Supplementary file for:

An overview of salient factors, relationships and values to support integrated energy-economic system dynamics modelling

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1. Economic growth and the factors of production

Exogenous growth models do not include human capital, innovation or knowledge as included in endogenous explanations of the growth process; and all economic growth that cannot be empirically explained by production factors such as capital (*k*), labour (*l*), land (*n*), and energy (*e*) is attributed to technological productivity (*A*). In exogenous growth theory, the rate of growth is determined exogenously through the savings rate in Keynesian theories (also referred to as the Harrod-Domar model after Harrod (1939) and Domar (1946)) or through technological progress in Neo-classical theories (also referred to as the Solow-Swan model after Solow (1956) and Swan (1956)). Most exogenous growth models explain growth in output (*Q*), through a combination of productivity (*A*), capital (*k*), and labour (*l*), but some models include non-renewable resources (Solow, 1974; Stiglitz, 1974; Hartwick, 1977; Dasgupta & Heal, 1979; Dixit, Hammond & Hoel, 1980) and energy (*e*) as separate production factors (Hudson & Jorgenson, 1974; Kümmel, 1982; Stern, 2000). Environmental pollution has also been included in production functions, effectively reducing technology's (*A*) balancing contribution to growth (Xepapadeas, 2005; Xepapadeas & Vouvaki, 2009).

In endogenous growth models it is assumed that human capital, innovation, and knowledge are generated within the economic system itself. Several approaches exist, namely neoclassical endogenous AK models (Romer, 1986; Barro & Sala-i-Martin, 1995), evolutionary Schumpeterian growth models of creative destruction (Aghion & Howitt, 1998), with resource, material, and energy constraints (Ayres & Van den Bergh, 2005; Ayres & Warr, 2005; Bretschger, 2005; Acemoglu et al., 2009; Warr & Ayres, 2012), and endogenous Unified-Growth long-wave models (Galor & Weil, 2000; Jones, 2001) that focus on explaining the longer-term process of economic development through a combination of factors such as technological progress and innovation, population growth and demographics, institutions, and human capital accumulation. In addition, endogenous growth models that focus on the material basis of economic growth, including the role of energy and natural resources as well as biophysical limits as governed by the laws of thermodynamics, have also been developed more recently (Smulders, 1995). Fröling (2011) specifically included energy as an input in an endogenous long-wave model.

2. Elasticities

Modelling equations for elasticities can be interpreted as follows:

$$E_d = \frac{P(dQ_d / dt)}{Q_d(dP / dt)} \quad (1)$$

- E_d, price elasticity of demand, measures the responsiveness of the quantity demanded of a good (Q_d) relative to a change in price (P) of that same good (see Equation 1). Outcomes are inelastic demand ($-1<E_d<0$), elastic demand ($E_d<-1$) perfectly inelastic demand ($E_d=0$) or unitary elastic demand ($E_d=-1$).

$$E_s = \frac{P(dQ_s / dt)}{Q_s(dP / dt)} \quad (2)$$

- E_s, price elasticity of supply, measures the responsiveness of the quantity supplied of a good (Q_s) relative to a change in price of that same good (see Equation 2). Outcomes are inelastic supply ($E_s<1$), elastic supply ($E_s>1$), no response or 'fixed supply' ($E_s=0$) or unitary elastic supply ($E_s=1$).

$$E_y = \frac{y(dQ_d / dt)}{Q_d(dy / dt)} \quad (3)$$

- E_y, income elasticity of demand, measures the responsiveness of demand for a good (Q_d) relative to a change in the income (y) of those demanding the good (see Equation 3). Outcomes are inferior goods ($E_y<0$), necessity goods ($0<E_y<1$), luxury or superior goods ($E_y>1$), or sticky goods ($E_y=0$).

