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A Framework for Characterising an Economy by its Energy and Socio-Economic Activities

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Abstract
Investigating the energy use of an economy in a resource-constrained world requires an understanding of the relationships of its economic, social, and energy-use elements. We introduce a novel whole-economy analytical framework which harmonises multiple national accounting procedures. The economic elements align with the international system of national accounts. In a modular fashion, our framework curates and maintains disparate accounts (economic stocks and flows, energy use, employment, transport) in parallel, but retains each of their unique measurement unit and accounting requirements. We present the UK as a case study to demonstrate how the data organisation and conditioning procedures are generic and will allow model development for other countries. The framework is capable of exploiting time-series ratios between different measurement units to give key functional relationships that vary gradually over time, are robust and thus useful for analysing national policy complexities such as decarbonisation, employment, investment and balance of payments. We use novel Sankey diagrams to visualise snapshots of the whole system. The framework is neither an exclusively economic, physical, nor social model. It upholds the integrity of each world-view through retaining their unique time-series datasets. As this framework is agnostic to the way in which a nation organises its economy, it has the potential to reduce tension between competing models and philosophies of economic development, environmental refurbishment, and climate change mitigation.

Keywords: Bio-physical, Energy Systems Modelling Fixed Capital, GDP, System of National Accounts.

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Box 1. Abbreviations and acronyms

BPM6	Balance of Payments and International Investment Position Manual, Sixth Edition
CFC	consumption of fixed capital
CPC	Central Product Classification
CVM	chain volume measure
FC	fixed capital
FCF	fixed capital formation
GDP	gross domestic product
GFCF	gross fixed capital formation
GVA	gross value added
HGV	heavy goods vehicles
ISIC	International Standard Industrial Classification
LGV	light goods vehicles
NPISH	non-profit institutions serving households
P-codes	transactions types of an economy
S-codes	sectors types of an economy
SEEA	System of Integrated Environmental and Economic Accounting
SNA	System of National Accounts
SUTs	Supply and Use Tables

Box 2. Units

Status measures:

- All physical assets refer to net fixed capital data so are in monetary units, £m (million pounds) or £b (billion pounds). These are inflation-corrected back to 1990 prices in accord with CVM (chain volume measure) source data.
- Population and employment as thousands of capita.
- Jobs as thousands and distinguished from employment.
- Households and dwellings as thousands.

Volume flows:

- Time step is annual so volume flows are per year (/yr).
- All economic volumes are derived from national accounts data so are in monetary units, £m/yr (million pounds) or £b/yr (billion pounds). These are inflation-corrected back to 1990 prices using the GDP deflator. Fixed capital formation is corrected by individual FCF deflators for each industry.
- Volume flows of energy fuels are in PJ/yr. Heat of combustion uses the lower heating value or net calorific value, for which heat in water vapour is not recovered. (There is no difference for combustion of coal since it produces only CO_2.)
- Volume flows of electricity are in TWh/yr.
- Travel is as vehicle-, passenger- or (freight) tonne-km/yr.

Context for monetary measures:

- For assets, £m of fixed capital.
- For economic production, £m/yr at basic prices (also known as factory prices or producers' prices).
- For economic final supply and demand, £m/yr at purchasers' prices (also known as market prices or final prices).

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1. Introduction

Researching the possible economic, social and environmental impacts of choices made by economic and physical policymakers and planners is critical to improving the decision-making process (Leontief, 1993; Ayres, 2008; Baptist & Hepburn, 2013). We introduce an analytical method capable of assessing national investment capacity in technical infrastructure such as for energy generation. The method addresses the systemic economic and bio-physical (natural resource) implications of such investments, to complement current macro-economic modelling approaches.

Where conventional economic tools – which deal purely with abstract flows of money and the efficient allocation of capital – fail to provide important insights, an investigation of the relationships between economic volume flows and more fundamental entities such as material flows, infrastructure, and energy is required (Leontief *et al*., 1985; Pedersen & de Haan, 2006; Ayres & Warr, 2012). We argue that a purely economic approach needs to be coupled or reconciled with physical materiality to develop an understanding of the important constraints and opportunities they impose on an economy's trajectory. For example, standard economic metrics may not consider properly exhaustible natural resources (Diaz & Harchaoui, 1997) and can lead to perverse subsidies (Baptist & Hepburn, 2013). Similarly failure to consider the important role of ecosystem services in the economic production process can lead to oversights and poor decision-making. We recognise the value of ecosystems services, but there is not as yet a consistent and satisfactory way in which to include ecosystems services in national accounts. However, Edens and Hein (2013) have made recent progress.

A previous difficulty of gathering time-series data is now being addressed, in part through 'open' Government and in part by modern information technology systems, enabling historic and contemporary data to be made readily available (ONS, 2012a, 2012b). This frees the modeller from the constraints of equations derived solely from theoretical considerations. Mining data to test and propose robust relationships, and allowing changes in the structure of relationships over time, is a matter of asking relevant and tractable questions, which is at the heart of the approach we describe.

Although it is not commonly used outside of economics, the concept of 'volume' in national accounts follows from separating price inflation from value (Lequiller & Blades, 2006). A standard economic approach considers the flow of money through a closed loop system initiated by household expenditure on goods and services provided by commercial and industrial activity, who in turn obtain intermediate commodities from other industries. The only independent inputs to the system are capital and labour.

1.1 The Bio-physical Approach

In contrast a bio-physical approach considers the economic system to be open, with natural resource inputs (energy and materials) comprising the essential 'free' input required to produce and activate capital and maintain labour, as intermediates in the value-adding production process. As an open system all energy and materials leave the system as low-energy high-entropy wastes. The volume measure of products from national accounts is taken as a good proxy for quantifying the amount of these products (Lequiller & Blades, 2006; United Nations *et al*., 2009). Jobs provided by industries are regarded as another necessary input in the process flow. The units for jobs are simply the number of employees at one time.

There has been interest in hybrid models to bridge the top-down and bottom-up divide (Hourcade *et al*., 2006); the bottom-up part has principally been considering technology-driven models. Our approach accounts for the energy demand (positive or negative) created by the adoption, deployment, and use of energy within an economy with physical and economic constraints. Taking the volume flows approach is to attempt a quantification of the capacity of an economy to function as well as to achieve major changes outside of the business-as-usual case. Examples include understanding the capacity of a nation to undertake (or respond to) military conflict, and to increase the standard of living for citizens.

The motivation for our paper is to understand and consider the capacity, bottlenecks, and opportunities to undertake a transition to alternative economies, be they low-carbon, low-growth, full-employment, or based on entirely new industries. Our aim is to work within economic constraints such as those imposed by limited Gross Fixed Capital Formation (GFCF), the upstream need for fixed capital and those imposed by the availability of energy (exergy). The SEEA (System of Integrated Environmental and

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Economic Accounting) accounting system contrasts with this by showing how natural resources and ecosystem inputs are drawn into the economy, and products and residuals are generated (European Commission *et al*. 2012). The framework is consistent with the System of National Accounts (SNA; United Nations *et al*., 2009), but unlike SEEA not a satellite to it (United Nations, 2011). We are not producing an accounting methodology, but a framework for analysing accounting data that will lead towards the specification of a model.

We want to understand the trade-off between complexity and how much information is 'just enough' to gain insight into how an advanced economy can make a critical transition. This necessitates a deep understanding of the relevant data and its limitations. A robust and flexible model for data analysis is required. The aim of our research is to show how data, which are readily available in many nations, can be used to find some of the key determining factors affecting how the investment feedback from economic output operates. Although we use data for the UK as a case study, we consider this as a generally applicable method. We are taking a systems approach which helps to single out the strongest and most significant elements affecting economic activity – the principal characteristics. It is important to note that (1) despite a heterodox approach to economic modelling and (2) the consideration of material/energy flows from a physical perspective rather than purely monetary, the analytical framework which we introduce is strictly aligned with the system of national accounts. This provides an important means of interpreting the effects using a language with which economists and the wider public are familiar.

1.2 The Structure of this Paper

This section spells out the key stages in the method which build up our analysis framework. The important point to make clear is the thread of how we make the problem tractable and simplify it sufficiently enough to yield a useful tool, yet one which remains powerful.

Section 2: demonstrates how the internationally accepted data and national accounting methods are exploited, and how they are conditioned to meet the needs of the research question.
Section 3: shows why, and justifies how, the large datasets are aggregated into physically meaningful groups and (data) flows. We show this for a single group (industry).
Section 4: expands this to all economic sectors, adding in the flows and relationships between industries. This is done in two steps to aid understanding.
Section 5: populates the skeleton with data for all sectors for a single year to show how the data can be visualised.
Sections 6 and 7: exploits the historical data to show useful ratios which naturally emerge from the analytical framework, and how this can be used to make physically justifiable projections.

The final sections draw together our conclusions and suggest how this framework will be operationalized in a dynamic model.

2. Data Sources

The framework is entirely data-driven. The concept of mapping the flows of economic outputs, energy, jobs and transportation through and around an economy requires knowledge of national accounts together with national statistics for employment, energy and transportation. Being data-driven means that the framework must adapt to how the data is structured. The natural source of economic data is national accounts. The accounting terms we use conform to the SNA because its recommendations cover how to compile measures of economic activity in accordance with strict accounting conventions and have international coverage.

We use the concept of industries which groups companies and organisations having the same principal activity, and follow the International Standard Industrial Classification (ISIC, United Nations 2008a) to identify these industry groupings. For transactions in goods and services we use the Central Product Classification (CPC; United Nations, 2008b). We note that while the CPC is a classification based on the physical characteristics of goods or on the nature of the services rendered, the ISIC for industries differs because it takes into account the inputs and the technology used by the production process. The definition of expenditure (final demand) by type of consumption follows SNA. Time-series data can be built up from annual Supply and Use Tables (SUTs) that give a comprehensive view of the components making up GDP (United Nations *et al*, 2009).

