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Ph.D. PROGRAM IN INDUSTRIAL ENGINEERING

DOCTORAL THESIS

ANALYSING AND MODELLING THE VARIABILITY OF RENEWABLE ENERGY SOURCES IN THE ENERGY TRANSITION

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Resumen

El uso de la energía ha jugado un papel fundamental en el desarrollo social desde los comienzos de la humanidad, permitiendo la expansión de su nicho ecológico a través del aprovechamiento de los potenciales físicos disponibles en la naturaleza. Sin embargo, hoy día nos enfrentamos al gran reto de reducir las emisiones que generan efecto invernadero por el uso masivo de recursos fósiles (materia orgánica fosilizada). La amenaza de extinción de ecosistemas enteros que permiten al ser humano perpetuarse como especie obliga a modificar el *modus operandi* que permite sostener el grado de complejidad social que hemos alcanzado como civilización. Para ello, parte de la academia aboga por transitar hacia sistemas energéticos 100% renovables.

Los modelos de evaluación integrada (IAM, por sus siglas en inglés de *integrated assessment model*) se emplean en el asesoramiento de políticas internacionales en materia de cambio climático y transición energética. Dado el amplio marco del sistema analizado están centrados en representaciones globales, por lo que su escasa resolución temporal no permite obtener resultados satisfactorios para el análisis energético. Las estocásticas, intermitentes, generaciones renovables fluctúan la potencia de generación de acuerdo con el recurso instantáneo presente. A pesar de la existencia de numerosas opciones para gestionar la estabilidad del sistema, no existe una única planificación energética óptima.

Objetivos

Primero, la identificación del campo de estudio en lo referido a métodos empleados y discusión vigente sobre sistemas regionales 100% renovables. Segundo, estudio y validación

de modelos de análisis de la variabilidad energética en el sistema eléctrico, con especial énfasis en Europa y el Estado español. Tercero, desarrollo de modelado de análisis energético horario para modelos de evaluación integrada.

Metodología

El proceso de investigación ha comenzado con una revisión de literatura. Posteriormente, tratamiento de datos disponibles y aplicación de estadística inferencial. Finalmente, el empleo de la metodología de dinámica de sistemas para conceptualizar y modelar retroalimentaciones en el modelo de evaluación integrada objetivo.

Resultados

Primero, se han identificado líneas de investigación emergentes desde la biofísica en la discusión sobre sistemas energéticos 100% renovables; reconociendo barreras técnicas, naturales y sociales en un panorama heterogéneo donde las herramientas computacionales están aún en intenso desarrollo. Segundo, el análisis estadístico sobre el caso del Estado español ha identificado diferencias en los patrones de generación renovable y consumo eléctrico, tanto estacionales como diarios y horarios. Además, las proyecciones a futuro han mostrado la magnitud de las necesidades de almacenamiento y transmisión interestatal hasta 2050 derivadas de la enorme apuesta "verde", alcanzando una eficiencia máxima del sistema eléctrico idealmente en 2035, y cayendo drásticamente desde 2040 en adelante. Tercero, se propone una configuración de sistema energético 100% renovable para España en 2050 sobre los balances de energía oficiales, detallando cada política aplicada por sector y tipo de energía. Se descubre así el papel fundamental que tomarán las tecnologías de acoplamiento entre el sistema eléctrico y el de calor, un incipiente sector del hidrógeno, y la profunda transformación del transporte. Estos convertidores entre tipos de energía (tecnologías "power-to-X") se explican a lo largo del documento, y gradualmente se cuantifican en la transición energética conceptualizada para el Estado español. Cuarto y último punto son los dos métodos reproducidos en IAMs para integrar la variabilidad renovable y sus efectos derivados, acompañados de resultados y limitaciones a superar.

Conclusiones

España es un buen caso de estudio por los datos disponibles y variabilidad en las condiciones meteorológicas de la región. La inmovilidad por nuevas instalaciones que flexibilicen el sistema eléctrico en esta región supondría un incremento exponencial de los cortes de generación (*curtailment*), afectando negativamente al sistema energético. La planificación de un sistema 100% renovable para esta región es posible con el modelo energético de resolución horaria empleado, sin caer en valores energéticos muy bajos para un estándar de vida decente. El despliegue de opciones de flexibilidad para el sistema energético planteado por el PNIEC ha de ser gradual siguiendo cierto orden de prioridades.

