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32961
Sustainable Energy Economics
Reading Sample

Course Unit 1
Economic Foundations of Energy and Sustainability

Fakultät für
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Course Unit 1: Economic Foundations of Energy and Sustainability

Course Unit 2: Energy Markets and Market Transformation

Course Unit 3: Behavioral Insights and Future Energy Pathways

1 Introduction

Imagine a morning without energy

The alarm clock stays silent – no electricity to power it. The shower runs cold, if it runs at all, since the water pump and the boiler both require power. There is no hot coffee or tea, no toasted bread, no refrigerated milk. The commute to work is impossible: petrol engines are idle, electric trains stand still, and traffic lights are dark. At the office, screens remain black, servers are shut down, and heating and lighting are absent. And this module, *Sustainable Energy Economics*, cannot be accessed, let alone studied: no internet connection, no server infrastructure, no device to read on. This brief thought experiment illustrates what energy economists mean when they describe energy as an essential input: a commodity whose absence not merely reduces welfare at the margin but makes modern economic and social life as we know it impossible. Every hour of every day, energy services underpin decisions and activities that we take entirely for granted – until they are gone.

Energy is the lifeblood of modern economies

Virtually every economic activity – from manufacturing and transport to digital communication and household consumption – relies on the continuous availability of energy services. Yet the production and use of energy is also the principal driver of anthropogenic climate change, and the transformation of the energy system is widely regarded as the central economic challenge of the twenty-first century. This course unit develops the conceptual and analytical foundations required to understand how energy markets work, why they often fail to deliver socially desirable outcomes, and how economic theory informs the design of policies for a sustainable energy transition.

The introduction proceeds in three steps. Section 1.1 traces the historical role of energy in economic development and explains why energy is both an indispensable input and a strategic commodity. Section 1.2 introduces energy economics as a specialized field of economics, motivates the use of market-based coordination, discusses the distinctive features of energy markets relative to those in textbooks, and outlines the rationale for energy policy. Section 1.3 finally connects energy with the broader sustainability agenda: it presents stylized facts on global energy use and emissions, develops the economics of climate change as a market failure, and frames the energy transition as a long-term transformation challenge linked to the United Nations Sustainable Development Goals (SDGs).

Two guiding questions structure the remainder of this introduction:

- Why is energy central to economic development and market coordination?
- How does the energy–climate nexus transform energy markets into a sustainability challenge?

Together, the answers provide the analytical lens through which the subsequent chapters on energy demand (Chapter 2) and on energy reserves and sustainability (Chapter 3) – as well as Course Units 2 and 3 – should be read.

1.1 The Role of Energy

Consumption good and production factor

Energy, in its most general physical definition, is the capacity to perform work. From an economic perspective, energy is simultaneously a *consumption good* – directly purchased by households for heating, mobility, or electrical appliances – and a *production factor* that enters virtually every industrial process (Weber et al., 2022). Unlike capital or labor, energy is consumable: it is irreversibly transformed during use and cannot be reused in its original form. This dual role makes energy a peculiar commodity whose availability and price affect both consumer welfare and industrial competitiveness.

From muscle power to industrialization

A glance at human history shows that societal development has been closely intertwined with the mastery of new energy sources (Zweifel et al., 2017). Pre-industrial societies relied almost exclusively on human and animal muscle power, complemented by firewood for cooking and heating. The Neolithic revolution, some 10,000 to 20,000 years ago, was made possible by the systematic exploitation of biomass for agriculture; the use of wind and water power expanded the energy base of advanced civilizations several millennia later. The decisive break came with the first industrial revolution in the late 19th century, when coal replaced muscle power as the dominant energy input, enabling the mechanization of production (see Figure 1). Industrial centers emerged in regions with easy access to coal, giving rise to large-scale urbanization but also to severe environmental problems – the term "smog" combining smoke and fog is a linguistic legacy of London's coal-based economy.