2.1 Data Conditioning

Most data are available annually and grouped by kind of activity according to ISIC or its equivalent. The Gross Value Added (GVA) data are available for the UK over the period 1990-2010; for 2003-2010 directly from input-output tables (ONS, 2012c) and for 1990-2002 extracted from the annual editions of 'The Blue Book'[1] (ONS, 2012b). However the industrial classification was changed in 2011 and backdated to 1997. Data prior to 1997 have been scaled to give continuity. Supply and Use Tables are not available for 1990-1991. These years have been extrapolated back from 1992 and scaled to sum to GDP for those years.

Investments in assets which last longer than one year are referred to as – variously – 'fixed assets', 'capital stocks', and 'fixed capital'. We use Fixed Capital (FC) throughout. Data for the GFCF – the Fixed Capital Formation (FCF) total requirement – are published for all years (ONS, 2010). However, the FCF components by each industry were not published for 2010 at the time of writing. The data has been extrapolated from 2009 and scaled for the sum to equal to the total for 2010.

The analysis framework depends on using metrics that are independent of time; therefore we have applied the GDP deflator across all economic measures – except for fixed capital. We make an exception for the formation of fixed capital because our framework handles fixed capital separately from economic flows, and we assume stocks of fixed capital to be an effective proxy measure for their size.

3. Methodology

Structuring the relationships of the flows to make the problem tractable is complex. This section explains the way we have aggregated the flows described in the resulting sections.

3.1 Level of Aggregation

Some industries are larger than others (by many metrics) and need to be distilled out from the complete dataset. By the same token, smaller entities can be aggregated together. This enables us to analyse the static relationships within the UK economy. We aggregate the list of industries under ISIC down to seven:

- agriculture, forestry and fishing ('agriculture'), ISIC section A,
- mining and quarrying ('extractive industries'), ISIC section B,
- supply of electricity, gas and water supply and water remediation services ('utilities'), ISIC sections D and E,
- manufacturing, ISIC section C,
- construction, ISIC section F, and
- service industry, ISIC sections G to U.

Dwellings contribute to the economy by virtue of rental. They form the seventh category, though not technically an industry:

- dwellings, CPC class 7211.

3.2 The Functioning Entity of One Industry

Our premise is that production cannot proceed unless infrastructure first exists, thus we characterise the economy by considering its fixed capital that make up the physical infrastructure. From a system point of view, infrastructure takes time to grow and establish, thus setting a ceiling in the short term to constrain production. Fixed capital giving rise to production – grouped by type of activity – are called industries; examples are power stations under the utilities industry, factories under the manufacturing industry, and commercial offices, schools and hospitals under the service industry. Dwellings are also fixed capital, but are not regarded as part of industry.

A schematic of the important flows related to fixed capital is illustrated in Figure 1. Flows at the top change the stock of fixed capital. Flows on the left are inputs to the fixed capital. By the industry's activity

[1] The 1990 edition is not available on-line at the present time.

(production), these are transformed into output on the right. We quantify these flows in the most relevant way while accepting that the types of measurements (of flows) are only proxies for real flows. The only stock of output is products used for FCF – this total output being GFCF. All other outputs are consumed within one accounting year. All industries have an economic output (by definition) which is their production. The sum of production over all industries in an economy (the gross value added) is the production approach, or output form, of the GDP (at basic prices) of the economy.

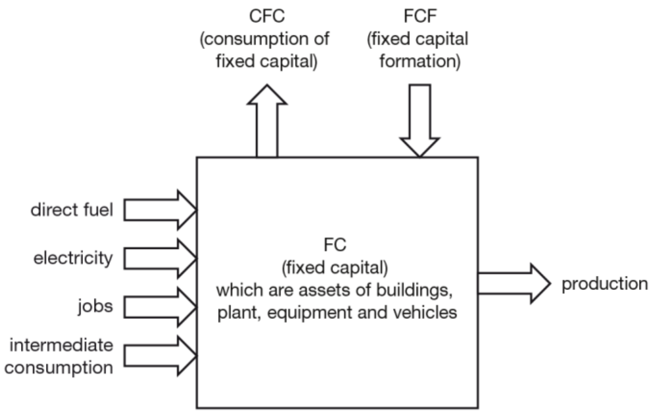

Figure 1. A schematic of the flows relevant to any single industry (one type of activity) within an economy.

The fixed capital for one industry consists of a large number of establishments and equipment at various ages, and can be quantified by its replacement cost. Over a year, say, the fixed capital will decrease as a result of physical deterioration or normal obsolescence, which is referred to as Consumption of Fixed Capital (CFC). Thus we can think of the fixed capital that goes to make up an industry as having an average lifetime. The fixed capital for one industry is constantly being replenished by investment, referred to as FCF. When the level of formation equals the level of consumption the size of the industry is constant. This is an example of stocks and flows, since FC, FCF, and CFC all use the same units, though formation and consumption include the denominator of time. To complete this picture of one industry, we consider its inputs that are necessary for production. The primary inputs are energy (as fossil fuels or electricity) and jobs – each are accounted for and tracked separately within the framework. This modularisation of data streams within our framework allows for new datasets to be added, or for further disaggregation of those already included. In this way, data on the volume flows of raw materials and water also could be included explicitly. At present, raw materials and water are implicitly accounted for by the energy required for their processing and their monetary value. Goods and services used in the course of production – intermediate consumption – are provided by other industries.

Each of the concepts in Figure 1 is quantified. The choice of units (Box 2) is important, and is discussed below. Note though that units of inputs and outputs are all different. In contrast to stocks and flows of the fixed assets, process flows describe inputs being converted to outputs.

3.3 Representing Economic Volume Flows

The primary objective of the SNA is not simply to provide guidelines on measures of changes in prices and volumes but to assemble a set of interdependent measures that make it possible to carry out systematic and detailed analyses of inflation and economic growth (United Nations *et al*., 2009). To this end, an important and valuable feature of national accounts is their concept of 'volume' for products. The accounts are constructed in price-independent volume terms. Volume measures are derived from total expenditure on a product by applying a price or deflator index. While price indices are derived for many sub-sets of products, we use the single over-arching GDP deflator (except for fixed capital and the point at which FCF changes fixed capital). This weights the individual deflators according to their contribution to GDP.

We take the volume concept in national accounts as a proxy measure of quantifying some of the flows in which we are interested. The measure of GDP easiest to express in volume terms is that of expenditure. The estimates of household consumption, capital formation, exports and imports can be deflated

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without much conceptual difficulty. However, price indices for services are more difficult to compile than for goods. The SNA notes that research work is actively in progress to derive volume estimates of output of services that take account of changes in their quality. In using the volume measure for economic flows of products, we take the view of equivalence between domestic production and imports. We do not seek to distinguish the origins for imported or domestic products. We recognise that if there is a radical change in the exchange rate, then our application of an economy-wide single deflator would mean the volume measure of imports would change. However the products themselves haven't changed so our proxy representation would be weakened. Rather than complicating our approach by applying a myriad of different deflators and maintaining separate accounts, we note that the GB economy has experienced a sufficiently stable exchange rate over the historical period to justify our use of a single deflator.

3.4 Representing Data on Dwellings

The SNA states that dwellings are assets used by their owners to produce housing services. Dwellings are a major class of fixed assets, for which data is available, but appear to have a low significance as an industry. The assets are found in the ISIC list under section L (of the service industry) class 6810 'real estate activities with own or leased property'. As a product, rental from dwellings appears under CPC as subclass 72111 'rental or leasing services involving own or leased residential property'.

National accounts measure what takes place in the economy, between which agents, and for what purpose. Given that the GDP of a country is viewed as an aggregate measure of production, the GDP measure would have an arbitrary component depending on the proportion of dwellings that are owner-occupied, yet the total of housing services provided is constant. To correct this otherwise arbitrary aspect, the SNA specifies that an imputed rental on owner-occupied housing, estimated from comparable properties in the rental market, is included in the production boundary and forms part of household consumption. We separate actual and imputed rental from the service industry and associate this total with the nominal industry of dwellings.

3.5 Representing Energy Demand Data

For energy, a better proxy for measurement of the flows is their energy units because these relate directly to the role of energy within the production process. However care must be taken when considering a mixture of energy and economic units of measures. We retain the economic volume flows along with energy flows despite evidence to suggest that the economic importance of energy, as represented by its share in the national accounts, is an underestimate (Ayres and Warr, 2009). Although the economic volumes are small, they are necessary for completing the sum of the GDP indicator.

Energy involves some specific infrastructure which has large enough fixed assets to warrant separate consideration outside of its overall industry. This infrastructure is generation plant for electricity (within the utilities industry) and refineries of crude oil to petroleum products (within the manufacturing industry).

3.6 Representing Transportation Data

Transportation has significant fixed capital and energy use. Although the CPC for products identifies transport services, transportation is wider than this definition. Leasing services fall within the service industry, but includes vehicles which are leased to different industries. Data for fixed capital of all industries identify transportation separately from the fixed capital of buildings and the assets within them of plant and machinery. However the contribution of their transportation to the production process within the industry is not identified separately. Vehicles owned by households are not deemed to have an economic role. We segregate all transportation (Section 5.4). Transportation assets are in the middle of a process that converts fuel to the output of vehicles that travel a distance (measured as vehicle-km per year or passenger-km per year, DFT, 2013).

3.7 Incorporating Data on Jobs and GVA

Gross Value Added (GVA) is the compensation of employees, plus gross operating surplus, plus taxes on production, less subsidies on production. In Figure 1, the volume measure of the output of basic products is the value added by the industrys' production process, its GVA.