La hora, como unidad de análisis, se ha demostrado suficiente para la planificación energética nacional e internacional, aunque una mayor resolución permitiría reconocer un mayor conjunto de variables.

La metodología aportada en el capítulo 5 permite proponer recomendaciones de planificación energética de forma transparente y justificada.

La interdisciplinaridad holística del trabajo ha permitido reconocer la importancia de los efectos de retroalimentaciones entre diferentes campos de estudio, en detrimento del detalle tecnológico, a la hora de abordar propuestas en materia de transición energética.

Abstract

Since the very beginning, energy has been crucial for the development of societies. Physical opportunities have converted potentialities to a real expansion of the human ecological niche. Once more, humanity faces a great challenge. The climate is changing, bringing with it dangers around the world that prevent new forms of life and harm the ecosystems that really support our species. One particular solution has claimed to be able to tackle the problem; that is, converting to a 100% renewable energy system while also trying to maintain a sustainable social complexity.

Photovoltaic solar power, onshore and offshore wind, and hydropower energy sources are the most prominent available technologies to sustain these decarbonized systems. However, an emerging discussion demands further modelling and analysis of the feasibility of fully renewable energy systems. One of the difficulties is related to the intermittent (stochastic) fluctuations that dramatically affect the traditional stable fossil fuel power system. Although there are several options to manage this intermittency, there is no unique configuration for energy planners.

Integrated assessment models (IAMs), traditionally focused on global representations, often lack high temporal resolution; so complementary technical models are employed to design the portfolio of generation capacity. This has been the main problem addressed in this doctoral thesis. Solving the gap in IAMs has required experiments in the field of statistics, mathematics, and system dynamics, among others.

The results obtained in this thesis have revealed significant findings. First, from a literature review, we have emerging research lines on the contribution of biophysics in the discussion concerning 100% renewable energy systems. Technological, natural, and social barriers have been recognized across papers, showing a non-homogeneous field where tools are intensively under development. Second, the statistical analysis of the variability of renewable energy sources in Spain has identified different seasonal, daily, and hourly patterns of electricity consumption and production. Furthermore, the future projection of this statistical exercise stresses the relevance of storage and transmission capacity in the analysed regions by 2030 and 2050 due to high, renewable contributions, reaching a maximum performance of the power system in 2035, falling sharply after 2040. Third, the use of an hourly energy model has justified a pathway towards a system only running with renewables for Spain, proposing policy recommendations from 2017 to 2030 and 2050. According to official categories, a detailed list of policies is shared by sector and fuel. The role of novel power-to-X and storage technologies are explained and gradually quantified in the conceptualized energy transition. Fourth, two methods are constructed to represent VRES in IAMs, reporting coherent results and limitations.

Three research articles contribute to the discussion concerning a deep integration of variable renewable energy sources (VRES) in the energy system of IAMs, with Spain as the case study.

Table 1: Abbreviations

Abbreviations	*Definition*
AFOLU	Agriculture, forestry, and other land uses
CCS	Carbon capture and storage
GEEDS	Group of Energy, Economy, and System Dynamics
GHG	Greenhouse gas
GIS	Geographical information system
$GtCO_2eq$	Giga tons of equivalent dioxide emissions
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
RES	Renewable energy source
SD	System Dynamics
VRES	Variable renewable energy source

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A mi madre, Teresa, en el año de su recuperación. A las que han formado parte de mi vida en el pasado y el presente.

Agradecer a mi familia – en versión extendida – y a mis amistades los tiempos compartidos, incluyendo quienes me han aguantado en trabajos dentro y fuera del Grupo de Energía, Economía y Dinámica de Sistemas y del Departamento de Ingeniería de Sistemas y Automática de la Universidad de Valladolid. Mención especial merece Alan Hynds, por su maravillosa corrección de la escritura inglesa, de la cual he aprendido más y mejor el idioma foráneo.

Un proyecto tan amplio como Locomotion genera mucho más que lazos académicos o profesionales. Desde los Balcanes hasta las frías tierras del norte de Europa, y desde la Iberia hasta las islas del Mar del Norte, pasando por el Mediterráneo. La transdisciplinariedad exige apoyo mutuo y honestidad entre quienes desarrollan tareas de investigación, un ámbito tan amable y dura como se quiera por todas las partes implicadas. A buen seguro que la simbiosis de conocimientos dominará la Universidad en todos sus ámbitos de aquí a una década, por lo que agradezco en general participar en este emocionante viaje hacia delante.

