluded that the NAS is still 8–12 tons/capita per year. The authors attributed this to a combination of factors including lower occupancy, urban expansion and affluence.

In this chapter, we have used concepts from industrial ecology to frame problems of the long-term future in terms of both stocks and flows and show how solutions are substantially influenced by the creation of physical wealth in stocks and how stocks can mitigate (or exacerbate) impacts and deliver services to society. The socio-economic metabolism framework is intended to represent the interaction of stocks across sectors and enable a more complete integrated assessment of policy options. As in many areas of industrial ecology, data availability is a hurdle, but the socio-economic metabolism framework discussed in this chapter provides a structured way for interpreting statistics on physical stocks; automated data collection and informatics provide the opportunity to capture physical transactions alongside monetary exchanges.

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