Showing jobs as an input in Figure 1 might be taken as double counting, but it is not. We need to make clear the distinction between a purely economic analysis and the physical flows approach. In the practical calculation of GDP, equality is presumed between the forms of GDP (income, output and expenditure). Compilation and reconciliation of SUTs is an important part of arriving at an accurate GDP value. This method is transferable between economies enabling trust and acceptance of the GDP figures. However the expenditure form is unique in its link to products and thus its use for calculating deflators. The expenditure form of GDP is taken as being the proxy for goods and services. This proxy is followed back up the production process so it is also a good proxy for industries and equated to GVA.

4. Considering the Whole Economy

The industry shown in Figure 1 is one part of an economy. The whole economy consists of all industries, which are dependent on each other as well sharing inputs and contributing to final outputs (goods and services). For clarity in understanding we will examine the (generalised) intermediate steps which comprise our analysis framework.

Consider an economy made up of three industries (Figure 2). Our system boundary is the economic territory's trading border, so sources of flows on the left are imports. The next sources along are domestic production, such as extraction of natural gas. Industries are designated by the yellow boxes to represent their fixed capital. Industries process their input flows to produce basic products, which emerge on the right. The volume of these output flows is GVA. The dashed box in the middle encloses the intermediate consumption by industries for each others' basic products. Imports and their equivalent domestic products are also shown as combining here, thus final supply of the (three) final products shown equals the sum of their domestic production and imports. Flows crossing the system boundary to the right are exports. Consumption by households is part of final demand. Also part of final demand are products that combine to form investment. This means they bring about the formation of the fixed capital of each of the industries.

More specifically, GDP is based on residency where the residence of each institutional unit is the economic territory with which it has the strongest connection. The economic territory includes the land area, airspace, territorial waters. It also includes territorial enclaves in the rest of the world, such as embassies and military bases, but these are small enough in the scale of the analysis here to be ignored. According to the Balance of Payments and International Investment Position Manual, Sixth Edition (BPM6; IMF, 2011), an economic territory, in its broadest sense, is any geographic area or jurisdiction for which statistics are required. By including the trading border of the economic territory, we can introduce imports and exports of products (goods and services).

Whereas Figure 1 is straightforward in that inputs lead to a single product type, the intermediate consumption, which is between industries, is more complicated. The approach to intermediate consumption in Figure 2 is to pull each industry apart, indicated by the broken borders for the sides for each pair of boxes that face each other. What emerges from the left-hand set of boxes is their own production (GVA). Also shown on the left are imports as if passing unprocessed behind the left boxes before adding to production. In the space between the pairs of boxes, industries provide some of their outputs to become others' inputs. Although intermediate consumption is represented here as progressing from left to right, the interaction of imports, GVA, and intermediate consumption is mixed up in a myriad of sequences of real processes within the economy. The main message to take from the schematic is that all products eventually emerge on the right, which we label as 'final supply', and go to just three destinations:

1. Final consumption within the economy – consists of products used by individual households or the community to satisfy their needs.
2. Exports of products go outside of the system to intermediate or final consumption in other economies.
3. Fixed capital formation of the assets within the economy.

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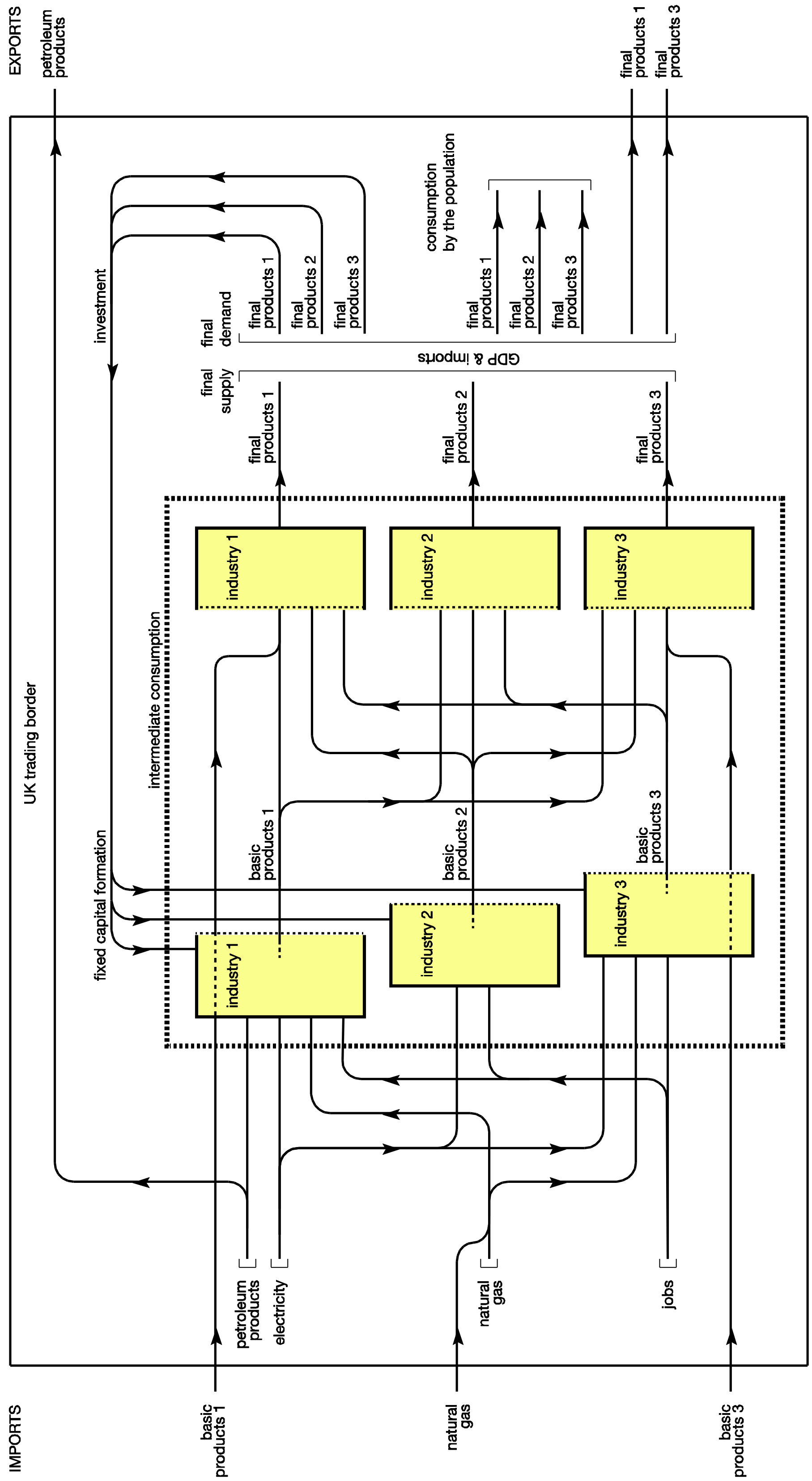

Figure 2. A simplified map of unweighted directional relationships (of flows) between the sources and consumers for some example industries. The diagram is read from left to right.

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In following a given product from left to right in Figure 2, it clearly takes on a different form after the stage of intermediate consumption. At the point of production (or GVA) basic prices are before any tax on products has been paid or subsidy due on products has been received. At the point of final supply, the units change to purchasers' prices. These are the amounts paid by the purchasers so are the actual costs to the users. The differences between basic and purchasers' prices will become clear further on when specific data for the UK is introduced. We can recall at this point two of the ways of viewing GDP. The expenditure form of GDP refers to expenditure by households, so is at the point of final supply in Figure 2. The expenditure form of GDP includes net exports, corresponding to exports minus imports. The output form of GDP is a different way of viewing the economy. It corresponds to the total of GVA by each industry.

Figure 2 also shows energy in this hypothetical economy. The energy supply is made up of domestic production (emanating from within our system boundary) together with net imports.

4.1 SNA Nomenclature for Sectors and Transactions

Our use of the terms 'sector' and 'transaction' complies with SNA. The whole economy (code S1) is divided into five mutually exclusive sectors S11 to S15 (Figure 3(a)) and listed in Figure 5. The fundamental units identified (United Nations *et al*, 2009) are the economic units that can engage in the full range of transactions and are capable of owning assets and incurring liabilities on their own behalf. These units are called institutional units. They are grouped together to form five institutional sectors, on the basis of their principal functions, behaviour and objectives. Together, S11 and S12 are sometimes known as market and loosely referred to as enterprise. Sectors S15 and S13 are sometimes known as non-market or social. Sector S14 is unique in being only a recipient of goods and services from the other four sectors. Other recipients of output from the economy are the flow P5 of capital formation and P6 of exports.

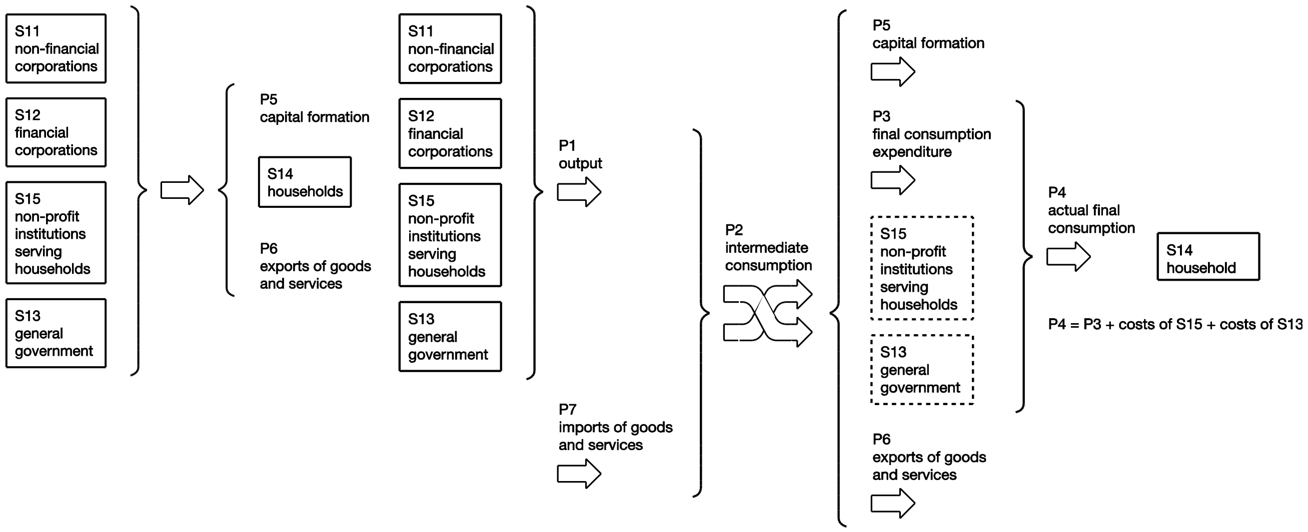

Figure 3. (a) The SNA divides all participants of the economy into five sectors (S11 to S15). (b) The seven types of transactions of the economy (P1 to P7).