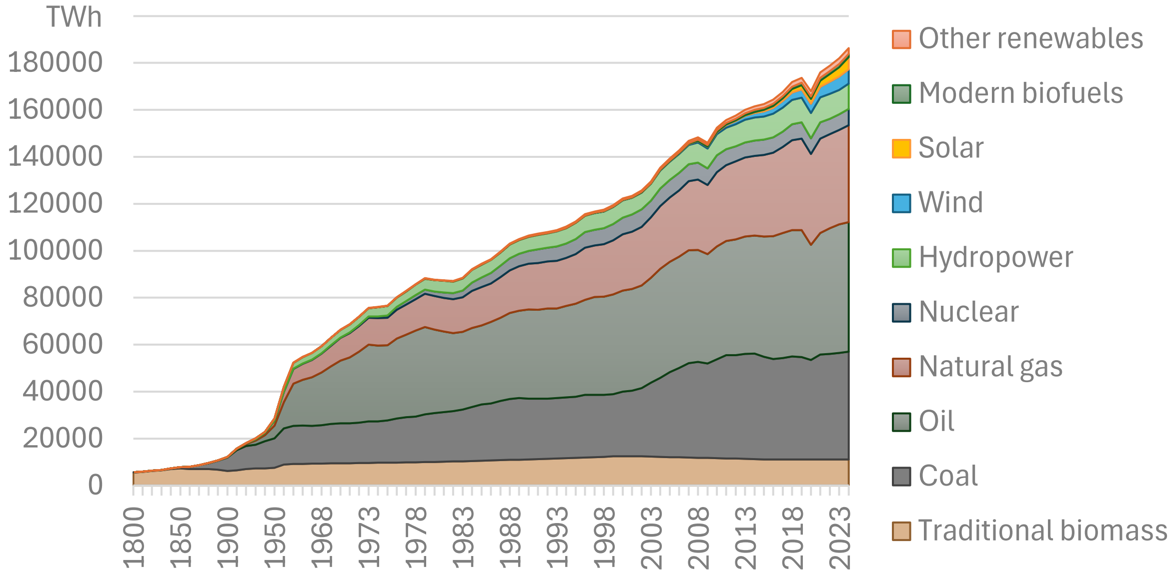

Figure 1: Global primary energy consumption by source. Primary energy is based on the substitution method and measured in terawatt-hours. Data source: Energy Institute - Statistical Review of World Energy (2025); Smil (2017)

From oil to the energy transition

Around the turn of the 20th century, crude oil began to supplement and partly replace coal, particularly in the United States. The relative abundance and high energy density of oil enabled mass mobility, suburbanization, and the global integration of supply chains. After the Second World War, electricity – generated mainly from coal, oil, gas, hydropower, and later nuclear fission – became the energy carrier of the service, information, and communication society. According to the International Energy Agency, global electricity generation more than doubled between 1990 and 2020, growing significantly faster than primary energy supply (IEA, 2025). Today, the energy system is entering a new phase of transformation: the diffusion of renewable generation technologies, advances in battery storage, and the emergence of renewable hydrogen and synthetic fuels are gradually reshaping the value chain from primary energy to final use.

Energy and economic development

The historical relationship between energy use and economic development is empirically robust. Across countries, per capita energy consumption correlates strongly with per capita gross domestic product (GDP), and major productivity gains have typically been associated with the introduction of new energy carriers (Weber et al., 2022). At the same time, the relationship is not deterministic: industrialized economies have demonstrated that further economic growth is compatible with stable or even declining primary energy consumption, a phenomenon known as *decoupling* (cf. Section 1.3.1). The OECD as a whole increased its real GDP by approximately 180 % between 1973 and 2016, while primary energy supply grew by only about 41 % (IEA, 2017) – a pattern of relative decoupling that has continued since, though absolute decoupling remains elusive and the pace of improvement has slowed in recent years (OECD, 2025).

Three broad observations emerge from this brief historical sketch.

First, the structure of an economy and its energy system are jointly determined: technological revolutions in energy provision have repeatedly triggered profound societal and economic change.

Second, each stage of development has been associated with specific environmental externalities – from urban air pollution in nineteenth-century industrial cities to the global accumulation of greenhouse gases today.

Third, the current transition to a low-carbon energy system is the first deliberate, policy-driven energy transition in history, motivated not by the scarcity of incumbent fuels but by the climate constraint on their use. The economic implications of this distinctive feature will be developed in Chapter 3 of this course unit.

Energy and coffee: a telling comparison

Consider coffee as a point of comparison. Like energy, coffee is geographically concentrated – Brazil alone accounts for 38 % of global supply, and together Brazil and Vietnam produce more than half of the world's coffee annually (see Figure 2) – and price volatility, trade dependencies, and supply shocks are familiar features of both markets. The comparison, however, quickly reveals what makes energy distinctive. Coffee is not an essential input: economic activity can continue without it, and it can be substituted by other beverages. It is storable, renewable, and transported via general-purpose infrastructure shared with other traded goods. None of this is true of energy in general, and least of all of electricity. What the comparison ultimately shows is that energy is not a commodity like any other – it is the material basis on which everything else depends.

