Energy systems-Making energy services available

Correljé, Aad

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3. Energy systems – making energy services available

Aad Correljé

1. INTRODUCTION

All human activities and behaviour depend on the availability of energy. Looking back into human history, we observe that energy has always been critical in what we call the process of civilization. The activities undertaken in societies, their size, their wealth and wellbeing, their power, their growth; it all depends to a large extent on their ability to make sufficient energy available. And to effectively use this energy in supporting, expanding and creating human activities (Smil, 1994, 2018).

Yet, apart from some food, nobody needs pure energy … What we care for are energy services, like light, heat, force, processes of chemical and physical conversion and the movement of electrons. Over time, by combining tools and technological devices with more or less specific sources and forms of energy, we have been expanding and extending our capabilities in doing and creating things, in moving around and in living in comfort. Indeed, it is through the fruitful combination of human needs, human curiosity and ingenuity and the creation of technologies making energy available to use it in useful ways, that human civilization exists. From the perspective of the individual human being, it is in the access to appropriate forms of energy given available appliances, that he or she is able to act physically and socially, to observe, to create and to live.

Locations, levels of income, traditions and culture, the degree of urbanization and the type of our economic activities are highly influential in defining the kind of energy services we use, and how these are provided, with what kind of technologies and energy. Lighting, heating, cooling, cooking, transport, manufacturing, industrial and agricultural energy use show up in markedly different patterns in different places.

What particular energy sources or carriers we depend on is strongly determined by the technologies we use in providing ourselves with energy services. Yet, these technologies generally evolve in the presence of particular sources of raw, or primary, energy. In history, we see quite a development in this respect. The supply of light, for example, evolved from using candles and burning animal fats, via petroleum lamps and gas light, to electricity-powered light bulbs and fluorescent tubes and the current LED illumination (Fouquet & Pearson, 2006). But also, the geographical presence of particular natural energy resources at specific locations has a huge impact. Even today, there is quite some variation in the technologies and sources of energy that are used for lighting by people around the world, involving kerosene, butane and propane, electric power from coal- and gas-fired power plants, nuclear power stations, hydro dams, diesel generators, a variety of solar- and wind-based solutions and more.

An abundant literature has been created drawing on a variety of disciplines, in which parts of the energy system are analyzed from all kinds of perspectives. Many papers and books are written on particular types of energy, the segments in the energy supply systems, determinants of supply, demand and consumption, the role of the industry and governments, social and cultural aspects and lately energy justice and social acceptance. To an increasing extent, often inspired by the urgency of a transition to a low- or no-carbon economy, many contributions to this literature take a 'systems' perspective. On the one hand this involves formalized, mathematical, computational techno-economic energy models. On the other, the notion of system is used to refer to its socio-technical nature (see for example the overviews provided by Andrews-Speed, 2016; Sovacool & Hess, 2017; Geels, 2020; Blondeel et al., 2021; Hoffman et al., 2021; Kok et al., 2021).

As it happens, however, in this literature the 'system' often appears as a highly abstract concept, regarding both the 'socio' as well as the 'technical' aspects. Indeed, the latter aspects are reduced to the *materiality* or *non-human* aspects or the *geographies* of systems, whereas the socio-aspects are abstracted in terms of *agency*, *power*, *multi-actor interactions* and *regimes*, as examples. These high-level abstractions may fit the ambition to construct a general theory of socio-technical change. Yet, their use reduces the practical applicability of the insights derived, which are also highly abstract and non-specific. Indeed, such levels of abstraction ignore the evolution in the dependencies and interaction between the natural resources and the technologies (available), and the way in which they are locally employed to create and supply useful and societally acceptable energy carriers. Too much abstraction disconnects this evolution from the patterns of governance, determining how particular energy carriers are valued and employed (or not) to provide the energy services sought by societies and individual human beings. Making progress in the energy transition requires a more concrete conceptualization of the way in which the energy system works and its governance (see Correljé et al., 2022).

In the following sections we construct a simple conceptual framework that will help to analyze and understand the way in which communities of human beings provide themselves (more or less effectively) with the energy they need to support their social and economic activities. Section 2 provides an insight how the notion of a *supply chain* helps us to understand the geophysical and technical aspects of 'harvesting' the raw energy, as found in nature, and bringing it as practically usable energy carriers to societies. This perspective is illustrated in Figure 3.1 and it applies to the (hopefully) sustainable system the future, as it did to the past. Section 3 explains how humans and societies make this supply chain of geophysical aspects and technical solutions actually work, turning it into a constantly evolving *value chain* by means of the institutional and economic coordination of the activities, driven by the values they (are forced to) maintain. Obviously, the meaning of value here is not limited to monetary values. Section 4 concludes.

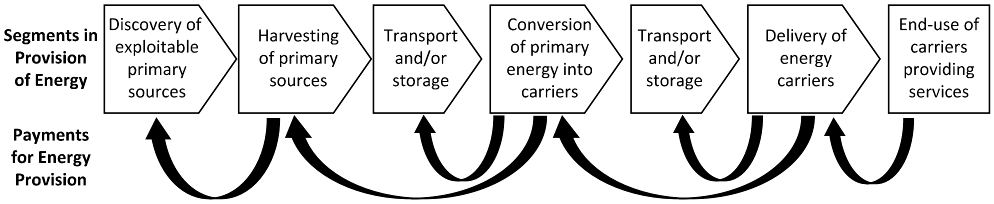


Figure 3.1 Schematic supply chain for energy provision

2. HOW ENERGY IS MADE AVAILABLE

Primary Sources

The way in which energy is made available to provide light, heating, force and other services to the so-called end-users starts with the presence or availability of primary energy sources. And there is quite a variety in the way in which these primary energy sources occur, either deep in the Earth's crust, or on the surface of the planet and in the atmosphere.