Transactions in the SNA are exchanges of economic value between institutional units (United Nations *et al*, 2009). All transactions of the economy consist of seven types (Figure 3(b)). Those involved with production are P1, P2 and P7. Those involved with final demand are P5, P3 and P6. P3 is final consumption *expenditure* by households. Households also benefit from the sectors S15 and S13, but their funding is indirect, through general taxation, so this is part of *actual* final consumption (P4) and simply adds their costs to household expenditure (P3).

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5. Data for One Year

Developing Figure 2, we can construct a complete dependency diagram for a whole economy, using the UK as an example. To compare levels of activity, an appropriate representation is as a Sankey diagram, where the widths of lines are proportional to size of flow, and functional separation into different product streams (Kennedy & Sankey, 1898). These are frequently used in energy and material flow studies (Schmidt, 2008) and recently for energy flows in shipping (Baldi *et al*., 2012). Commonly, Sankey diagrams use the same units throughout (or have a point of conversion). We introduce a novel aspect by merging economic and physical flows – and data with different units of measurement – into a single representation which can be interrogated to reveal meaningful relationships which better reflect the structure and nature of an economy. Figure 4 is a Sankey diagram of the flows for the UK economy for 2010. We describe the principal Sankey elements below, and introduce some of the possible numerical analyses in section six.

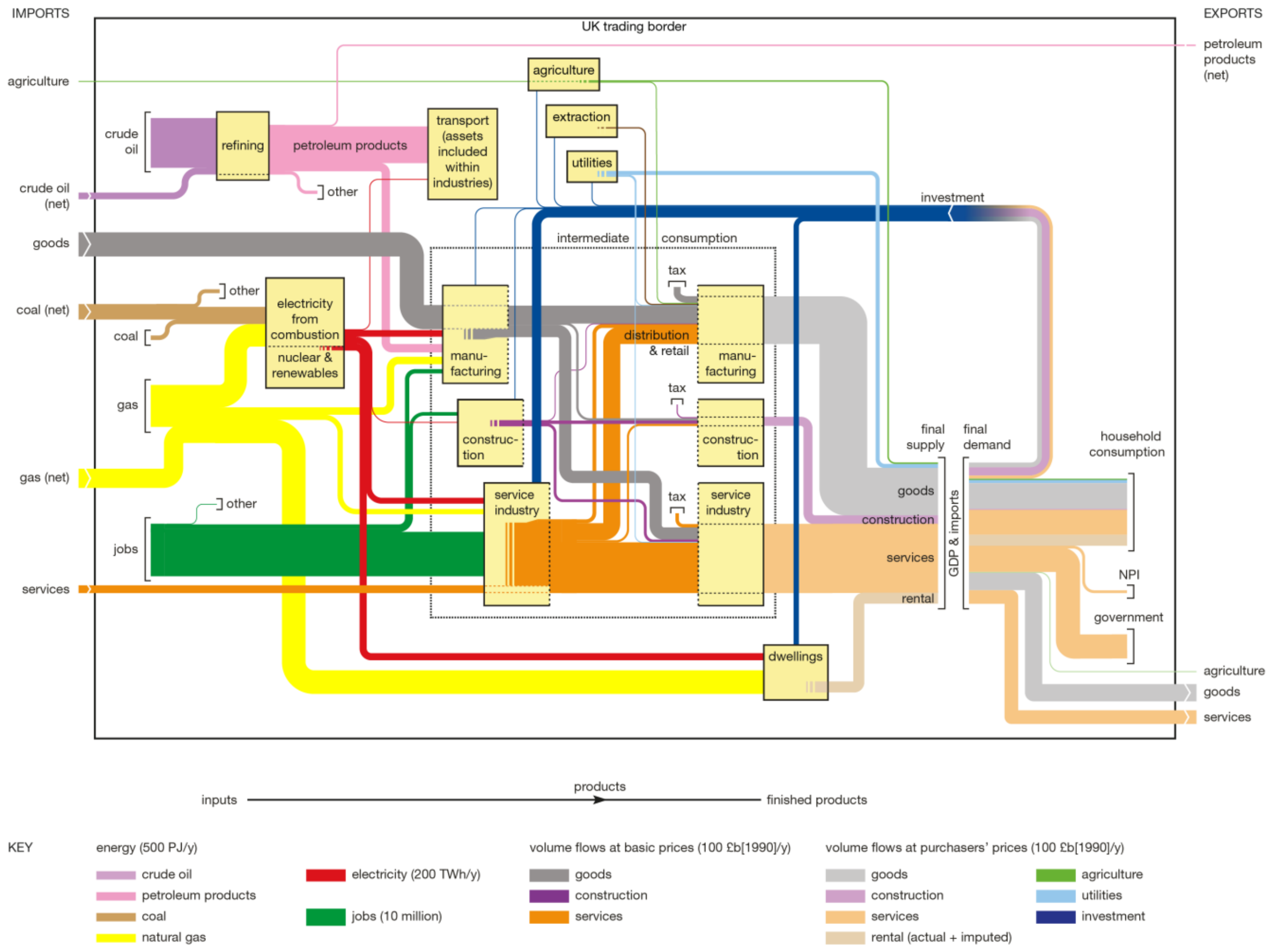

Figure 4. A high-level Sankey diagram of the relationships between industries shown here for energy, jobs and economic volumes flows with data for the UK economy in 2010. All fixed capital within the economy is represented by boxes (there is no significance to their dimensions.) All horizontal Sankey lines are flows from left to right with the sole exception of 'investment', which flows back from right to left. Each fixed-capital process transforms inputs into outputs (from left to right). Fixed capital is increased in size by investment (blue lines). The investment line is not shown for either 'refining' (part of manufacturing), 'electricity…' (part of 'utilities') or 'transport'. Domestic production by industries (GVA) is shown by Sankey lines that start broken and emerge solid. These lines change width for the manufacturing and service industries to represent the change from GVA specified by industry groupings, to output specified by product groupings. NPISH is non-profit institutions serving households.

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5.1 Basis of Aggregation

Looking at the economy as a whole in Figure 4, we can see the justification for the level of aggregation chosen. There is the expected division of goods and services. Inputs to their industries of manufacturing and service are very different: manufacturing is a high user of energy and service is the largest employer.

The separation of the construction and dwellings industries is unusual, but has important advantages. Contrasting the features of construction with manufacturing and service, the key features are that construction's main destination from final supply is to GFCF, it is a large employer, and it has no imports or exports. Dwellings are a significant user of energy which is accurately shown as associated with being a producer of rental (housing services). However, dwellings do not provide any employment. By separating rental from the output of the service industry means that service better reflects the flow resulting from the fixed capital and inputs to the service industry.

5.2 Incorporating Assets in the Framework

All of the fixed capital of all industries and dwellings are represented by boxes in Figure 4, as in Figures 1 and 2, though the size of the boxes has no significance in this diagram (fixed capital within households, such as white goods, is not included in national accounts). Each box has a blue line for FCF. Compared to the introduction of flows in Figure 1, consumption of fixed capital, CFC, is not shown but is taken as being implicit for all the boxes that represent fixed capital.

The three smaller industries of agriculture, extraction, and utilities are all shown at the top with their fixed capital formation entering their bottom edges. For the extractive industries, the fixed capital is responsible for the domestic extraction of crude oil, coal and gas. Their origination is shown on the left. For the utilities industry, this is split between power generation on the left and the rest of this industry at the top. Furthermore, refineries are split out from manufacturing.

5.3 Incorporating Economic Volume Flows in the Framework

In terms of the contribution to GDP, Figure 4 shows that the highest GVA for the UK economy are the three larger industries and dwellings. Their associated outputs are called:

- Goods from manufacturing, CPC groups 2-4.
- Construction services, CPC group 5.
- Services, CPC groups 6-9 less CPC class 7211.
- Actual and imputed rental from dwellings, CPC class 7211.

Due to their dominance, we only need to consider the intermediate consumption for manufacturing, construction, and services. For the three smaller industries and their products, only net intermediate consumption to the three larger is considered, which is justified by their small net intermediate and final volumes in Figure 4. One additional line is required. The SNA picks out 'transport and trade margins' (also known as distributors' trading margins) which we treat as a special case of intermediate consumption of the service industry (mostly going to manufacturing). Data is separately itemised for this in national accounts. It makes a significant difference between goods at basic prices, from import or production, to goods at purchasers' prices for final supply. Another point to make about purchasers' prices (on the right) is that it includes net taxes (less any subsidies) on products. Since these taxes increase the proxy measure of the volume of goods, they are shown in the Sankey format as increasing the line width.