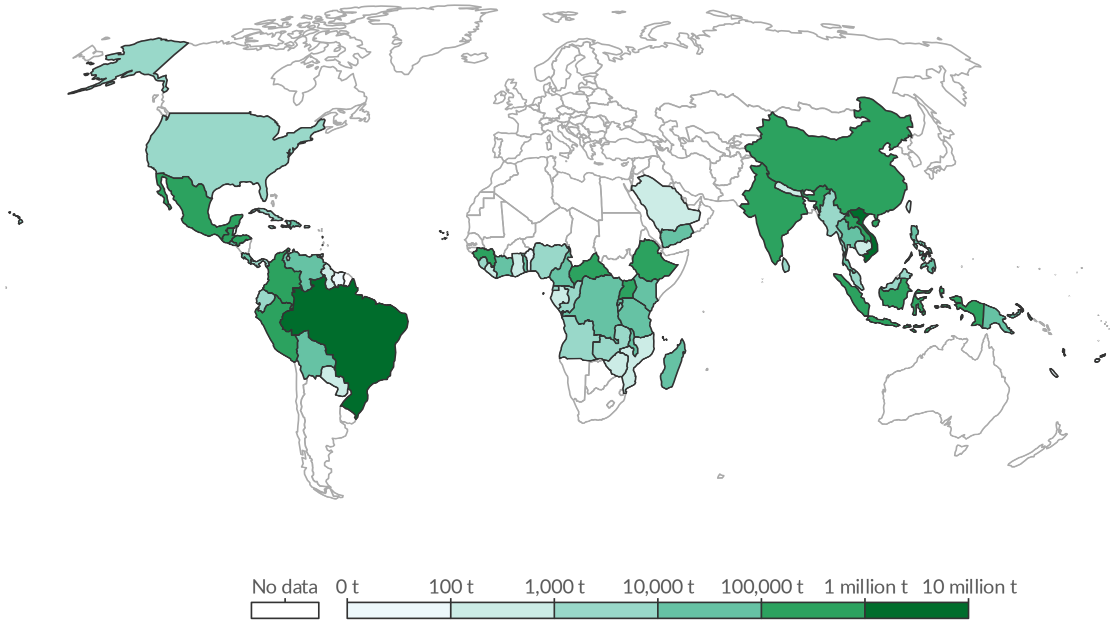

Figure 2: Coffee bean production, 2024. Green coffee beans are coffee seeds (beans) that have not yet been roasted. Data source: Food and Agriculture Organization of the United Nations (2025). OurWorldinData.org/agricultural-production | CC BY

Energy as a strategic commodity

Beyond its quantitative importance, energy therefore also plays a strategic role that no agricultural commodity has achieved on a comparable scale. Many energy resources are unevenly distributed geographically, giving rise to international trade, geopolitical dependencies, and recurring concerns over security of supply. Long-lived infrastructure, such as pipelines, refineries, power plants, transmission lines, ties investment decisions to assumptions about prices, demand, and technology that may prove wrong. This combination of capital intensity and irreversibility lies at the heart of many of the particularities of energy markets discussed in Section 1.2.2. The economic analysis of energy, therefore, cannot be reduced to standard commodity analysis: it requires explicit attention to time, uncertainty, network effects, and political economy.

1.2 Why Energy Economics?

Energy economics applies the tools of microeconomics, industrial organization, and public economics to the production, distribution, and consumption of energy. It treats energy not as a purely technical subject but as the outcome of decisions taken by households, firms, and governments under conditions of scarcity, uncertainty, and externalities. The discipline emerged as a distinct field in the wake of the oil crises of the 1970s, when the strategic and macroeconomic implications of energy supply disruptions became evident, and has since expanded to cover liberalized electricity markets, climate policy, and the economics of the energy transition (Zweifel et al., 2017).

Three reasons justify treating energy as a separate subject of economic analysis. First, the price mechanism plays a particularly visible role in coordinating energy supply and demand, both within countries and across global markets (Section 1.2.1). Second, energy markets exhibit systematic features rooted in the physical, geological, geographical, and technical properties of the energy commodities traded; these features cause real-world energy markets to deviate from the idealized model of perfect competition (Section 1.2.2). Third, these deviations regularly motivate government intervention to correct market failures, secure supply, or align the energy system with broader social objectives (Section 1.2.3).

1.2.1 Pricing and Market Coordination

The price mechanism and Pareto efficiency

In a competitive market economy, prices coordinate the decisions of millions of decentralized actors. The first fundamental theorem of welfare economics states that under conditions of perfect competition – atomistic agents, complete markets, perfect information, absence of externalities and public goods – the resulting allocation is Pareto-efficient: no individual can be made better off without making another individual worse off (Mas-Colell et al., 1995). Equilibrium prices simultaneously convey information about scarcity, provide incentives to economize on inputs, and clear markets by equating consumers' marginal willingness to pay with producers' marginal cost.

The competitive benchmark applied to energy

Applied to energy, this benchmark model yields powerful insights. The wholesale price of electricity, for example, reflects the short-run marginal cost of the marginal generator (see Course Unit 2, ch. 2). The price of crude oil aggregates global information on extraction costs, transport bottlenecks, expected demand growth, and geopolitical risks. The competitive benchmark allows economists to ask normative questions, such as: How much capital should be invested in exploring new energy sources? How much should be allocated to energy efficiency or to the substitution of fossil fuels by renewables? How much abatement of environmental emissions is economically warranted? In an idealized setting, the answers follow from the equality of marginal benefits and marginal costs across all relevant alternatives (Zweifel et al., 2017).

Where the benchmark falls short

The competitive benchmark, however, is far from a faithful description of actual energy markets. Energy commodities are typically not produced under conditions of atomistic competition; price signals are distorted by externalities, by network constraints, and by long-lived investments that respond only slowly to changing fundamentals. A naive application of the textbook model would therefore yield misleading policy conclusions. The role of energy economics is precisely to make the competitive benchmark useful by carefully relaxing each of its assumptions and analyzing the consequences. The remainder of this section sketches the most important deviations.

1.2.2 Particularities of Energy Markets

If energy were a commodity like any other, energy economics would be redundant: the standard microeconomics toolbox would suffice. The reason this is not the case lies in the inherent properties of energy carriers and energy infrastructures that systematically alter how markets function. These properties can be grouped along four dimensions – physical, geological, geographical, and technical – each of which generates characteristic economic consequences (Weber et al., 2022; Zweifel et al., 2017).

Physical properties

Energy obeys the laws of thermodynamics, and these laws translate directly into economic constraints. The first law – conservation of energy – implies that energy is never produced or consumed in an absolute sense, but only converted from one form to another, with each conversion incurring losses. The second law sets an upper bound on the efficiency of these conversions and explains why the useful energy services delivered to consumers are always smaller than the primary energy extracted from the environment. A particularly consequential physical property is the (non-)storability of different energy carriers. Coal, oil, and gas can be stockpiled at moderate cost, smoothing out fluctuations between supply and demand over weeks or months. Electricity, by contrast, must be generated and consumed virtually simultaneously, since direct electrical storage at grid scale is (or has been up to now) technically demanding and economically expensive. This non-storability is the root cause of price volatility in wholesale electricity markets, of the need for ancillary services, and of the very high consumer surplus associated with reliable electricity supply (Weber et al., 2022). Energy density – the amount of usable energy per unit of mass or volume – is another physical property with strong economic implications: it determines transport costs, storage requirements, and the suitability of an energy carrier for particular end uses, which is why hydrocarbons continue to dominate aviation and heavy transport despite progress in electrification.