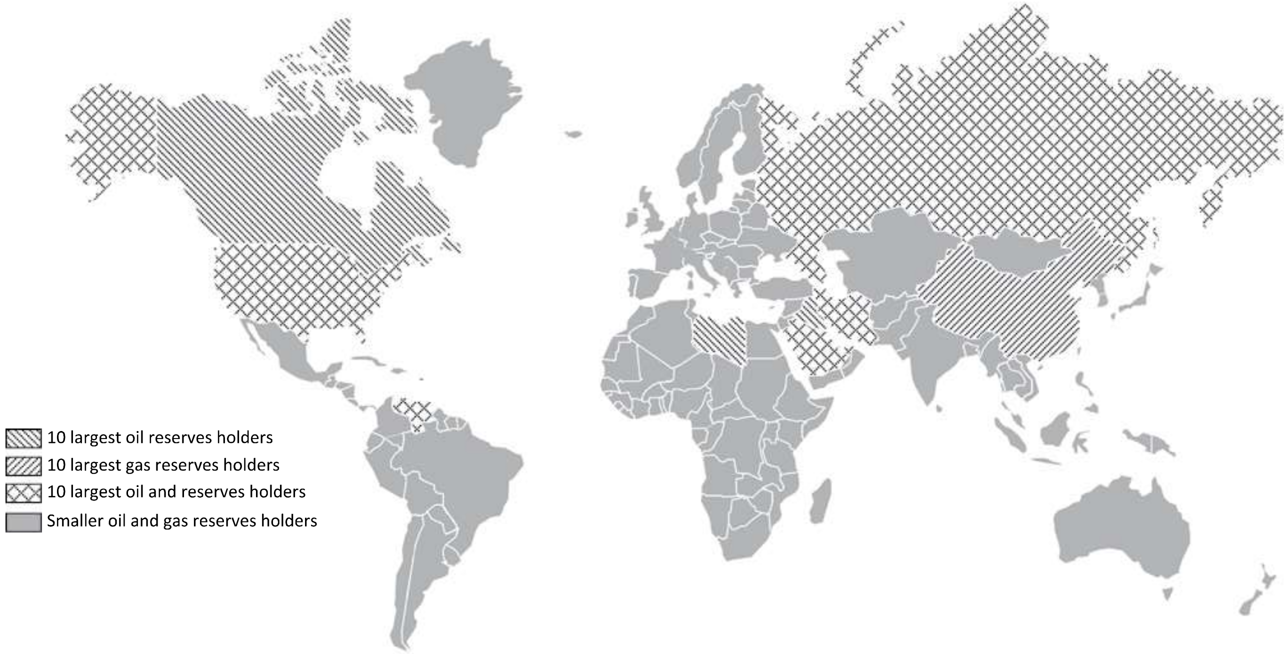
More or less deep under the ground we have deposits of fossil energy in the form of different varieties of carbonized vegetation, ranging from peat, brown coal or lignite, to bituminous coal and anthracite. There is petroleum, originating from ancient fossilized organic materials, like zooplankton and algae on sea or lake bottoms that were covered by layers of sediments, under increasing pressure and temperature. Today petroleum can be found in a large variety of crude oils, all with a different composition, or in the form of bitumen, tar sands or shale oil. Then there is natural gas, a naturally occurring mixture consisting primarily of methane, but present in a huge variety of compositions of gases and materials. Natural gas is often found in association with petroleum deposits, but also emerges from coal fields and it exists even as frozen methane hydrates deep on the floor of the oceans. The Earth's crust also contains deposits of uranium that in a processed form is the main fuel for nuclear power plants. And, finally, the high temperatures deep down in the Earth may provide geothermal energy. This appears generally in the form of hot water or steam that can be 'harvested' either close to the surface or at greater depths, depending on the local geology.

On the surface of the Earth, humans find and use all kinds of biomass in a more or less processed form, like firewood, peat and materials and residual waste from a variety of crops. Even animal fats are used, like whale oil. Moreover, there is the energy contained in flowing water in rivers or stored in natural or artificial lakes or in tidal sea movements. In the atmosphere, primary energy is available in the form of wind energy and by the radiation of the sun, either as heat or light.

The presence of all these sources of primary energy at particular locations and areas is a consequence of historical and geophysical conditions, which can be summarized as an interaction between the geological, biological and climatological history. And obviously, also the current local climate has a main impact via the exposure of the Earth's surface to sun and wind and also the water cycle, which creates the conditions for the growth of bio-based fuels and the availability of water for hydro plants.

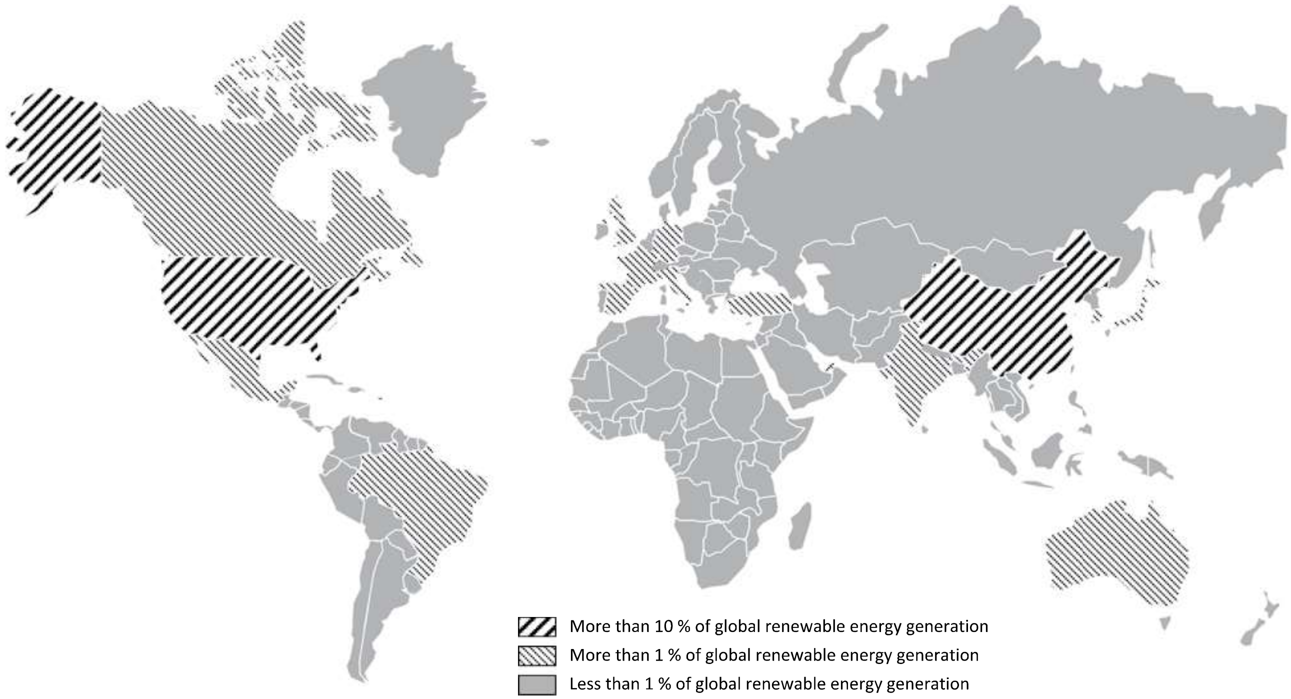
Therewith, the feasibility of 'harvesting' these primary sources of energy is by and large geophysically and geographically determined (see Figures 3.2 and 3.3). This implies that the distribution of these sources is highly uneven, not only on a global scale, but also regionally, or even locally. Some areas are endowed with a wealth of different easily accessible sources, while others are facing sheer scarcity. Obviously, on the one hand, this has attracted humans and their particular activities to those places where the resources were readily available. On the other hand, it induces attempts to transport the energy from the places where it can collected to the places where it is wanted.

The ability to 'harvest' and to 'move around' energy, but also other resources and produced goods and people, is a function of the development of technologies. In essence, this comes down to processing the raw, primary, sources of energy in such a way that they can be



Source: *BP Statistical Review of World Energy*, 2021.

Figure 3.2 *Distribution of oil and gas reserves*



Source: *BP Statistical Review of World Energy*, 2022.

Figure 3.3 *Generation of renewable energy including wind, geothermal, solar, biomass and waste, and not accounting for cross-border electricity supply* transported and/or stored, and in creating the ways of using and managing this process in an effective way (see De Gregori, 1987; Zimmermann, 1951).