Although Figure 2 shows a part of final demand within the economy as benefitting the population, national accounts distinguish between purchases made by households and services from Non-Profit Institutions Serving Households (NPISH) and Government. NPISH include foundations, membership organizations, religious organizations, and trade unions, which are funded indirectly. Government services are provided to the community or to individual households but are also paid for indirectly, being financed through taxation and other forms of Government income.

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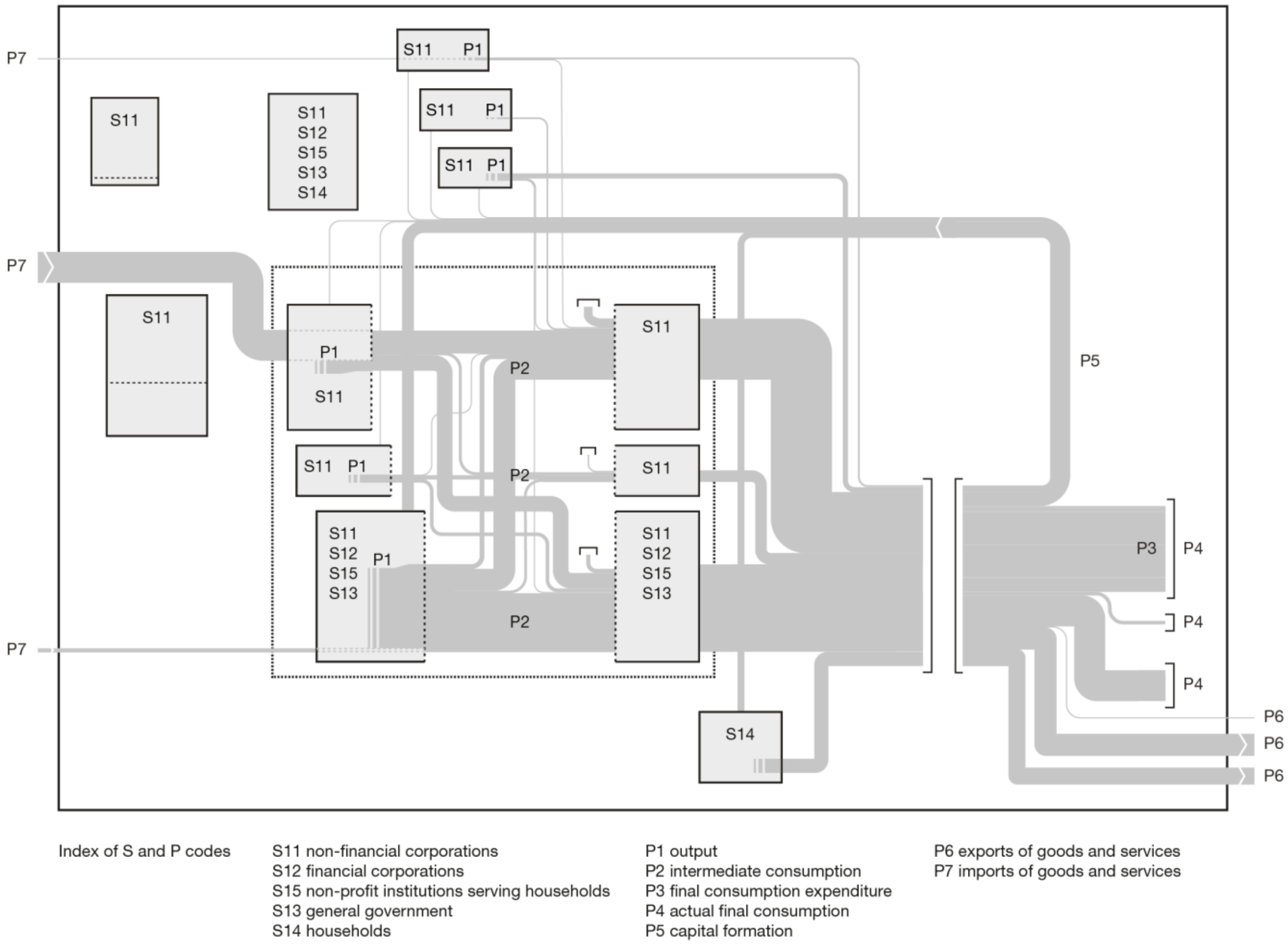

Figure 5. Overlay of the economic flows and infrastructure of Figure 4 with the S- and P-codes of Figure 3.

Figure 5 shows how the economic aspects of Figure 4 relate to the S- and P-codes in Figure 3. All the boxes in Figure 4 relate to the S-codes for sectors. For economies where production activities undertaken by households, such as agriculture not for own use, is significant, the 'S14' label would need to be put into appropriate industry boxes of Figure 5.

5.4 Incorporating Transport in the Framework

From an energy perspective, all transportation is brought together at one point in Figure 4. Greater detail is given in Figure 6. The fixed capital in Figure 6 are grouped by their use for either passengers or freight transport. The change in capital, through FCF and CFC, is not shown. Inputs to transportation are petroleum products and electricity.

Outputs shown on the right are selected according to relevance and the availability of robust data. For instance, the annual motor test ensures an accurate record of total travel of the entire car fleet (vehicle-km/yr) In the case of road freight, data of tonne-km/yr is collected for trucks (heavy goods vehicles, HGV) but not for vans (light goods vehicles, LGV). Care is needed with transport equipment used for international travel and freight to ensure consistency between energy use and the specific travel for which it is used.

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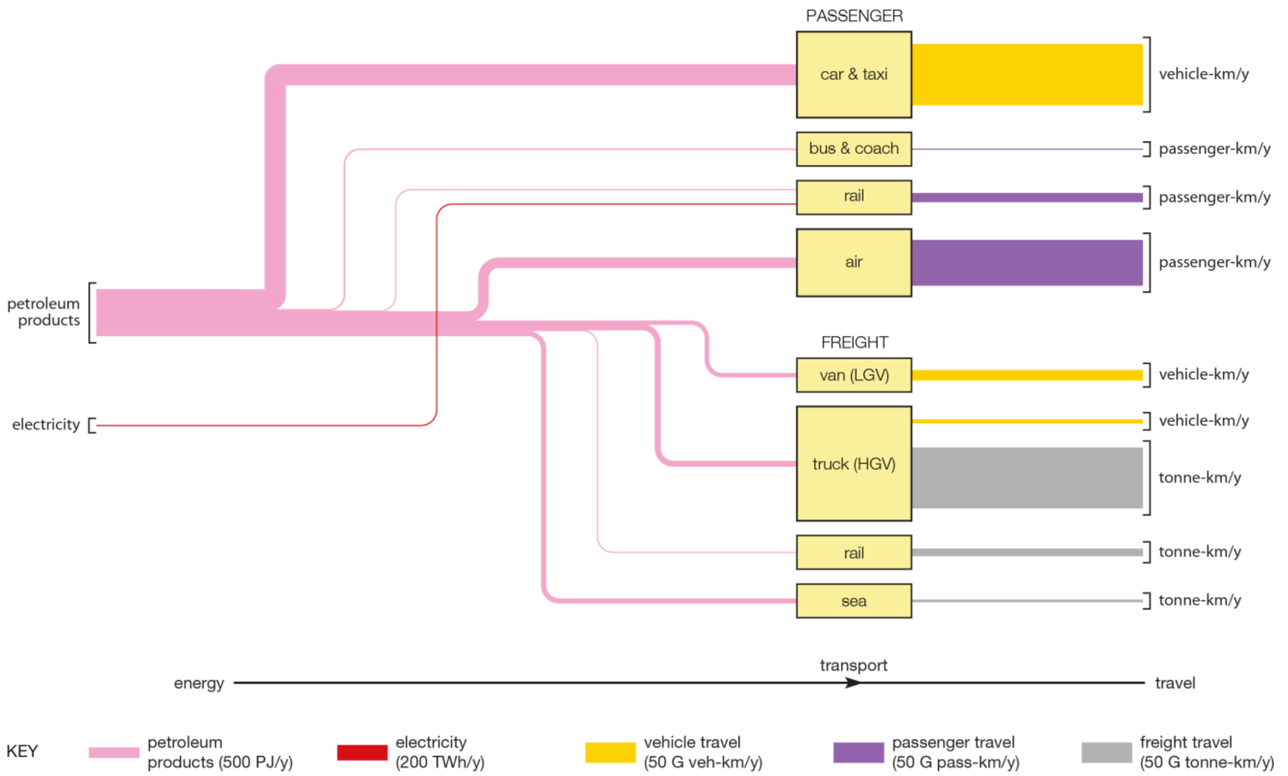

Figure 6. A Sankey diagram to show detail of energy use by UK transport using data for 2010, Volume flows of energy (on the left) are used to create 'mobility' (on the right). (LGV: light goods vehicles. HGV: heavy goods vehicles.)

5.5 Incorporating Population and Jobs in the Framework

The connection between jobs in Figure 4 and the whole population of the country is shown in Figure 7. In contrast to Figures 3 and 4 this diagram only categorises volume, and does not represent flow. It links three parts of Figure 4: jobs (left in Figure 4), dwellings (bottom in Figure 4) and households (right in Figure 4). Jobs (right) are categorised by the industries as aggregated in the framework. The chain is completed by the 'population' forming households, which reside in dwellings. The SNA defines households as where consumption is undertaken, but defines income as earned by individuals.

The logical starting point is population. To the left, the population is grouped into households which the SNA define as the consuming unit (on the right in Figure 4). Further to the left, households reside in dwellings, corresponding to the nominal dwellings industry at the bottom of Figure 4. From population going to the right, the divisions are first by age, followed by whether economically active for the labour force. There is then a change of unit to 'jobs', which is the data reported by the industries as the employers (ONS, 2013). The industry groupings at the top right are as shown in Figure 4.