Geological properties

Fossil energy resources are the product of geological processes spanning millions of years and are, on any human timescale, non-renewable. Their economic exploitation is governed by two distinct concepts that must be carefully distinguished: resources, defined as the total estimated amount of an energy carrier present in the Earth's crust, and reserves, defined as the share of resources that can be extracted profitably with currently available technology and at prevailing prices (Zweifel et al., 2017). The boundary between the two is itself an economic variable: rising prices, technological progress, or improved geological knowledge can shift resources into the reserves category, as the shale oil and gas revolution in the United States has demonstrated. Geological characteristics also vary across deposits in ways that matter economically. Extraction costs typically rise with cumulative production, as the most accessible deposits are exploited first. Reservoir-specific properties such as porosity, permeability, depth, and chemical composition influence not only the cost of extraction but also the environmental footprint and the value of the extracted product. These geological realities give rise to intertemporal allocation problems that lie at the heart of resource economics and are formally analyzed through the Hotelling rule (Chapter 3).

Geographical properties

Energy resources are highly unevenly distributed across the globe. More than half of the world's proven oil reserves are concentrated in the Middle East; natural gas reserves are dominated by a small number of countries, including Russia, Iran, and Qatar; coal is more evenly distributed but still concentrated in a handful of producing nations (IEA, 2025). Renewable resources are no exception: solar irradiation is highest near the equator, productive wind sites cluster along coastlines and in specific topographic settings, and hydropower potential is concentrated in particular river basins. This geographical heterogeneity has three economic consequences. First, energy is a globally traded commodity, with international trade flows shaped by the spatial mismatch between resource endowments and demand centers. Second, transport costs and infrastructure constraints create distinct regional markets – global for oil, increasingly global for liquefied natural gas, predominantly regional for pipeline gas and electricity. Third, geography is a source of geopolitical leverage and supply security concerns: the oil shocks of the 1970s, the European gas crisis of 2022, and the emerging strategic competition over critical minerals for the energy transition all illustrate that the political economy of energy cannot be separated from its geography.

Technical properties

Energy infrastructures are characterized by high capital intensity, long technical lifetimes, and pronounced economies of scale and network effects. Power plants, refineries, pipelines, and transmission lines typically operate for 30 to 60 years, so investment decisions taken today shape the energy system for decades. Many components of the energy value chain – in particular, electricity and gas networks – are natural monopolies: the unit cost of providing transport services declines with throughput over the entire relevant range, making it economically wasteful to duplicate parallel networks. Natural monopolies are therefore typically regulated rather than left to competitive markets, raising specific questions of tariff design and investment incentives (Weber et al., 2022). Network effects also generate coordination problems that markets alone cannot solve: a hydrogen producer will hesitate to invest without secured demand, while a potential consumer will not switch to hydrogen without a reliable supply – the classic chicken-and-egg problem of infrastructure rollout. Finally, the technical complexity of energy systems – the need to maintain frequency and voltage stability, to manage reactive power, and to ensure n-1 security – imposes operational constraints that must be translated into market rules. Modern electricity markets therefore consist not of a single market but of a layered architecture of forward, day-ahead, intraday, and balancing markets, each addressing a different time horizon and a different physical service.

Together, these four sets of properties explain why energy markets cannot be analyzed with the textbook model of perfect competition alone. They give rise to externalities, market power, asymmetric information, and coordination failures, all of which provide the rationale for the energy policy interventions discussed in the next section.

1.2.3 Energy Policy

The energy trilemma

Energy policy can be defined as the set of government interventions that shape the production, distribution, and consumption of energy. Its rationale derives from the particularities discussed above: where markets fail to deliver Pareto-efficient outcomes, government action can, in principle, improve welfare. The challenges of energy policy are typically summarised in the so-called energy trilemma: the simultaneous pursuit of (i) security of supply, (ii) economic competitiveness and affordability, and (iii) environmental sustainability (World Energy Council, 2023; Zweifel et al., 2017).