Conversion

Some sources of so-called primary energy can be used directly without being fundamentally 'processed', like trees that can be cut and turned into firewood, coal that can be mined and be burned immediately thereafter. Peat only requires dredging and drying for some time. Natural gas just requires a 'light' treatment to get rid of the liquid components and contaminations. Low temperature geothermal energy in the form of hot water can, with heat exchangers, be applied directly in district heating. Some wood may also be turned into charcoal or pellets, to improve the quality of the fuel. Yet, other primary sources have to be radically converted into the kind of end-use energy 'products' that fit the appliances in use. Crude oil is transformed into a range of petroleum products in a complex refining process, yielding fuels like heating oil, transport fuels like gasolines, diesel, liquid petroleum gas (LPG) and kerosene for aviation and domestic purposes. Also, other gases and petrochemical feedstock emerge from this process. Uranium has to be processed intensively before it can be used in nuclear plants. And thereafter an equally complex treatment and processing of the waste starts.

Similar fuels and materials may be manufactured using alternative primary sources. Gasoline, for example, can be replaced by automotive ethanol produced from sugarcane. Biodiesel can be manufactured from rapeseed or a variety of other vegetable oils and fats. The Fischer–Tropsch process enables the conversion of carbon monoxide and hydrogen or water gas into liquid hydrocarbons like diesel or gasoline, using coal, natural gas or biomass in the process.

Many primary sources are converted into electricity or hot water as energy carriers, to bring the energy to the end-users. Electricity as a form of end-use energy can be generated using primary or manufactured energy sources, like fuel oil or diesel, coal, natural gas, biomaterials, residual waste and uranium in nuclear plants. The use of flowing water in rivers or water stored in reservoirs generates hydroelectricity. Power can also be produced by converting solar radiation, either the light or the heat, or with wind turbines. Geothermal energy can be turned into electricity too, particularly when the temperatures of the water (or steam) flowing from the Earth's crust are high.

A relatively new phenomenon is hydrogen as an energy carrier. For a long time, hydrogen has been used as an essential component in many chemical processes, particularly in the manufacturing and desulphurization of petroleum fuels and petrochemical products. Traditionally, hydrogen gas is produced from fossil fuels, either by steam reforming of natural gas and other light hydrocarbons, or partial oxidation of heavier hydrocarbons and coal gasification. Yet, it can also be produced from biomass gasification, with zero CO_2 emission methane pyrolysis, or by electrolysis of water with any source of electricity: solar, wind, geothermal power, coal, nuclear, etc. It is particularly in the fact that hydrogen can replace storable fossil liquid fuels and gases, while potentially being produced with low CO_2 emissions, that the interest in hydrogen as a carrier of end-use energy has recently gained great attention.

There is a huge variation in the scale of the processes and plants with which electric power and other energy carriers can be produced. This is a consequence of the technical characteristics of these processes and economic and other considerations. Some of the technologies mentioned above preferably require power plants with large-scale generating capacities, like nuclear energy, coal-fired plants and hydroelectric dams. Other technologies can be applied at different scales, like natural gas, diesel and biofuels that can be burned in larger plants, but also in relatively small or even portable units. Solar plants and wind turbines have a relatively small scale per unit, but they are often combined in 'parks' with a significant capacity. It can be observed that the scale of these processes is not a static given. Innovation and the ongoing development of technologies are both expanding the feasible generation capacity of wind turbines, solar panels and hydrogen electrolysis for example, while also enabling a miniaturization of other technologies, like nuclear reactors and gas- or hydrogen-fired units.

Another crucial characteristic of these conversion processes, either large or small scale, is the ability to control their output of usable energy. First of all, there are those processes which for their operation depend on the actual presence of their primary energy input, like solar, wind and hydro energy. To some extent this is a function of their location and the seasonal effects on the daily and annual variation of the weather. The latter is also true for the availability of residual or dedicated biomaterials, which may depend on the local agricultural seasonal cycle and rainfall – or actually the prevailing local system of water management. Then, there are processes which just have to be fed with sufficient dedicated primary energy resources, to be delivered at the plant at the right time, like oil refineries and gas- and coal-fired and geothermal and nuclear power plants. Smaller electricity generators use either gas or liquid petroleum fuels.

Yet, in these processes the technicalities (and the associated economics) determine the feasibility of more or less rapidly adjusting the operation and output of the plant, in response to the actual momentary demand for energy. Large coal and nuclear plants are preferably operating as constantly as possible, without fluctuations. The same goes for geothermal facilities, in which the flow of the water should be constant to avoid obstruction in underground layers through which the water flows. Also, the process of adapting the output of oil refineries, in terms of the structure and the volumes of the several fuels produced, is fairly rigid. In contrast, other technologies, like natural gas-, diesel- and biofuel-driven generators, and hydroelectricity with dams, can be turned on and off at will, without negative consequences for their functioning and efficiency.

Transport

From the above, it can be concluded that there is a large variety in conversion processes providing the various sorts of end-use energy carriers. As stated, it is a fact that the location of many sources of primary energy is given, as a consequence of their natural and geophysical characteristics. This implies that either the end-users will have to locate near the source of their energy, or that transport is required. Often the conversion or end-use of the energy takes place elsewhere. This is in part a consequence of the minimum efficient scale of the facilities, which indicates a bundling of capacity at a certain location, or the clustering of units like turbines in a wind park. Moreover, in their control and operation, some of these processes depend on external circumstances, like the weather. So, there should be substitute back-up facilities available to serve the end-users' demand for energy services, that can be managed at will. And then there are technologies which allow for moderation of their output at short notice, whereas others are more rigid in their employment. Therefore, transport is an essential component in the final provision of energy services to end-users.