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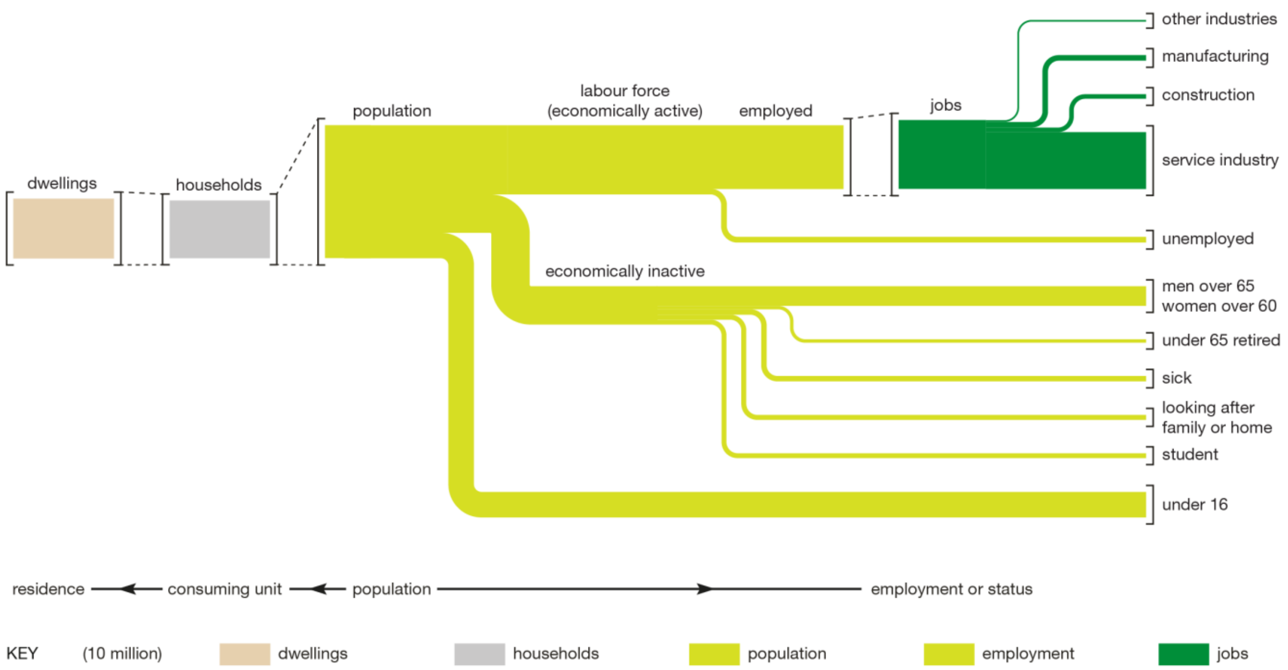

Figure 7. A Sankey diagram categorising age and availability for employment of the UK population using data for 2010 (ONS, 2011). In contrast to our other Sankey diagrams, all the quantities are stocks or status measures; none are flows with per-year units.

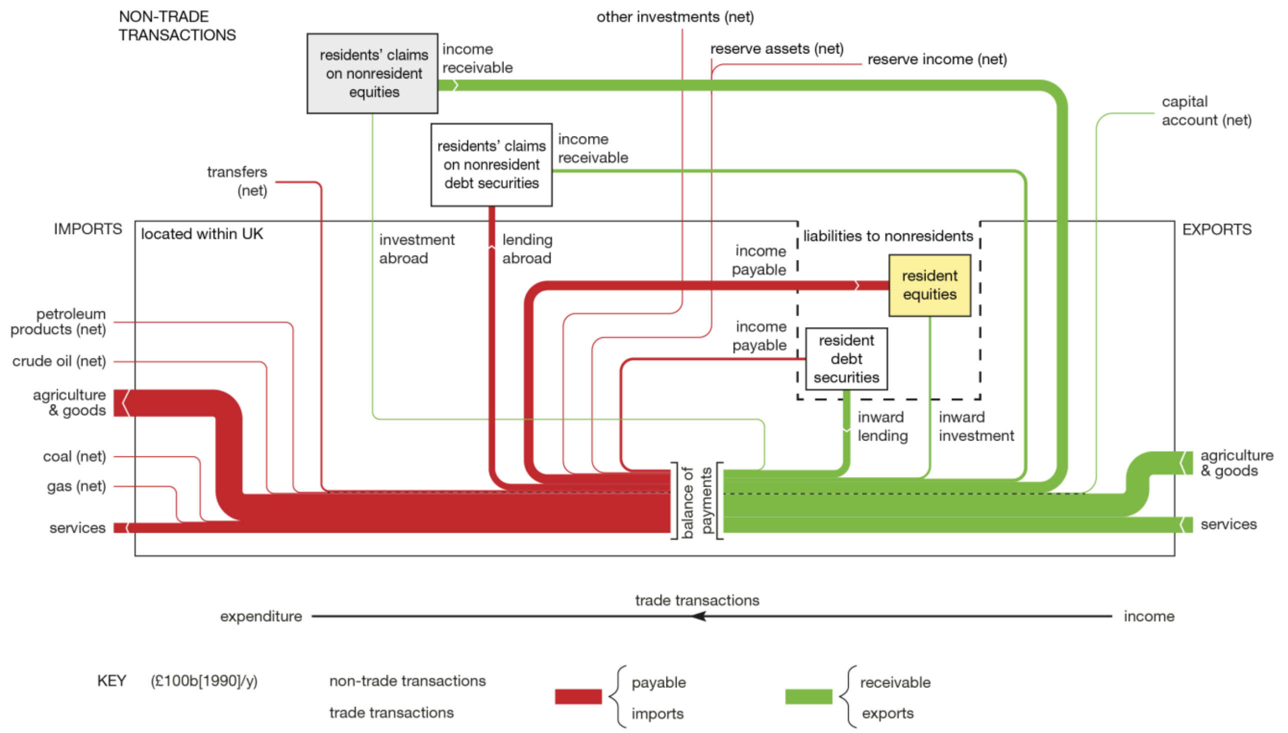

Figure 8. A Sankey diagram of the monetary flows of all transactions that make up the UK balance of payments for 2010.

5.6 Incorporating the Balance of Payments in the Framework

Balance of payments concern the parts of the Sankey diagram in Figure 4 which change from volume to monetary flows. The concepts for an economy introduced so far have all been about the innate quantities, whether goods, services, energy, or people doing jobs. Within our system boundary of an economic territory, the interaction of all these, though mediated by money, is constrained by the slow moving relationships summarised in Figure 4. The balance of payments is shown in Figure 8. with the transactions divided into trade (on each side) of the goods and services account, and non-trade (all at the top). The left- and right-hand sides are equivalent to the volumes flowing from left to right in Figure 4 (each matched by monetary flows here from right to left). One exception is that while the net volume flow of petroleum products in energy terms is an export (on the right in Figure 4), in monetary terms the net flow is as an import (on the left here). Non-trade transactions along the top have horizontal lines for the primary income, secondary income and capital accounts. Vertical lines are transactions in the financial account of purchase and sale. Reserve assets ends with both vertical and horizontal lines since it combines entries from both the primary income and financial accounts. Related to Figure 4, boxes represent financial assets and liabilities with the focus here on their location and ownership rather than their type of production. Other investments from the financial account are mainly intra-bank transactions across national borders. Grouping of the main transactions of the UK economy in 2010 according to the BPM6 (IMF, 2011) of current, capital and financial accounts are shown in Table 1.

Table 1. Categorisation of the main items in the UK balance of payments. To be read in conjunction with Figure 8.

Accounts	Direction of transaction		
	Payable (red)	**Net (red or green)**	**Receivable (green)**
Goods and services account * (trade)	Imports		Exports
Primary income account *	Income payable		Income receivable
Secondary income account *		Transfers	
Capital account		Capital account	
Financial account	Equities bought by residents		Equities bought by nonresidents
	Debt securities bought by residents		Debt securities bought by nonresidents
		Other investments	
		Reserve assets	

* One of the three elements comprising the Current account.

The Trade Account

The current account covers transactions that do not give rise to future claims and includes all of trade, more formally called the goods and services account. Comparing Figures 4 and 8, the left- and right-hand sides are complementary. An inward flow of imports on the left in Figure 4 is matched by an outward flow of funds (to the left) in Figure 8. On the right hand side, exports in Figure 4 are matched by funds flowing in Figure 8. One exception in the case of the UK (in our example year of 2010) is that while the net volume flow of petroleum products in energy terms is an export on the right in Figure 4, in monetary terms the net flow is as an import on the left in Figure 8 (DECC, 2012; ONS, 2012a, 2012b). This results from differential pricing of the particular petroleum products traded.

The Non-trade Account

Non-trade transactions consist of the remaining items in the current account of the primary and secondary income accounts together with all items in the capital and financial accounts (IMF, 2011). Non-trade and trade transactions are divided from each other by the horizontal dashed lines in Figure 8. As in the earlier Sankey diagrams where boxes represent fixed capital, boxes here represent some of the financial assets and liabilities related to the financial account with the focus on their geographical location and ownership (not type of productive activity) in relationship to residents. Boxes for equities, being related to the value of corporations, are directly comparable to the fixed capital boxes in Figure 4. We introduce boxes to represent debt securities, consisting mostly of bonds, which have no specific connection to any particular fixed capital. Our system boundary can also be viewed as encompassing all residents according to BPM6, being those institutional units with the strongest connection to the economic territory. The two boxes outside our system boundary are financial assets belonging to residents, so are called their claims. The two boxes inside our implied rectangular system boundary belong to nonresidents, so are liabilities of residents. All the vertical lines are transactions on the financial account. Those ending on the bottom of the boxes are either outward flows when payable by residents to increase assets or decrease liabilities or inward flows when receivable by residents. Transactions on the sides of boxes are from the primary income account , consisting of dividends or interest, and are always one way.