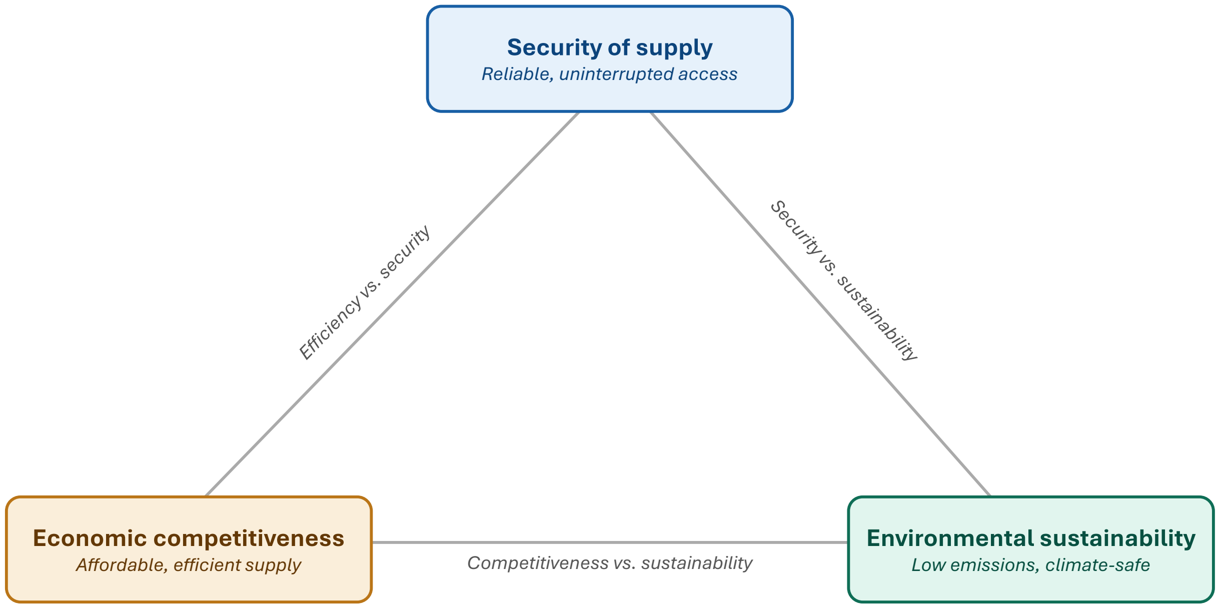

Figure 3: The energy trilemma. Source: own illustration.

Shifting policy priorities over time

The three objectives are sometimes complementary but more often in tension. Improvements in energy efficiency, for example, tend to enhance both cost-effectiveness and environmental performance, illustrating complementarity. By contrast, the rapid phase-out of fossil fuels may improve environmental performance while temporarily compromising supply security or affordability, an example of antagonism. Policymakers therefore face genuine trade-offs that must be resolved through political processes. The relative weights attached to the three objectives have shifted over time. In the 1970s, the oil crises pushed security of supply to the top of the agenda; in the 1980s, attention turned to the risks of nuclear power and the promotion of renewable energy; the 1990s and 2000s were dominated by market liberalisation and competition policy; and since the adoption of the Paris Agreement in 2015, environmental sustainability – and in particular climate neutrality – has become the most prominent objective in many jurisdictions. Russia's invasion of Ukraine in 2022 and the disruption of Middle Eastern oil and gas supply following the Iran conflict in 2026 serve as stark reminders that security of supply can re-emerge as the dominant concern with little warning, fundamentally reshaping the trilemma's internal balance.

Instruments of energy policy

Instruments of energy policy can be grouped along several dimensions. With respect to environmental objectives, a key distinction is between price-based instruments (carbon taxes, fuel taxes, levies), quantity-based instruments (emissions trading schemes, renewable quotas), and command-and-control regulations (emission limits, efficiency standards, technology bans). With respect to investment in low-carbon technologies, instruments range from feed-in tariffs and contracts for difference to investment grants, tax credits, and public procurement. Finally, market design rules in the context of capacity mechanisms, balancing arrangements, congestion management shape the operation of liberalized electricity and gas markets (Weber et al., 2022). Each instrument addresses a specific market failure, and the appropriate choice depends on the underlying source of the problem, on informational requirements, and on distributional considerations.

A central insight of energy economics is that policy interventions are themselves subject to failure. Information asymmetries, regulatory capture, time inconsistency, and political pressures can lead to outcomes that are even inferior to those of the unregulated market. The analysis of energy policy, therefore, requires careful attention not only to the theoretical case for intervention but also to its practical design and implementation.

1.3 Energy, Climate, and Sustainability: What is the Link?

Energy is at the same time the foundation of economic prosperity and the principal source of greenhouse gas (GHG) emissions. Roughly three-quarters of global GHG emissions originate in the energy sector, broadly defined to include electricity and heat generation, transport, industrial energy use, and buildings (IPCC, 2023). Any credible strategy to limit global warming, therefore, has to focus on transforming the energy system.

This section first reviews the stylized facts on global energy use and emissions (1.3.1), then introduces climate change as the paradigmatic example of a market failure and the corresponding economic instruments (1.3.2), and finally discusses sustainability as a long-term transformation challenge (1.3.3).

1.3.1 Energy Use and Emissions

The global energy mix

Global total primary energy supply reached approximately 654 exajoules (EJ) in 2024, up from 536 EJ in 2010, an increase of over 20 % in a decade and a half (IEA, 2025). According to Figure 4, fossil fuels continue to dominate the energy mix, supplying close to 80 % of global primary energy. Renewables, including hydro, wind, solar, biomass, and geothermal, accounted for roughly 15 %, and nuclear power for about 5 %. The energy mix differs substantially across regions: hydropower is dominant in parts of Latin America, coal in China and India, while Europe relies more heavily on natural gas, nuclear, and renewables. A first sign of structural change, however, is becoming visible at the margin. Global energy demand grew by over 2 % in 2024, well above the long-term average of 1.4 % per year recorded between 2010 and 2023, partly driven by record heatwaves and surging cooling demand (IEA, 2025). According to the IEA's Global Energy Review 2026, growth slowed to 1.3 % in 2025, but the composition of that growth shifted markedly: solar PV and natural gas together met more than 40 % of incremental demand, and low-emissions sources combined contributed nearly 60 % of total growth (IEA, 2026). This was the first time on record that a modern renewable energy source, solar PV, accounted for the largest single share of global energy demand growth, supplying more than one-quarter of incremental demand. Nonetheless, the absolute volumes of fossil fuel consumption continued to rise in 2025, albeit at a slower pace than in 2024, and the shares of oil, coal, and gas in the primary energy mix remain broadly unchanged.