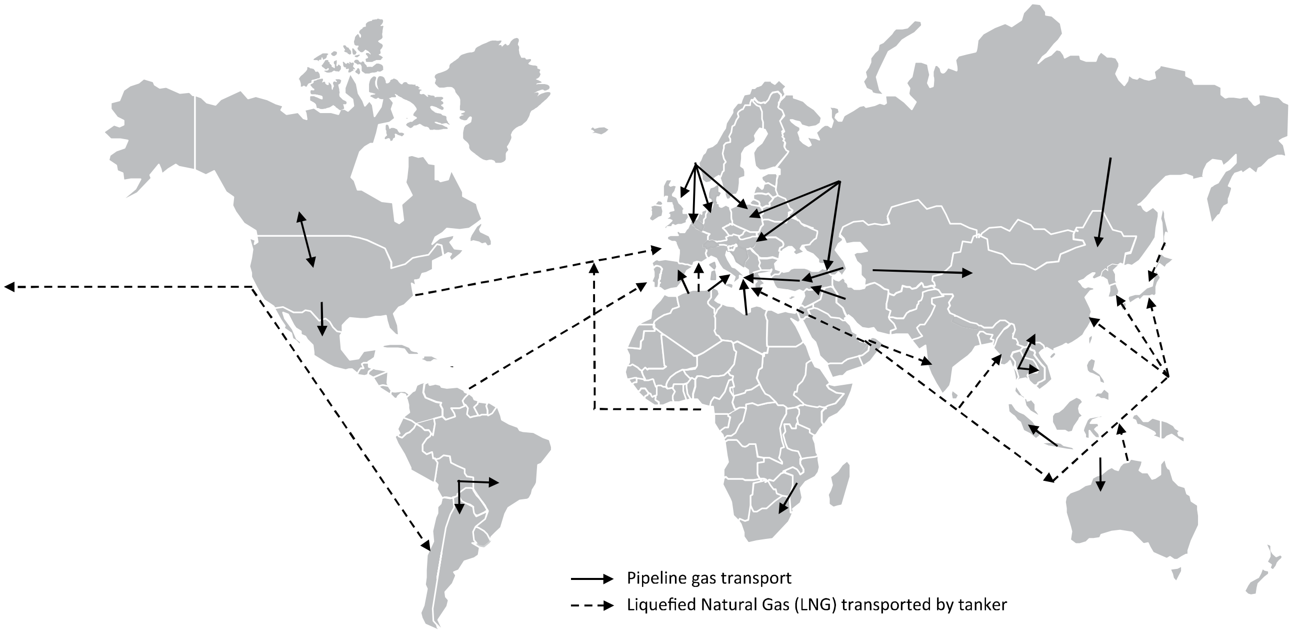
Primary energy resources, like crude oil, coal, uranium and natural gas generally have to be transported from where they are extracted from the Earth to processing or conversion plants, like oil refineries, power plants or hydrogen electrolysis plants. This may involve large-scale, long-distance transport by pipelines, ships or railroads. Figure 3.4 shows the global trade movements of natural gas by pipelines and ships. In contrast, hydro, geothermal and wind and solar energy resources are converted into electrical power on site, requiring the transport of electricity to the end-users. Biomass, with a relatively low density of energy per unit of weight or volume, is often used locally in many forms. But it is also transported over larger distances.

The manufactured energy carriers, or fuels, are transported by ships, pipelines and railroads to large scale users, like power plants or (petro)chemical and other industries, and to the areas of consumption. This is illustrated in Figure 3.5 for both traditional crude oil-based and bio-based fuels. There, local distributors, vendors and petrol stations take care of the distribution to the end-users. The electricity generated in power plants is, via high-voltage transmission lines, transported to regional distribution grids which supply domestic consumers, small commercial users, or public services. Similarly, natural gas is transported via high-pressure transmission pipelines to regional distribution grids which supply the consumers. Geothermal energy has its limitations in being transported over longer distances without large energy losses, but also requires its distribution by pipelines among the end-users. Hydrogen, in its infancy as an end-use energy carrier, is currently mainly transported by truck, but plans exist to create larger scale hydrogen grids, to facilitate an expansion of its use.

Depending on the type of end-use energy, the final distribution varies strongly. Petroleum products, firewood and biofuels are offered to consumers by service stations and retail vendors, supplied from refineries or regional depots. However, the supply of electricity, natural gas and district heating is taken care of by local distribution grids, connecting each and every house or building or business with the supply system. This implies that the expansion and adaption of these distribution systems has to be carried out in close coordination with the patterns of location and of energy consumption and the shifts therein. To a growing extent, the development of so-called decentral generation of solar electricity and the production of green biogas has an impact in functioning of these systems. Indeed, traditionally being operated as one-way supply systems, these developments impose the need to evolve towards a bi-directional modus.

As a consequence, a multitude of possible connections exists between the locations of primary energy production, among the several types of conversion units and with the different end-users. It is obvious that the location of these connections, the modes of transport and the throughput capacities determine the pattern of the energy flows that can be facilitated. Moreover, this pattern is partly a consequence of natural and geophysical and also social characteristics. Indeed, pipelines or wires cannot be constructed in deep seas or across high mountains. Also, their acceptance by the people living in their neighbourhood is becoming a debatable issue lately.

Also, scale is important in relation to the mode of transport. Large volumes of energy, like natural gas or oil that are continuously transported between fixed locations, may benefit from having pipeline connections, if possible. Generally, the larger the scale of the transport capacities in pipelines, the lower the cost per unit of energy transported. This indicates the need to build pipelines which can be used by multiple users. Alternatively, shipping may be a solution, also to transport end-use fuels, which provides more freedom in origin and destination. On land, an alternative may be railroad or trucks, as relatively high-cost options.



Source: *BP Statistical Review of World Energy*, 2021.

Figure 3.4 *Major trade movements of natural gas*

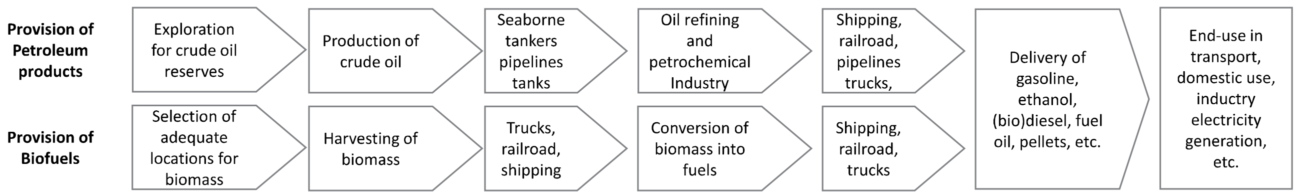


Figure 3.5 Supply chain for petroleum products and biofuels, serving the same type of end-users

Storage

In the production, conversion and transport segments of the supply of energy outlined above, variations in supply and demand may happen which affect the availability of end-use energy and therewith the quality of the services desired. Such variations may have many origins. They may have economically driven causes, such as shifts in supply and demand and prices, sometimes as a consequence of seasonal variations in availability or the need for energy. Other economic causes may involve firms going bankrupt, lagging investments, sudden shifts in the costs of materials and equipment. There may be accidents and technical failures, like fires and explosions in installations and pipelines, collisions with ships, trains, broken cables, etc. These may have natural causes like hurricanes, flooding or lack of water, snowfall and earthquakes. But there also political issues, like wars, strikes, boycotts, embargos, trade conflicts. And there may be social issues, like trade union activism, local protests, civil unrest, extremist environmentalism. In the worst case, such disturbances may cause a breakdown of supply (or demand) on a local, regional or even international scale. In milder cases, disturbances reduce the availability or affect the quality of the energy service supplied (Correlje & Van der Linde, 2006).

Ideally, given the importance of energy as a basic component for the functioning of societies and their economies, the supply chain should have the operational capacity to produce and transport sufficient energy to match peak demand at all times. That, however, would require production, conversion and transport capacities that would go unused much of the time. Indeed, so-called demand peaks occur only occasionally and are often – but not always – predictable. In particular, energy use for heating or cooling purposes exhibits a strong seasonal pattern. The same goes for the production and conversion segments.

Nevertheless, since such problems are bound to happen and supply and demand will always fluctuate, there should be some buffering or storage capacity to overcome disturbances in the production of raw energy, its conversion and transport to the end-users and the variation in end use. So, storage in the several segments of the chain is an important component in the provision of energy. This may involve so-called commercial storage to be employed by firms to manage the more or less predictable day-to-day and seasonal supply and demand fluctuations. But there may also be the need for so-called strategic storage, to overcome supply disruptions of several weeks or even months. These could be operated either by firms or governments. Moreover, there should be some redundant capacity and optionality in the production, conversion and transport of energy. A demand-side alternative is to ensure that end-users can switch to a substitute energy service.