We show the non-trade transactions of other investments and reserve assets as net flows which can change from inward to outward from year to year. Other investments for the UK are mainly intrabank transactions across national borders. If these were to be shown as gross flows they would dwarf other non-trade flows, but are more meaningful when shown as net. Flows for reserve assets for the UK are only published as net. We combine their contributions from the primary income and financial accounts for simplicity.

Constraint of Balance of Payments

The balance of payments includes imports, which from a systemic point of view in the framework offers two advantages and one constraint. The first advantage is that imports are flexible, as long as there is the foreign exchange for their purchase. The second is that through money, any sort of import can be reconciled with an export through cash payments. But the overriding constraint of the balance of payments is that it should balance, as emphasised by how the national inward and outward flows are brought together in the centre for direct comparison of their totals.

6. Temporal Variations from 1990

Each entity within the Sankey diagrams has time-series data associated with it, even though the diagram itself visualises the complete dataset only for a single year. Our time-series data starts at 1990. This date is a compromise between the availability of the wide range of data that we require and our desire for a balance of the historical perspective with the projection into the future. Prior to about 1990, historical data becomes less complete, categories change, and data collection and processing methodologies pre-date significant recent alterations. For example, SUTs for the UK economy are not available before 1992. We give a small number of examples of the raw data flows and how our framework allows for the data to be systematically exploited in a straight-forward manner. This is the first step in operationalizing the framework.

Time-series data for fixed capital and output, Figure 9(a), show behaviour for the 21-year period since 1990 for the service industry (ONS, 2010). Both volume output and fixed capital have increased steadily while the volume output shows a slight decrease for the last three years of 2008-2010. Figure 9(b) shows the ratio between these two quantities, which is the economic output compared to physical assets. This is similar to the concept of return on capital. Since 1997 this ratio has been declining steadily.

Two of the inputs used by the service industry (ONS, 2012b) are shown in Figure 10. Thermal energy in Figure 10(a) is made up of solid fuel, heating oil and gas. Their proportions in 1990 were 8%, 27% and 65% evolving by 2010 to just oil and gas at 11% and 89% respectively (DECC, 2012). Total consumption has been decreasing over the historical period. Figure 10(a) shows the amount used per unit volume output of Figure 9(a). Fitting an exponential decay to the steady decline since 1995 suggests approach at -3.5%/yr to an asymptote at 16% of the 1995 level. The trend of employment in the service industry in Figure 10(b) is shown as mostly increasing (ONS, 2011). However when taken as a ratio with volume output of Figure 9(a), the trend has mostly been downward over the historical period. Fitting an exponential decay to the steady decline suggests approach at -3.0%/yr to an asymptote at 54% of the 1990 level. In 1995 and 1996, there was a temporary slowing of the decline, but the ratio appears to have returned to the overall decay trend. The data deviates in 2008 and the question is whether this signals an end to the decay or whether there will be a later return to the trend line, as there was in 1997.

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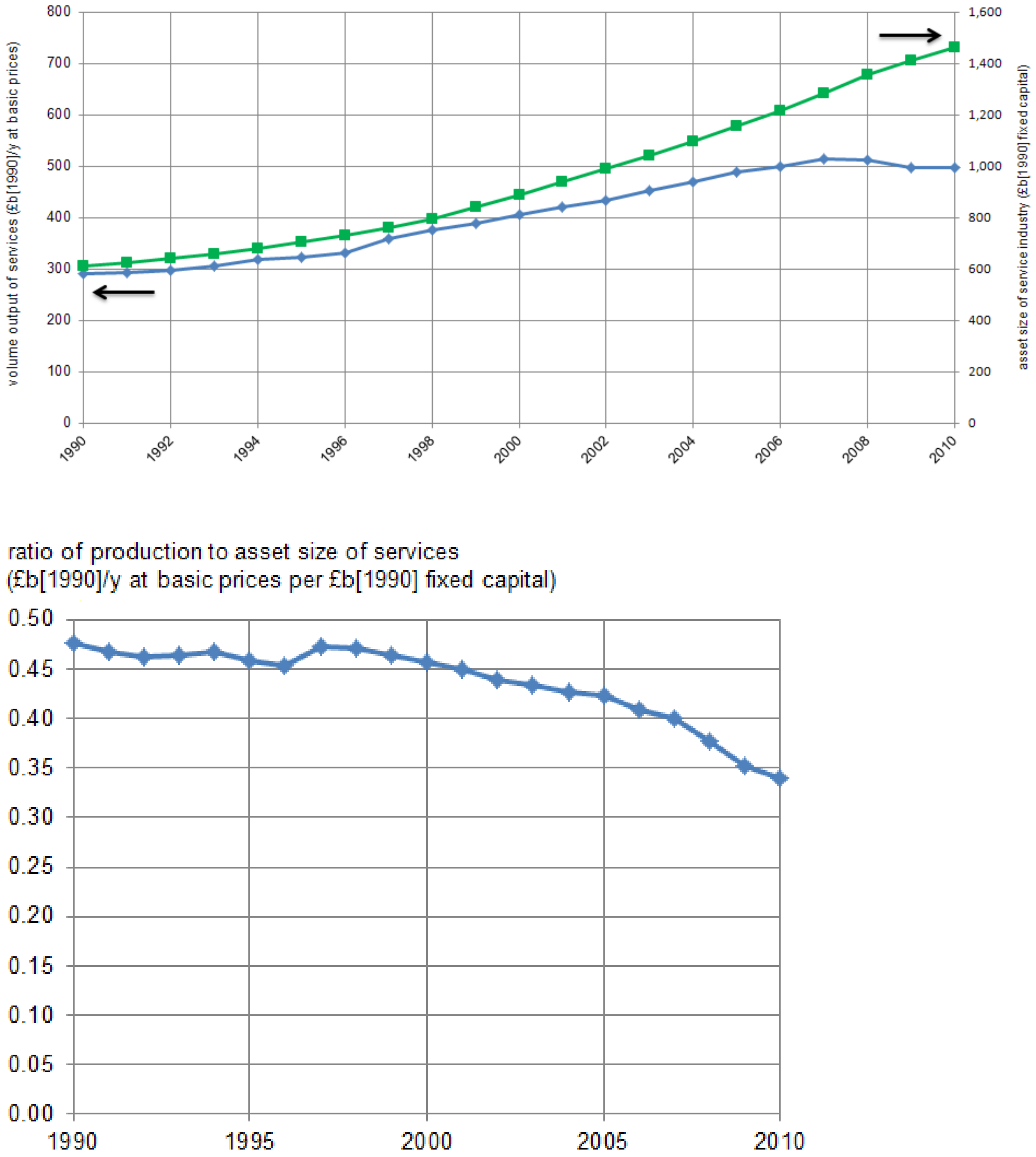

Figure 9. Examples of temporal data for the UK service industry over the period 1990-2010. (a) Annual production (GVA) and the size of fixed capital, (b) ratio of production to size of asset.

7. Relationships Between Flows

At this point we depart from analysing and visualising structural connections in the economy and time-series data, and turn to predictive relationships. The ratios in Figure 9(b), 10(a), and 10(b) can be added to the format of Figure 1. For the service industry, this is shown in Figure 11 with the ratios represented by the dashed arrows. The direction of these dashed arrows is the first step of operationalizing the framework into a computational model. The bowtie symbols on the flows in Figure 11 – like mechanical valves – represent regulators of the flow.

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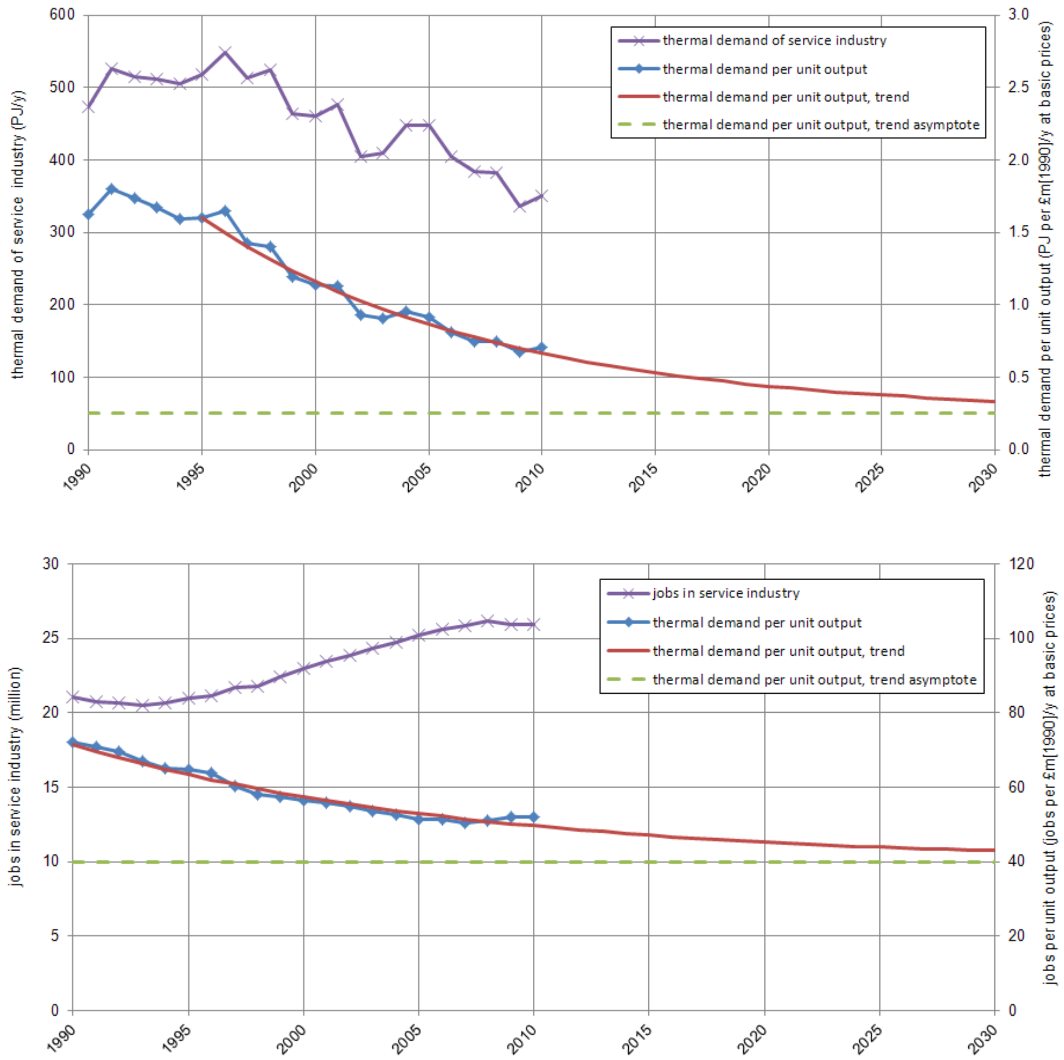