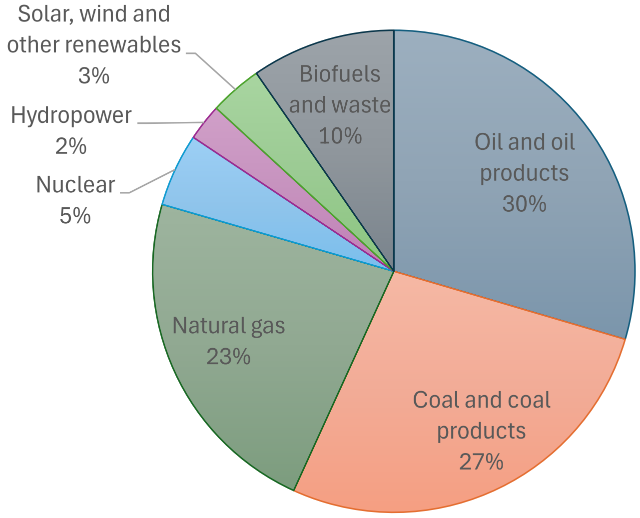

Figure 4: Share in total energy supply by source, World, 2024. Data Source: IEA (2025)

The rise of electricity

Electricity, as a secondary energy carrier, has grown faster than total primary energy supply for decades. Global electricity generation increased from about 6 PWh in 1973 to approximately 29 PWh in 2022, and continued to accelerate thereafter: in 2024 alone, electricity demand surged by around 1,100 terawatt-hours (TWh), nearly twice the long-term average, with record contributions from wind and solar PV (IEA, 2025). In 2025, electricity demand grew at nearly three times the rate of overall energy demand, confirming what the IEA has described as the onset of an Age of Electricity (IEA, 2026). Electrification of end uses, from industrial heat pumps to electric vehicles, is widely expected to accelerate further as part of the energy transition (Weber et al., 2022). Reflecting this structural shift, the carbon intensity of electricity supply has begun to decline: renewables now account for roughly one third of global electricity generation, up from about one fifth a decade ago, and their share continued to rise in 2025 as record renewable capacity additions, some 800 gigawatts (GW) globally with solar PV alone accounting for three quarters of new installations, surpassed total growth in electricity supply (IEA, 2026). Globally, however, fossil fuels still generated close to 60 % of electricity in 2024, down from 66 % in 2015 (IEA, 2025).

Emissions and the carbon budget

On the emissions side, global CO_2 emissions from energy combustion and industrial processes reached an all-time high of around 38 gigatonnes (Gt) in 2024 (see Figure 5). Rather than declining, emissions set a new record again in 2025, rising by a further 0.4 % to exceed 38 Gt for the second year running, a level consistent with trajectories far above the Paris Agreement's 1.5 °C temperature target (IEA, 2026). Cumulative CO_2 emissions since the beginning of the industrial era are now estimated at well over 2,400 Gt, narrowing the remaining carbon budget compatible with the 1.5 °C target to roughly 380–400 Gt as of 2024 (IPCC, 2023). In addition to CO_2, the energy sector emits methane (CH_4) from coal mining, oil and gas extraction, and biomass combustion; nitrous oxide (N_2O) from biomass burning; and a range of local air pollutants, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, and heavy metals, with significant adverse effects on human health and ecosystems (Weber et al., 2022).

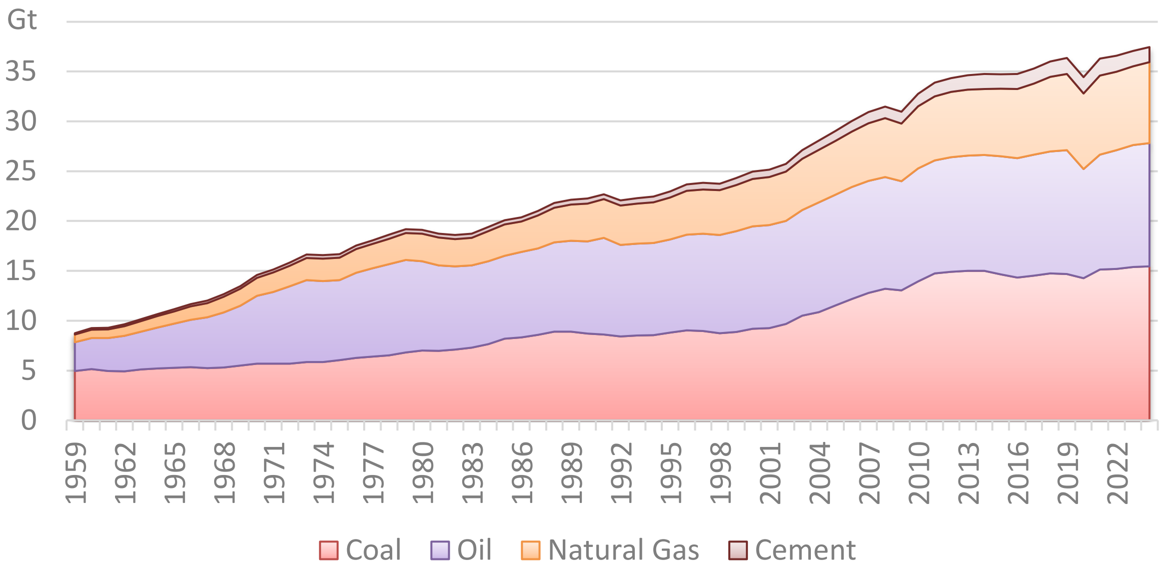

Figure 5: Annual CO_2 Emissions by Fossil Fuel, 1959–2024. Data Source: Global Carbon Project (GCB2024); Andrew & Peters (2025)