It is important to realize that the feasibility and the cost of storage varies for the different primary resources and end-use forms of energy. Large-scale storage of crude oil, refined fuels, biomaterials and coal is not complex, given sufficient space. Natural gas can be stored in empty gas fields or aquifers at relatively low cost, when these are locally present. Alternatives are more expensive, however. Also, hydrogen can be stored, although this technology is still in development. Local storage of all these fuels is also possible, but the smaller the scale the higher the cost. Electric power, however, is not easy to store on a large scale and it is still quite expensive on a small scale, like in batteries. Generally, for power the solution is to store the primary energy and convert it into electricity when needed. The storage of heat is also a problem, because of the losses over time.

A critical problem for storage is in the provision of sufficient capacity to cover the daily, monthly, seasonal and strategic needs for storing whatever form of energy. But it is economically unwanted to create too much expensive capacity, because then the facility won't be used, and the investment does not create revenues. So, the risk arises that there is underinvestment in sufficient (strategic) storage capacity to cover critical shortages. Moreover, there exists a complex relationship between the price-signalling functioning of a market, for whatever type of energy, and the presence of energy in storage. In short, there exists a discrepancy between 'need for storage' from the social and the system perspective and the incentives for individual firms and operators to create sufficient storage capacity at the 'right' locations.

Supply Chains

From the above, it is obvious that the provision of energy to fulfil the services a society depends on a balanced interaction of a chain of technical functions facilitating the production, the conversion, the storage, the distribution and the end use of the different types of energy (see Figure 3.1). This is true in today's complex society, with a range of sources of primary energy and a variety of types of end-use energy for different purposes and tasks, as much as it was in the past.

It is important to realize that the provision of these various types of energy involves actual supply chains, in which the consecutive segments or functions are connected and interdependent. Figure 3.5 shows the supply chain for petroleum products and for biofuels, serving the same type of end-users. Problems in upstream segments of a supply chain may cascade to downstream segments and cause unwanted shortages in end-use energy. Mid-stream problems may affect both sides of the chain. This primarily affects today's systems in which the supply chain segments are actually physically connected, like in electricity or gas systems, where the networks constitute so-called essential facilities. Yet, also less tightly connected systems now and in the past, like the supply of coal, firewood, peat and petroleum products, are vulnerable to supply disruptions when conversion plants, means of transport, storage facilities or distribution centres are malfunctioning. So, an actual coordination of the functioning and the interaction of the several segments of the system is necessary. On a day-to-day and a seasonal basis supply, conversion, transport and storage facilities have to work together in providing the right volumes of the energy demanded to the end-users in specific locations, at the right time.

Modern energy supply, like electricity for example, often involves a number of these supply chains which are (inter)connected at the several stages, as is shown in Figure 3.6. Indeed, end-use electricity can be produced with coal, gas, hydro or nuclear energy, or in wind, solar and biomass facilities. The operator of the transmission grid selects the plants to provide the electricity needed. Yet, decentral wind and solar generation may also be coupled directly to the distribution grid, or even to the domestic system of the end-user. In end use, alternatives exist for heating and cooking, like electric power, gas, geothermal energy, oil products, and even wood and peat-based fuels. And in transport and the industry, petroleum fuels compete with bio-based fuels, gases and electricity. Hence the question arises how all these technical functions are selected, connected and matched, so that an adequate provision of energy is created.

Over the longer term, energy supply and demand have to deal with other types of potential disruptions and transformations. Here, the problem is in the uncertainties about the development of primary energy resources and technologies in the future, in the development of future demand for energy-specific services and in changing locational and demand patterns.

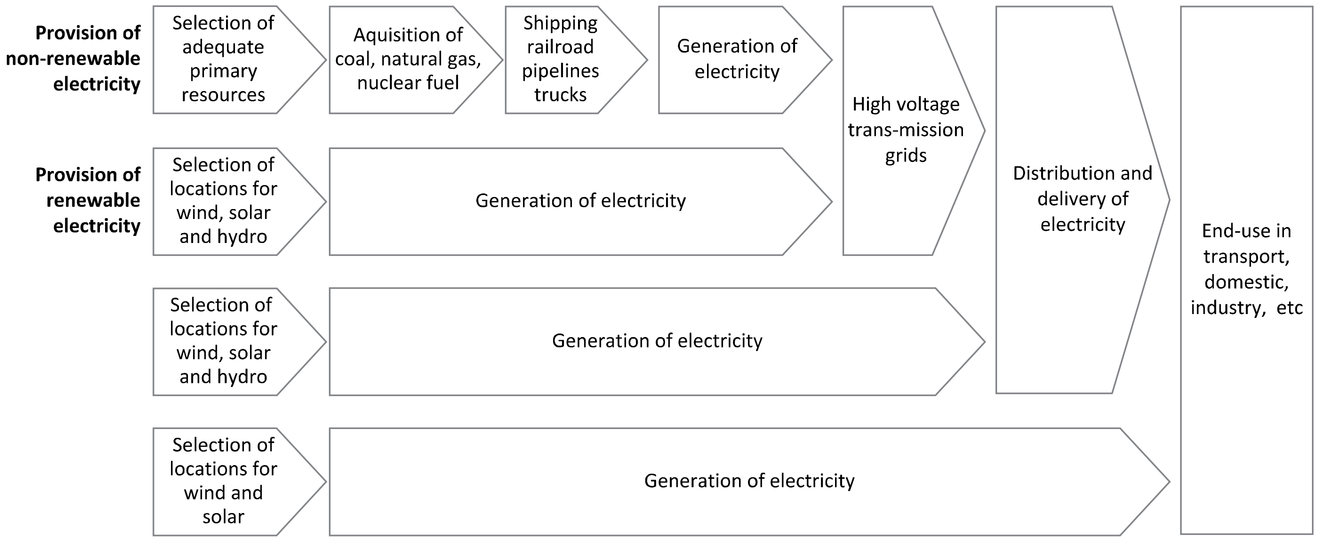


Figure 3.6 Interconnected supply chains in electricity supply

To ensure the availability of energy services in the future, either or not anticipated shifts in the production and end use of energy services must be taken into consideration as far as possible. And they have to be translated by the industry into investments in additional production, transport and storage capacities, in a timely manner and at the right locations.

3. WHAT MAKES THIS WORK?

Value Chains

Once we realize that these supply chains consist of connected technical functions and processes, enabling the manipulation of natural and physical occurrences, stocks and flows of primary energy and energy carriers from the sources to their end use, the issue of coordination becomes important. In the past, the cutting of trees, the gathering of the wood, the transport to areas of end use and the packaging and selling of the firewood in the cities before the cold winter started required a well-timed process of organizing all these activities. Indeed, the right people with their tools and their transport and storage facilities had to be coordinated in their activities, to ensure the availability of sufficient people, tools and firewood at the right time and place. If coordination failed, the consequences were either shortages in wood and hardship, or over-supply, with potentially large economic consequences for the suppliers. The same goes for the provision of other energy carriers, like whale oil, peat and coal, petroleum, electricity and gas later in history. And also today, the energy transition involves the gradual expansion of solar, wind, modern bio-based and other technologies, which has to 'fit' with the decline of fossil fuels, unless the latter are combined with CO_2 sequestration technologies.