Figure 10. Examples of temporal data for two inputs needed by the UK service industry over the period 1990-2010. Data for the service industry production in Figure 9(a) is used to calculate the ratios. (a) Annual use of thermal energy (mostly gas) and ratio of thermal energy to production, (b) need for jobs and ratio of jobs to production.

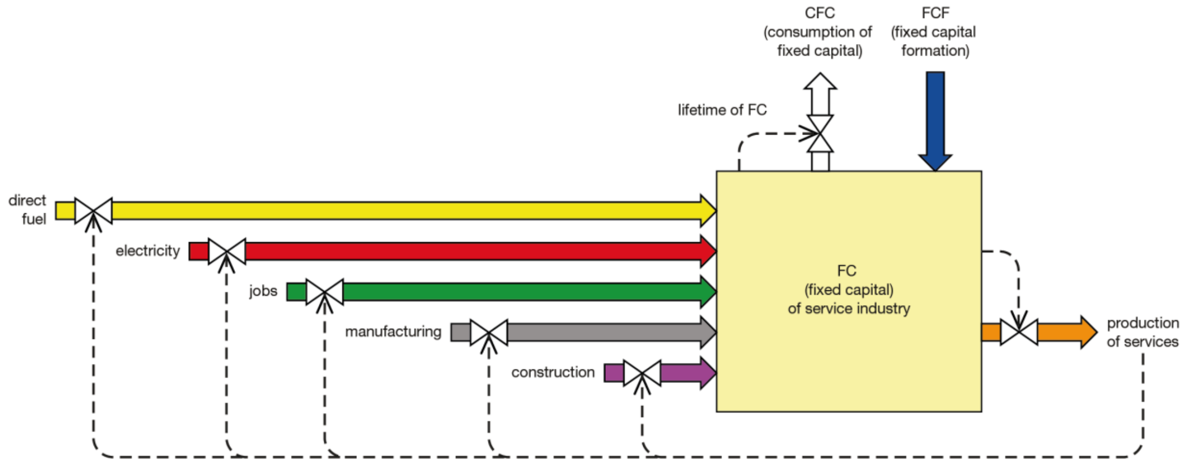

Figure 11. A schematic diagram showing the dependencies (dashed lines) used in the framework between flows and the fixed capital of an example industry (service). The dependency for FCF is not shown in this schematic.

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We have established that the stock of fixed capital has a lifetime. This means, according to the format of Figure 11, that the value of fixed capital when divided by the lifetime gives the value of CFC. When introducing one industry in Figure 1, we assumed that fixed capital must be in place before production is possible. In Figure 11 we can consider production as linearly dependant on the size of the fixed capital by a constant of proportionality. It shows the dependencies (dashed lines) used in the framework between flows and the fixed capital of the service industry. Flow of CFC is related to fixed capital by the lifetime of fixed capital. Production is dependent on fixed capital, with the time-varying constant of proportionality calibrated by taking the ratio of historical production to historical fixed capital. Similarly, each of the inputs is separately dependent on production with their own constants of proportionality calibrated from historical data (the origin of the input flows is shown in Figure 4). Finally if we consider all the inputs as being linearly dependant on production, each input would have its own constant of proportionality. Most of these relationships are between mixed measurement units. For example, if production is in £million[1990]/yr and consumption of electricity in TWh/yr, then the constant of proportionality of electricity needed per unit of production would be TWh/£million[1990].

8. Discussion

Using the UK as a case study of how the framework can be exploited, we can make observations about the service industry since 1990. First, economic output compared to physical assets (return on capital) has been declining steadily; and second, both the amount of thermal energy and the number of jobs each needed per unit of output show falling trends. We suggest these trends can be realistically extrapolated into the future using best-fit decay curves. Employing staff is a major cost for all establishments in the service industry, so it is not surprising that there is continuous pressure to reduce these costs by productivity gains to stay in business in a competitive market. However, if unemployment overall is not to rise as jobs-per-unit-output falls, then the service industry will need to compensate for the loss of jobs. The historical data shows that the economy has managed to accomplish growth of the service industry but with a consequent large draw on investment, the thickest FCF line in Figure 4.

We stress that the framework reveals the physical requirements of the service industry thought by many to be virtual. The (blue) investment line of the Sankey diagram of the complete UK economy is largely directed to the service industry. This shows graphically how difficult it is for policy to effect radical change in the pursuit of new industries, rebalancing between industries, climate change mitigation, and environmental repair. Alternatives need access to investment, yet it is clear that redirecting sufficient capital from one industry to another has consequences and opportunity costs. A corollary is the possibility that the service industry will need continually to expand posing the challenge of when consumers' demand for services might saturate, thus triggering large increases in unemployment. Alternatively, the working week will have to be shortened to retain high rates of access to paid work and workplace contribution.

By rationalising a large set of disparate accounting procedures, the framework integrates procedures that collect, curate, inter-relate, and produce time series of national data essential to longer term strategic policy making. Our immediate goals for the use of the approach are to derive a base case scenario out to 2030 or 2050, building on the foundation of the rationalised and robust 21-year history. This will allow us to focus on strategic questions of economic and societal structures in one or two human generation's time. This also allows the unpicking of complex sets of sometimes hidden assumptions behind long term policies, such as greenhouse gas mitigation and workforce development. Once a base case scenario is established, the simulation-through-time capability of our framework allows exploration of simple one-issue policies (for example, heat pumps for housing, or electric vehicles) or more complex sets of interacting issues (for example, accelerated deployment of renewables or reduced household consumption).

With the advent of 'open data' and 'big data', the framework will become richer as it has been designed to make easy the addition of new annual data. The modular structure of data within the framework allows for new datasets to be included. Rolling out this framework and procedures across different countries could foster cross-country comparisons on an exactly comparable basis that should catalyse cooperation on global issues that have started to be tackled individually by governments. The robust data rationalisation and simulation capabilities allow potential transition points or physical un-realities to be highlighted easily. Because the approach accepts all datasets and accounting procedures as pragmatically equal, it gives little scope for disagreement between competing views. How policymakers then react to these tensions is the key determining factor for a transition to a low carbon economy.

9. Conclusions

The framework has its roots in a large set of computational frameworks developed over the last 30 years ranging from purely physical to purely economic – straddling the two principal philosophies. What makes the framework different is its embrace of the important tenets of policy credibility. It is compatible with the international SNA and its key whole-economy indicators, such as GDP, maintaining the *lingua-Franca* of policy discourse. In this context, our framework introduces distinct flows to enable more effective data mining. Tuning the level of aggregation of these complex datasets makes the volume of data manageable without losing systemic features. The mapping of dynamic economic and energy flows and relationships to the existing structure of national accounts is a unique strength of the framework. Furthermore, this is a novel type of Sankey because it represents these different units and flows in an integrated way. This physically meaningful visualisation method enables us to display data schematically to assist in drawing conclusions directly about the features within the economic and other data flows. In this way, our framework brings a new perspective to exploiting economic data (Supply and Use Tables), balance of payments accounts and energy data (energy balance). For instance, the balance of payments Sankey diagram brings all three accounts (current, capital and financial) together, or finding systematically sets of relationships within an economy which are key determining factors affecting investment (GFCF) resulting from economic output. Taken together, these make the richness in the national accounts more accessible for understanding their relevance for energy analysis purposes. However, we note three points for caution. First, in the aggregation process, loss of some detail will occur, for example all services aggregated together. Second, an underlying assumption is of relative currency stability. Our framework presumes equivalence between imports and domestic production (GVA) so as to express both as volume flows that can be combined (the grey lines that become one in Figure 5). However the concept of economic volume flows (at constant prices) are set up only for GDP. Thirdly, there is no coverage of prices or inclusion of price elasticities. Therefore policies that seek to change purchasing behaviour by changing taxation cannot be handled analytically within our framework and would need tools that can model ownership of assets and economic volume flows. Although our framework and other tools are complementary, we posit that our framework should be applied first to verify physical and economic viablity before going on to develop detailed pricing mechanisms. This includes developing an understanding of how to avoid perverse subsidies and potential resource contraints.

There is considerable scope for using the framework for mining the UK data, and for further enriching the dataset. A useful development will be to separately account for the volume flows of water and raw materials (such as steel, aluminium, aggregates, and cement). An obvious next step is to create datasets for other nations. The inclusion of data for water would then be very important for nations reliant on desalination. The key piece of future work, however, is to operationalize the framework into a dynamic model to enable policy options and scenarios to be examined.

Acknowledgements

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