Economic growth and energy decoupling

An important stylized fact concerns the relationship between economic growth and energy use. In industrialized countries, a relative and partly absolute decoupling between GDP and primary energy supply has been observed since the 1970s. OECD primary energy supply has grown by approximately 41 % since 1973, while real GDP has grown by about 180 % (IEA, 2017), a pattern that has continued in subsequent years, though the pace of improvement in energy intensity has slowed: the IEA estimates that global energy intensity fell by only 1.1 % in 2024, well below the rates of 2 % or more recorded in the 2010s (IEA, 2025). The decoupling reflects a combination of structural change from energy-intensive manufacturing to services, efficiency improvements, and, more recently, the partial substitution of fossil fuels by renewable electricity. In many emerging economies, however, energy consumption continues to grow rapidly alongside income, and the decoupling of CO_2 emissions from GDP, the more relevant indicator from a climate perspective, has so far been less pronounced.

Taken together, the stylized facts establish three key points.

First, the energy sector dominates global GHG emissions; without a fundamental transformation of energy production and use, the climate goals of the Paris Agreement cannot be reached.

Second, the energy mix is highly inertial: fossil fuels still account for close to 80 % of primary energy supply, and the rate of change required to meet the 1.5 °C target is unprecedented, even as record volumes of renewable capacity are added annually.

Third, the distributional dimension of energy use is significant, both between rich and poor countries and between current and future generations. These three features motivate the deeper economic analysis in the subsequent sections.

1.3.2 Climate Change and Market Failure

Climate change as market failure

From an economic perspective, climate change is the largest and most pervasive market failure ever observed (Stern, 2007). Greenhouse gas emissions arising from energy production and use generate global external costs – damages to third parties that are not reflected in the market prices of fossil fuels. In the absence of corrective intervention, energy is therefore systematically underpriced relative to its social cost, leading to overconsumption of fossil fuels and underinvestment in low-carbon alternatives.

The Pigouvian tax

The analysis of externalities dates back to Pigou (1932), who argued that activities that generate external costs should be subject to a tax equal to the marginal external damage, so as to align private with social marginal cost. The condition for the welfare-maximizing emissions level is that the marginal benefit of an additional unit of emission, measured by the marginal profit foregone if the emission is avoided, equals the marginal external cost it imposes (Zweifel et al., 2017). A Pigouvian tax set at this level internalizes the externality and restores Pareto efficiency.

The Coase theorem and its limits

An alternative perspective is offered by Coase (1960). The Coase theorem states that if property rights over the environment are clearly assigned and transaction costs are negligible, private negotiations between polluters and affected parties will lead to a Pareto-efficient outcome irrespective of the initial allocation of property rights. The theorem highlights the role of property rights in environmental economics and provides the intellectual foundation for tradable permit schemes (Zweifel et al., 2017). In practice, however, the assumptions of the Coase theorem are rarely satisfied in the context of climate change: transaction costs are enormous, causality is diffuse, the number of parties is essentially the entire world population, damages have very long latency periods, and many of those affected (future generations) cannot participate in negotiations at all. These limitations explain why climate policy is dominated by government instruments rather than by decentralized Coasian bargaining.

The economic toolkit for climate policy comprises three main instrument families:

Price-based instruments – carbon taxes and emission-based fuel taxes – set a price on emissions, allowing polluters to decide how to respond. Their main advantage is cost-effectiveness and certainty about the carbon price; the main disadvantage is uncertainty about the resulting emissions level. They can generate substantial public revenue, which may be recycled to reduce other distortionary taxes (“double dividend”).

Quantity-based instruments – emissions trading schemes (ETS), such as the EU ETS – cap aggregate emissions and allow market participants to trade allowances. They guarantee an environmental outcome but introduce price volatility, which complicates investment planning. ETS designs differ along many dimensions, including coverage, allocation methods, banking and borrowing rules, and price stability mechanisms.

Command-and-control regulations – emission standards, technology mandates, efficiency requirements – directly prescribe behavior. They are conceptually simple and politically often easier to implement, but typically less cost-effective than market-based instruments because they do not exploit differences in marginal abatement costs across emitters.

Beyond carbon pricing

In addition to these instruments addressing the climate externality directly, energy policy uses a wide range of complementary tools – subsidies for renewable energy, investment grants for grid expansion, support for research and development, public procurement of low-carbon technologies – that address specific co-existing market failures such as learning-by-doing externalities, capital market imperfections, and network coordination problems. The economic case for such instruments must be made on a case-by-case basis: each policy should be justified by a specific market failure that the price of carbon alone cannot correct (Acemoglu et al., 2012).