So, the manipulation of physical phenomena, like growing trees, peatlands, whales or deposits of coal and petroleum, and the use of wind and solar energy in such a way that they can be turned into useful energy resources, requires a variety of cooperating people (often organized in firms), that see an incentive in engaging in the process of exploitation and provision. Moreover, these people are to be incentivized and enabled to develop and employ the required and socially accepted tools and technologies to operate the separate – but dependent – parts of the supply chain in a more or less harmonized manner.

This implies that, apart from their technical functioning as a supply chain, public and private actors in the several segments have to be able and willing to conclude economic transactions with one another. These transactions arrange for the primary sources to be harvested or mined, and that they are processed, that the fuels or the electricity are transported and or stored and that they are eventually distributed and provided to the end-users. In return, as shown in Figure 3.1, these transactions provide a valuable flow of money from the paying end-users to the operators of these segments of the supply chain. So, the supply chain also functions as a value chain. To be sure, 'value' is not only about the 'simple' exchange of volumes of energy at a price. There are many more aspects to energy transactions, like quality, reliability, ecology, origin, etc., that determine the 'value' to both producers and users.

People, Supply, Demand, Scarcity and Prices

The incentives to supply and to consume are considered to be created in a 'market' were producers and consumers exchange goods or services. They do so at a price reflecting the value suppliers and consumers consider respectively profitable given their cost of production, or acceptable in the light of the utility they acquire. In such a market, prices are determined as a function of scarcity; the balance between the availability of a good via supply and demand, as a function of profits, usefulness and utility. Scarcity creates a high price, which is a signal to start providing something, or to reduce its use and shift to an alternative. This also applies to the separate segments of the supply chain where firms specialize in undertaking specific intermediate tasks, like buying and (re)selling semi-finished products up until the final end use of the good, or providing services such as conversion, transport or storage. Moreover, the creation of new tools and technologies or attempts to 'harvest' new resources are also taken care of by 'entrepreneurial' innovators and creators, in the expectation of generating value and profits by producing new useful technologies, eventually.

The basic understanding of how and when all these people and firms take part in operating the value chain is that they act on their expectations as to what they see as profitable or valuable money-wise. This is essentially how the standard approach to economics explains the coordination of how the several actors involved in the process of production and supply and the consumers act and decide in an 'ideal' market. Nevertheless, in the real world, what people or industries see as profitable, or valuable, or even worthwhile to engage in, is not only a simple matter of given costs, prices and profits or utility.

Market Failures

As explained above, a major issue in the energy system is that it requires coordination between the evolution of demand for energy and the use of capacities in the several segments, to avoid either bottlenecks and shortages, or expensive unused excess capacities. As is generally acknowledged, in the energy system there are serious impediments to the functioning of an 'ideal' market in which supply and demand interact in a balanced manner, swiftly reacting upon the information embedded in prices. The origins of these reservations are various and differ for the various value chains, like petroleum, gas, coal, biomass, electric power, etc. Generally, they are labelled as market failures or market imperfections.

As for the impact of *market failures*, it is argued that the energy market is not to be trusted because of the interaction of large sunk investments involved in production, conversion and transport assets, the lack of information, long lead times of investments and construction, economies of scale, a weak price elasticity of demand, the geological, technical, economic and political uncertainties risk, the small number of producers and the possibilities for opportunistic behaviour.

As regards demand, a crucial aspect of the energy market is that the demand for electricity or fuels is a *derived* demand. Indeed, energy enables end-users to secure specific services, like transportation, heating, illumination, etc. Yet, as such, there is no objective demand for a particular type of energy, but for the most appropriate form of end-use energy. This may be electricity, gas, a petroleum product or even wood, given end-use characteristics and the market and social context. For the shorter term, generally, there are no readily available alternatives, as users will have invested in their appliances and installations at home. When, however, they have to decide upon new appliances there is a possibility to switch to other sources of energy. As a consequence, the short-term price of elasticity of demand for energy is fairly low. The amount of energy consumed is generally dependent on levels of income, economic activities and the weather. Obviously, when prices for a particular energy carrier rise substantially, the inclination to shift to alternatives becomes greater.

Adjustment of the production of different types of energy to shifts in demand does not happen easily either. Investments in production, transport and storage assets are sunk and the capital costs are high and fixed, as compared to the variable cost. Hence, producers of primary energy and conversion facilities will keep on going, as long as their revenues are sufficient to cover the relatively modest variable cost. So, despite oversupply and low prices in the market, firms continue producing while not recovering their full costs. But the corollary is that industry is also slow in committing investments in new capacity when demand surges. Wait and see … Adjustment is slow.

The availability of energy services is a fundamental aspect of each and every society. As is argued above, this is all about the interaction of the technological shape and structure of the different supply chains, with their economic aspects, and the way in which these systems are coordinated. This coordination brought about by the institutional framework that governs both the technical operation of the supply chains, as well as the economic transactions taking place therein. To a greater or lesser extent, the technical and economic characteristics of a system, determine the (necessary) contracting practices and joint ventures of the firms in the chains and their customers. *Vice versa*, the organization of the system influences the selection of technological options (see Correljé et al., 2014).

Industry Coordination

As stated, the value chain for most types of energy involves a number of interfaces, where primary energy, semi-finished and end-use products change hands between the firms active in the several segments of the industry. These interfaces could take the shape of ‘markets’. Yet, as stated above, the market is not trusted. This implies that forms of explicit coordination have always been sought in the energy industry to protect investments and ‘appropriate’ margins to survive business cycles. Here the argument is that commercial and other risk has to be covered, including the risk of potential opportunistic behaviour of other firms in the chain.

Historically, a variety of contractual and ownership structures have been used to coordinate the exchanges, ranging from vertical and horizontal integration to more or less detailed long-term contracts, collective agreements among firms, industries demanding state regulation and spot markets with standardized contracts. Moreover, firms have integrated, forward and backward, into those segments of the value chain where high rents are generated or withdrew when rents were too low. Hence, horizontal cartels have been established between firms to ban competition and coordinate investments. Prominent examples of private ‘market coordination’ are Rockefeller’s Standard Oil in the US at the end of the 19th century and the Seven Sisters cartel of the big international oil companies between 1928 and 1959. Also, OPEC is such a producers’ cartel since the mid-1970s, but then under control of oil producing states (Correljé & Van Geuns, 2011). In the coal, gas and electricity industry, cartels and long-term contracts are a well-known phenomenon, while also the exploitation of biomaterials, like wood, peat, sugarcane, etc. is often ‘managed’.