$$E_{ij} = \frac{P_j(dQ_{d,i} / dt)}{Q_{d,i}(dP_j / dt)} \quad (4)$$

- $E_{i,j}$, cross-price elasticity of demand, measures the responsiveness of the demand for one good i ($Q_{d,i}$) relative to the price of another good j (P_j) (see Equation 4). Products are either complements ($E_{i,i}<0$), substitutes ($E_{i,j}>0$), or independent from each other ($E_{i,j}=0$).

$$E_{Qx} = \frac{x(dQ / dt)}{Q(dx / dt)} \quad (5)$$

$$\frac{1}{E_{Qx}} = \frac{Q(dx / dt)}{x(dQ / dt)} = 0 \quad (6)$$

- E_{Qx}, output elasticity, measures the responsiveness of output (Q) relative to any one input (x, which can be any of capital (k), labour (l), land (n), energy (e), materials (m), or knowledge (h)) (see Equation 5). Outcomes are either constant returns to scale (E_{Qx}=1), increasing returns to scale (E_{Qx}>1), or decreasing returns to scale (E_{Qx}<1) in relation to any one input factor (x), while other input factors are kept constant. Looking at Equation 6, output (Q) is said to be 'decoupled' from the input (x). These output elasticities are denoted as output elasticity with respect to capital ($E_{Qk}=\alpha$), with respect to labour ($E_{Ql}=\beta$), with respect to energy ($E_{Qe}=\varepsilon$), with respect to land ($E_{Qn}=\nu$), with respect to knowledge ($E_{Qh}=\eta$) and with respect to materials (if modelled as 'active partner' in production process) ($E_{Qm}=\mu$).

3. Macro-substitutability

Elasticity of substitution between two factor inputs or goods is measured as the percentage response of the relative marginal products of the two factors to the percentage change in the ratio of their quantities, as per Equations 7 and 8:

$$E_{xy} = \frac{d\ln(\frac{y}{x})}{d\ln(MRTS_{xy})} \quad (7)$$

where $$MRTS_{xy} = -\frac{dy}{dx} = \frac{MP_x}{MP_y} \quad (8)$$

The marginal product (MP) of an input factor is the extra output that can be produced by using one more unit of the input, keeping the quantities of other inputs to production constant.

In the case of two factor inputs, functions for the elasticity of substitution are straightforward, such as the elasticity of substitution between capital and labour (E_{KL}), between capital and energy (E_{KE}), between energy and labour (E_{EL}) or between energy and materials (E_{EM}). In the case of three or more factor inputs, nested functions are needed, such as the elasticity of substitution of capital/labour and energy ($E_{KL,E}$), capital/energy and labour ($E_{KE,L}$), energy/labour and capital ($E_{EL,K}$), capital/labour and energy/materials ($E_{KL,EM}$), capital/labour/materials and energy ($E_{KLM,E}$) or capital/labour/energy and materials ($E_{KLE,M}$).

4. Technical substitutability

From a technical point of view, substitution from one type of energy to another is rarely simple. Important factors include:

- which raw energy types (fossil fuels, renewables, etc.) or energy carriers (electricity, refined liquid fuels, hydrogen, etc.) are being substituted,
- whether sufficient reserves of previous or new energy types are available,
- whether machines (wind turbines, solar panels, oil wells and refineries, etc.) are available at low enough cost to produce the new energy types,
- whether machines (the electric grid, tankers, etc.) are available with enough capacity to transport the new energy types, and
- whether machines (factory machines, consumer goods, etc.) are available at low enough cost to consume the new energy types.

How long do economy-wide energy transitions take? Fouquet (2010) noted that, historically, primary energy substitutions (such as wind-to-coal and coal-to-oil) take several decades from the beginning of diffusion into the economy to dominance in the economy. Previous energy substitutions were accomplished because new forms of energy were perceived by consumers to be both (a) better and cheaper for achieving human needs and (b) worth the investment in new energy conversion devices. It takes time to transition from one energy source to another, in part, because of the need to convert emplaced capital (from sailed ships to coal-burning ocean liners, for example). And, historically, total energy consumption was greater after major energy substitutions occurred. (For example, see Figure 7 in Fouquet and Pearson (2006) which shows that consumption of lighting increased dramatically in the United Kingdom after the change from tallow candles to gas.)