The social cost of carbon

A particular feature of climate externalities is their intertemporal character. Emissions today cause damage over decades and centuries, so the optimal carbon price depends on how we discount future damages. The choice of discount rate has enormous consequences for the inferred social cost of carbon (SCC), as illustrated by the diverging conclusions of the Stern Review (Stern, 2007) and Nordhaus (2017). Estimates of the SCC range from a few tens to several hundred euros per tonne of CO_2, reflecting differences in assumptions about damages, discounting, and risk aversion. This intertemporal dimension also distinguishes the climate problem from classical pollution problems with localized, short-term damages, and it links climate economics directly to the broader question of sustainability (Section 1.3.3) and the economics of exhaustible resources (Chapter 3).

1.3.3 Sustainability as a Transformation Challenge

The concept of *sustainable development* was prominently defined by the Brundtland Commission as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 41). While the definition is intuitively appealing, its operationalization in economic models has led to a rich literature that distinguishes among alternative notions of sustainability.

Weak and strong sustainability

A standard distinction is between *weak* and *strong sustainability* (Zweifel et al., 2017). Weak sustainability assumes that natural capital (resources, ecosystems) and man-made capital (machines, infrastructure, knowledge) are substitutable: a decline in natural capital can be compensated for by an equivalent increase in man-made capital, so long as the total capital stock is non-decreasing. The Hartwick rule (Hartwick, 1977) and the work of Solow (1974) formalize this idea by showing that, under restrictive conditions, constant consumption can be maintained over time if the resource rents from extracting an exhaustible resource are fully reinvested in reproducible capital. Strong sustainability, by contrast, regards certain forms of natural capital – the climate system, biodiversity, key ecosystem services – as essentially non-substitutable and therefore subject to absolute limits. Climate policy in the spirit of the Paris Agreement leans toward the strong-sustainability paradigm: the global mean temperature increase is treated as a binding constraint that cannot be offset by additional man-made capital.

Environmental, economic, and social dimensions

Sustainability in the energy sector is multidimensional. It encompasses *environmental* aspects (climate change, air and water pollution, land use, biodiversity), *economic* aspects (efficiency, affordability, productivity, innovation), and *social* aspects (energy poverty, distributional fairness, public health, democratic participation). These dimensions are interrelated and sometimes in tension. Carbon pricing, for example, may increase the affordability burden for low-income households unless accompanied by appropriate revenue recycling. The siting of wind turbines or transmission lines may improve aggregate welfare but generate local opposition. The phase-out of coal mining affects regional employment and may require structural support to be politically sustainable.

The UN Sustainable Development Goals

The United Nations 2030 Agenda integrates these dimensions in a set of 17 *Sustainable Development Goals* (SDGs) adopted in 2015 (UN, 2015). Several SDGs are directly relevant for the energy sector: SDG 7 calls for affordable, reliable, sustainable, and modern energy for all; SDG 13 demands urgent action to combat climate change; SDG 9 addresses resilient infrastructure and sustainable industrialization; SDG 11 covers sustainable cities and communities; and SDG 12 addresses responsible consumption and production. Energy decisions are therefore embedded within a broader framework that explicitly recognizes the interplay among economic, social, and environmental objectives (Weber et al., 2022).

Sustainability as a transformation challenge

Sustainability as a transformation challenge differs from the standard problem of efficient resource allocation in three important respects. First, it involves *structural change* rather than marginal adjustments: replacing the fossil-based energy system requires the simultaneous transformation of generation, networks, end-use technologies, business models, and consumer behavior, with significant interactions and coordination problems. Second, it requires *long-term investment under deep uncertainty*: asset lives of 30 to 60 years exceed any reliable forecast horizon for prices, technologies, or policies, and capital decisions taken today shape the system far into the future. Third, it raises questions of *intergenerational coordination*: the costs of climate mitigation are borne primarily by current generations, while the benefits accrue mostly to future ones, creating a fundamental commitment problem that economic and political institutions must address.

Analytical tools for the energy transition

Modern energy economics has developed analytical tools tailored to this challenge. Resource economics provides intertemporal optimization models that determine the efficient extraction path of exhaustible resources under a climate constraint (Chapter 3). Investment theory under uncertainty – real options analysis, scenario planning, robust optimization – informs decisions on capital-intensive infrastructure. Behavioral economics complements the standard rational-choice framework by recognizing biases, social preferences, and bounded rationality that affect energy decisions (Course Unit 3). Integrated assessment models combine climate science with economic analysis to quantify trade-offs between mitigation, adaptation, and damages. Together, these tools form the analytical backbone of the sustainable energy transition.

Three guiding insights conclude this introduction.

First, energy is too important – both economically and environmentally – to be left to market forces alone, but it is also too complex to be governed by central planning. The pragmatic task of energy economics is to design markets and policies that combine the informational and incentive advantages of decentralized decisions with corrective interventions where market failures are most severe.

Second, the climate constraint has fundamentally altered the economics of energy: scarcity is no longer driven primarily by the depletion of fossil reserves but by the atmosphere's limited capacity for absorption. This shift transforms the analytical framework, as discussed in Chapter 3.

Third, the energy transition is a generational project that demands a long-term, system-oriented perspective.

The remaining chapters of this course unit, and the subsequent course units of the module, develop the conceptual, empirical, and methodological tools required to engage with this project as an economist.

1.4 References

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