Public Coordination

Among governments there also is a distrust that reliance on the unfettered market will yield maximum welfare to their economies, however. There is a strong notion that the both the exploitation of energy resources and the provision of energy belong to the ‘national interest’ of a country, not only as drivers of economic activities and social and political stability, but also as a requirement for military strength. So, many governments from producing as well as consuming countries intervene in the energy sector. Traditionally, public authorities have taken a variety of roles, as policy-makers, tax-collectors, in awarding concessions, providers of subsidies, regulators and as owners and operators of public enterprises. So, changing policies, shifts in tax regimes, nationalization or privatization, adjustments in regulatory regimes, geopolitical and strategic objectives and safety issues have an impact on the technical and economic functioning of the value chains. Therewith, public authorities have a strong influence on the use of natural energy resources and the provision of energy services to the end-users. Moreover, the activities in the value chain may take place in different countries. So, these value chains are international and involve several jurisdictions; sometimes cooperating in arranging their energy supply, but also competing with conflicting aims and interests.

Often the coordinative mechanisms and cartels of the industry have been interpreted as *market imperfections*; as firms' collusive attempts in abusing their market power to collect high monopoly rents, by curbing industry output, by fixing prices or by dividing markets among the 'competing' firms. This interpretation has brought about corrective forms of state intervention, ranging from competition policy and the regulation of private firms' monopolistic behaviour to industry nationalization and the establishment state-owned enterprises. Obviously, such interventions by governments have been influenced and inspired by their ideological perspective and by their interests regarding the distribution of the rents in the value chain. Besides, states have also intervened, responding to demands from the industry and consumers for support and protection. Indeed, a crucial element in the energy value chains is the struggle over the rents between producer countries, consumer countries and the industries, governments and consumers involved. This struggle is a consequence of the significant distributional effects that emerge from the different forms of organization and coordination of the firms in the value chain.

Forms of state intervention

There are five basic forms of state intervention in energy systems. The first, most general form of intervention involves the provision of permits and concessions that allow firms to undertake specific activities. Historical examples are the permits to construct wind or water mills and to collect wood from forests, peat concessions, etc. Today, almost every exploitative activity is subject to public planning and permitting procedures, which also establish norms and standards in respect of safety, environmental protection, land-use and spatial planning, emissions, health impacts, etc. Other generically applicable requirements to parties (or substances) concern, for example, the obligation to maintain emergency stocks and quality standards. Such rules apply in varying ways to the segments of the value chain. However, it can be observed that there are large differences in the stringency of these norms between different countries. This variation in stringency does not only apply to the norms as such, but also to the local enforcement of such norms.

The second form of intervention involves the establishment of taxes and levies on specific products and activities, or their subsidization. Such instruments may serve a number of purposes like the redistribution of rents between the several types of consumers, the stimulation or discouragement of specific activities of an industry and among consumers, the protection of the national industry or region and generating income to the state. Important examples are the taxation and levies on production, sales, and export and import of specific energy resources, CO_2 emission taxes and subsidies for renewable energy production or consumption and for innovation.

The third form of intervention implies the outright regulation of activities of an industry. Examples are the granting of (partial) monopoly rights to firms undertaking specific activities, like the exploration for energy resources in a particular area, their production, conversion, transport, storage and retail trading. Also, production, supply and other quota are established for specific types of energy and firms. Import and export of specific types of energy may be controlled. In many countries there is regulation of wholesale or retail prices of crude oil and products, coal and gas and of transport tariffs. Also, investments, the returns on investments and financial elements are controlled. And finally, there are rules in respect of industry locations and obligations for foreign investors to use local labour and other resources; the local content rules.

The fourth form involves public ownership in the industry, either directly controlled by the state or municipalities, or at arms' length via public shareholdings in firms. In the former case, generally, the aim is to actively influence the industry and/or control over the local market, reducing the power of other (foreign) firms. In the latter case the objective is often either revenue generation or financial support. Other arguments for public ownership are the acquisition of technology and access to up- and downstream markets. Public firms may also establish joint ventures with national or foreign private firms.

The fifth approach involves competition policy, under which states seek to reduce the market power of firms, consortia and cartels. This may happen, either through the traditional remedies of competition policy, like a forced fragmentation of the dominant firms or competitive bidding for retail and other concessions, or via the establishment of a countervailing power; often a state-owned firm.

Restructuring the Energy Market

As from the end of the 1970s, the above forms of public intervention and market coordination were increasingly criticized, initially in the Anglo-Saxon world. 'Rolling back the state' á la Margaret Thatcher and Ronald Reagan and the introduction of competition would allow for a more efficient provision of energy, water, public transport and other public services. The traditional perspective had denied the feasibility of effective competition in these sectors. The new hypothesis was that competition would be possible in some segments of the supply systems and that this would improve the performance of the system as a whole. In the energy sector, essentially, only the transportation and distribution segments of the industry were accepted as being a natural monopoly, because of economies of scale and scope, high, sunk, fixed costs of pipeline and power line construction, and low variable costs. The other segments, upstream power and gas production and wholesale and retail trade, were considered to be potentially competitive markets if the industry would involve a sufficient number of firms.

As from the early 1980s, the intervention of states in the energy industry shifted from the direct regulation of private firms' activities and transactions and public ownership, towards the creation of markets by altering the structure of the industry. By providing the consumers, or traders, with a choice with respect to their suppliers and the type of contracts, they would be enabled to select the supplier offering the most attractive conditions. Suppliers, traders and retail sellers were assumed to increase, or protect, their market share by improving supply and price conditions and by developing new marketing strategies. Moreover, they were expected to adjust their operations through the selection of more efficient technologies and mergers and acquisitions, so that they would be able to survive in the newly emerging competitive market.

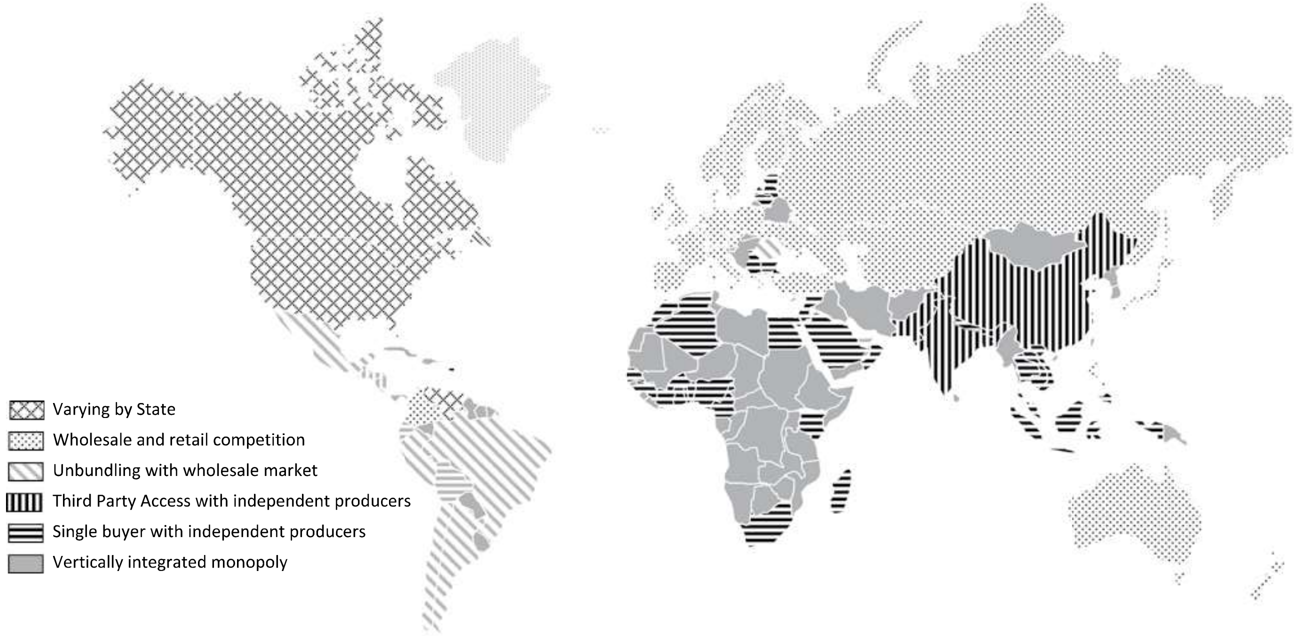
To enable competition in the traditionally vertically integrated utility companies, a variety of stylized models can be distinguished, which have been implemented by national governments, as is shown in Figure 3.7 (see Correljé & De Vries, 2008). The simplest model separates the production or conversion activities from the supply networks and introduces competition among these producers. Producers of gas and power sell in competition with each other to a 'single buyer' utility company. The price of the gas and power sold to the utility is determined through competitive bidding among the producers for a supply contract. The utility takes care of the transmission and the distribution to the consumers. An anticipated dynamic result of this approach is that producers are free to select their production technologies, locations and primary energy sources (coal, gas, wind, etc.), with the objective of enhancing their expected competitive advantage vis-à-vis each other.