If integrated energy-economy modelling is to focus on understanding pathways and policies for transitions from fossil fuels to renewable energy sources, recent work by Jacobson and Delucchi (Jacobson, 2009; Jacobson & Delucchi, 2009; Delucchi & Jacobson, 2011; Jacobson & Delucchi, 2011) is salient. They evaluated requirements for a complete world energy substitution to wind, water, and solar (WWS) primary energy sources and a fully-electric energy carrier system. Their work highlights the nature of the challenges of capital dependencies. With some exceptions (such as ocean shipping, long-distance road freight transport, and air travel), the substitution to an all-electric energy system is technically achievable today but requires massive infrastructure investments and comes with significant cost.

An incomplete list of factors involved in the WWS substitution proposed by Jacobson and Delucchi (2011) includes:

- Capacity and reliability of the electrical grid when significantly higher penetration of intermittent sources (wind and solar, in particular) and increased power transmission distances (required when generation locations are far from consumption locations) are present.

- Complete substitution in the transportation system from internal combustion engines using refined liquid-fuel energy carriers (gasoline, diesel, and aviation fuels) to electric motors with storage batteries.
- Availability of investment capital, especially for constructing millions of new wind turbines, billions of solar panels, millions of electric motors, millions of fuel cells, and a significantly-enhanced electrical grid required by the WWS plan.
- Availability of investment energy for manufacturing new energy production and consumption machines.
- Availability of raw materials such as rare earth metals for electric motors, lithium for batteries, and platinum for fuel cells.

A partial list of factors that are underestimated or not considered by Jacobson and Delucchi (2011), and will increase the costs of a WWS system, includes:

- compensation for owners of obsoleted but still-useable assets (fossil fuel power plants, gasoline and diesel vehicles, oil and gas pipelines, gas ovens, etc.) (Tverberg, 2009)
- erosion of value for owners of stock in companies with obsoleted assets (Tverberg, 2009)
- an unspecified amount of energy storage at extremely low cost (Brook, 2011)
- significant underestimate of costs for an enhanced electrical transmission grid (Preston, 2011)
- operations and maintenance costs (Moriarty, 2011)
- underestimate of future electricity consumption rates (Moriarty, 2011)

The Global Energy Assessment (GEA) (Johansson et al., 2012) suggests the following policies to achieve energy substitutions from fossil fuels to renewable energy carriers:

- Removal, or at least substantial reduction, of subsidies to fossil fuels without carbon capture and storage.
- Stimulation of development and market entry of new renewable options.
- Emphasis on energy efficiency in all end-use sectors.

The GEA's plan would require additional investment in the energy sector amounting to 2–3% of GDP per year for the next 40 years (or longer). If we accelerate the GEA plan to match the timescale of the WWS plan (20 years) and if we assume that the costs scale linearly, the GWS plan reaches 4–6% of GDP per year. Thus, the WWS and GEA plans are roughly comparable in terms of investment cost to purchase substitutability of renewable energy sources for non-renewable energy sources.

5. Energy cost share

The components of energy cost share in a given time period (CS) are energy type (i), energy price for each type (p_i), energy consumption rate for each type (Q_i), and GDP. The energy cost share for an economy at a given time t is calculated by Equation 9.

$$CS_t = \frac{\sum_i p_{i,t} Q_{i,t}}{GDP_t} \tag{9}$$

Additional research is needed to (a) isolate the economic effects of energy cost shares for different energy types (coal vs. oil, for example), (b) assess differential energy cost share effects for regional economies, (c) understand the evolution of energy cost shares as an economy develops, and (d) understand the dynamic system interactions with other elements of the economy that lead to a stable corridor of energy cost share over time.

6. Power plant efficiency

Power plants are heat engines that take in heat at a given rate (Q_H) at high temperature (T_H) and reject heat at a different rate (Q_C) at low temperature (T_C) as they produce a rate of final energy, work (W) in the form of electricity.

The thermal efficiency of a power plant's heat engine is given by Equation 10:

$$\eta = \frac{W}{Q_H} \tag{10}$$

The theoretical maximum efficiency of a heat engine (Carnot efficiency) is a function of its operating temperatures and is given by Equation 11:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H} \tag{11}$$

The existence of an upper (Carnot) limit to heat engine efficiency indicates that increasing the efficiency of heat engines cannot, by itself, completely address the challenge of depleting non-renewable energy sources.

A finite-sized plant that operates at the maximum efficiency (η_{Carnot}) for a given T_H and T_C has no output: the rate of production of sellable energy (W) is zero. Thus, there is an efficiency–power tradeoff. For an existing plant with non-zero fuel, operations and maintenance, or capital recovery costs, there is an economic incentive to produce energy at a high rate (W), thereby obtaining revenue to cover costs and turn a profit. Thus, the efficiency–power tradeoff is made in favour of power at the expense of efficiency in real-world plants.

Curzon and Ahlborn (1975) were the first to quantify the efficiency of a heat engine operating at maximum power output, i.e. a heat engine operating at the point where it is producing sellable energy at the maximum possible rate (Equation 12):

$$\eta_{max\ power} = 1 - \sqrt{\frac{T_C}{T_H}} \qquad (12)$$

A power plant *maximises* revenue when it operates at maximum power ($\eta_{max\ power}$). In contrast, a power plant that operates at maximum thermodynamic efficiency (η_{Carnot}) *has no revenue*. Real-world power plants operate near the maximum power conditions ($\eta_{max\ power}$), because there is an economic incentive to do so.

The difference in efficiency for power plants operating at maximum power ($\eta_{max\ power}$) and maximum efficiency (η_{Carnot}) for the same T_H and T_C is significant: a hypothetical coal-fired power plant operating with T_H = 565°C (838K) and T_C = 25°C (298K) will have η_{Carnot} = 0.64 and $\eta_{max\ power}$ = 0.40.

Energy services efficiency (η_{ES}) can be defined as follows (Equation 13):

$$\eta_{ES} = \frac{ES}{E_{primary}} \qquad (13)$$

where ES is the rate of energy service provision (such as passenger-kilometers/year) and $E_{primary}$ is the rate of primary energy (in units of GJ/year) needed to supply the energy service, its primary energy footprint. Heun, Owen, and Brockway (2018) have developed new techniques to calculate the primary energy footprint of energy services.

7. Energy services efficiency

The energy intensity of an economy (*I*) during period *t* is defined as follows (Equation 14):

$$I_t = \frac{E_{primary,t}}{GDP_t} \tag{14}$$

where $E_{primary,t}$ is primary energy consumed by the economy and GDP_t is gross domestic product in time period *t*. We note that when the first derivative of energy intensity with respect to time (dI_t/dt) is less than zero, an economy exhibits relative decoupling of economic activity from energy consumption. If the following (Equation 15) is true

$$\frac{1}{E_{Qe}} = \frac{Q(dE_{primary,\,t} / dt)}{E_{primary,\,t}(dQ/dt)} = 0 \tag{15}$$

then the economy is said to exhibit absolute decoupling from energy consumption.

The rebound effect (*RE*) is defined as follows (Equation 16):

$$RE = 1 - \frac{S_{actual}}{S_{expected}} \tag{16}$$

where S_{actual} is the actual energy savings and $S_{expected}$ is the expected energy savings from an energy services efficiency intervention. A 10% rebound effect indicates that only 90% of an expected energy reduction has been achieved for the same level of service provided.

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