A more ambitious model requires utility companies to provide 'third-party access' (TPA) to traders in their transport systems. The essence of this model is that, in competition with the incumbent utilities, new traders appear that purchase gas and power from producers, to sell that to consumers, while using the transport system of the incumbent utility. These new traders would be allowed to sell to large industrial users, in competition with the pre-existing incumbent utility. So, an industrial wholesale market would also emerge. Producers may then benefit because of the increase in the number of potential buyers, whereas large end-users benefit from a greater choice in suppliers and competitive conditions. Incumbent utilities retain the monopoly of supply to small consumers, but they may be able to purchase and resell energy at lower prices too. In addition to the dynamic advantages from the simple model above, this model also creates a certain freedom of contracting, in which traders are able to bargain with industrial consumers over the preferred price structures and supply conditions, including the choice of primary energy sources.

An even more radical model fully separates natural gas and power supply and trading from pipeline transmission, distribution and storage activities. This so-called 'unbundling' should facilitate competition in wholesale and retail markets, by terminating incumbent firms' advantages in controlling access to the transport systems and creating a level playing field for all trading parties. It creates a number of competing supply companies that purchase gas and power in the wholesale markets and resell it to their large and small customers, using the transportation systems of dedicated transmission and distribution companies. Effective wholesale and retail competition should reduce the need for end-use price regulation. Short-term contracts balance supply and demand and provide market participants with the flexibility they need. Liquid wholesale spot markets are expected to emerge, yielding prices that continuously reflect the market value of natural gas and power. In this model, traders are able to bargain with all large and small consumers over the preferred price structures and supply conditions.

This latter model obviously opened the way for all kinds of contracts incorporating qualitative and contractual consumer preferences, like different types of more-or-less green energy, locally generated energy, contract duration, price linkages with the wholesale market. It also opened the door for consumer collectives either buying particular types of energy, or collectively investing in their own local, decentral, production of energy.

A corollary of this market restructuring was that many of the traditional forms of state intervention had to be abandoned, as they would distort the competitive market process.



Source: IEA/OECD (2016) *Repowering Markets: Market design and regulation during the transition to low carbon systems*, Paris.

Figure 3.7 *Models of electricity system organization*

Nevertheless, public policy still seeks to achieve particular objectives, like environmental improvements, CO_2 emission reductions, energy efficiency measures, regional economic development, etc. To this end, the notion of *market-based instruments* emerged. Such policy instruments provide incentives to firms and consumers to alter their activities through taxing or subsidizing processes or products, or by creating tradable property rights for emissions. As a consequence, they are assumed to create competition and innovation among firms in the market in achieving the objectives sought.

4. CONCLUSIONS AND DISCUSSION

The sections above have briefly shown how communities are supplied with the energy they need to support their social and economic activities. The generic overview that we presented here is that of a *system* in which a variety of natural, or geophysical, primary sources of energy are converted into practically usable and attractive energy carriers of various kinds. Providing these energy carriers to the end-users requires the conversion(s), transport, storage and distribution and trading of both primary and end-use energy. These different activities in the several phases of the supply chain are undertaken by means of humans employing particular technologies. Over time, these technologies have been created, selected and employed, drawing on human ingenuity and experience. And this will continue in the future.

In order to make the energy supply chain work, these human activities are to be coordinated. This coordination is organized in 'the market' which provides certain incentives, creating value to human actors in a variety of roles and positions in the value chain. The way in which these incentives arise in such a 'market' and what activities in the chain they support or discourage is strongly determined by the public–private governance of the system, within its broader societal context. It is obvious that the notion of 'value' in the chain is not necessarily limited to the classical economic values like prices, revenues, cost and profits. It also requires the consideration of a much wider set of private and public values that (will) play a role in the choices and approaches made by individuals, collectives, business and public policy in respect of the organization of the supply of energy.

This conceptualization of an energy system enables us to observe and discuss the interactive process in which particular primary sources of energy are employed, the way in which technologies and locations are developed, selected and used to enable this, and how patterns of governance create the particular incentives to actors to produce, convert, transport, buy, sell and use them in a specific way. It helps us in distinguishing and understanding the consequences of local differences in the way this process may evolve. This also includes situations in which the system spans different countries, where both public and private actors have to interact in a more-or-less dependent setting, while the governance in each of these may be different.

In the introduction it was argued that a techno-economic systems approach often involves formalized, mathematical, computational energy models. In parallel, much of the socio-technical systems literature has a tendency to reduce the socio aspects to terms of *agency*, *power*, *multi-actor interactions* and *regimes*, while the technical aspects are reduced to the *materiality* or *non-human* aspects or the *geographies* of systems. Of course, such notions provide a nice high-level characterization of the issues at stake. Yet, the message of this chapter is that such levels of abstraction discount the very concrete connections and interdependencies between natural resources and the way in which available or innovative technologies are (or can be) employed to create and supply useful and societally acceptable energy carriers. This is all about the interaction between public and private actors in value chains, where concrete patterns of values and instruments of governance eventually determine how particular resources, technologies and energy carriers are valued and either or not used to provide energy services to societies.

Obviously, today, the notion of 'a value chain' is an overly simplistic concept, as the energy system is evolving into a complex grid of interconnected value systems, instead of the neatly separated systems for firewood, wind, peat, oil, coal, gas and electric power of the past. Understanding the complexities of energy system integration in a more detailed manner demands a structured approach that connects the nature of the resources, with relevant and newly emerging technologies and the way in which they can be applied in a particular economic and socio-political context, adapting the governance in place, while taking into consideration the prevailing and emerging societal values (Correljé et al., 2022). It is only through such a fine-grained understanding of the complex socio-technical system of energy provision and the conflicts and tensions that arise in the transition that we will be able to replace the unwanted effects and components of the prevailing system.

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