Dedication

"...Porque vivimos a golpes, porque apenas si nos dejan

decir que somos quien somos,

nuestros cantares no pueden ser sin pecado un adorno.

Estamos tocando el fondo.

Maldigo la poesía concebida como un lujo

cultural por los neutrales

que, lavándose las manos, se desentienden y evaden.

Maldigo la poesía de quien no toma partido hasta mancharse.

Hago mías las faltas. Siento en mí a cuantos sufren

y canto respirando.

Canto, y canto, y cantando más allá de mis penas

personales, me ensancho.

...

Quisiera daros vida, provocar nuevos actos,

y calculo por eso con técnica, qué puedo.

Me siento un ingeniero del verso y un obrero

que trabaja con otros a España en sus aceros"

La poesía es un arma cargada de futuro.

Rafael Gabriel Juan Múgica Celaya Leceta. Poeta e Ingeniero.

Chapter 1
Introduction

This chapter has the reader as objective, to clarify what, who, where, when, and why this dissertation has been conceptualized and materialized. Let us answer these questions through a formal scheme.

This doctoral thesis has been developed within the Recognized Research Group named the Group of Energy, Economy, and System Dynamics (GIR-GEEDS in Spanish) of the University of Valladolid (UVa). The research of this group is interdisciplinary, covering topics in energy, economy, environment, and social affairs. System dynamics (SD) is the principal methodology used in the group to conceptualize and discuss complex relationships in holistic systems. The SD software used to measure such systems in the normal, everyday work is Vensim DSS.

The major research line of the group is the development of integrated assessment models (IAMs), whose purpose is the quantitative representation of the world, aiming to answer questions regarding sustainability, climate change, and energy transition. As one may expect, these models are demanding ever greater detail to surpass both the high-quality requirements of European projects and the scientific gaps traditionally avoided for the sake of simplicity. The modelling project involving and funding this work has been LOCOMOTION[1], a new generation of IAM developed from previous relative models developed by the research

[1] LOCOMOTION project: "Low-carbon society: an enhanced modelling tool for the transition to sustainability" (01-06-2019 to 21-05-2023). H2020-LC-CLA-2018-2. Project Number 821105. The website of the project is https://www.locomotion-h2020.eu

group, i.e., MEDEAS[2] and WoLiM[3], together with other partners with knowledge of other IAMs, such as World6, TIMES, LEAP, GCAM, or C-Roads.

Specifically, GEEDS has highlighted, along the conclusion sections of the published articles as well as in internal discussions, the limitations to providing a good representation of the variability of renewable energy sources. This modelling becomes relevant in scenarios of energy transition, where the resource imposes the availability of energy in the short term, scenarios that are, indeed, very real nowadays. In addition, the exploitation of variable energy sources also takes place in the specific research line of GEEDS concerning the energy return on (energy) invested (EROI). As we shall see, the infrastructure required to manage increasing contributions of the so-called *clean energy* assumes extra energy costs, a penalty in the famous indicator.

Overview and personal perspective of the role of energy in the society

Which type of society we want to imagine and promote? This should be the starting point to develop a set of policy recommendations to bring our concerns about climate change and usage of fossil fuels to reality. After the society is defined, sciences and engineering came into play for estimating the demands, capacities, potentials, i.e., the feasibility of proposals and their effects into the real world. Then, around a feedback loop, the system is analysed again to further comprehend and improve the knowledge about it and how-to-do manuals for assessment.

My interest in this area of research arose when reading about the following three questions:

- How many energy transitions have there been in human history?
- What role has energy played in such transitions?

[2] A scientific explanation of the MEDEAS model, including the scope and results can be found in (Capellán-Pérez et al., 2020).
[3] There are two publications of the GEEDS group with this model, (Capellán-Pérez et al., 2014) and (Capellán-Pérez et al., 2015).

- How can energy transitions be studied from an engineering perspective?

These questions are certainly the competence of interdisciplinary research. In general, I see interdisciplinary as a necessary collaborative element that looks for the synthesis of diverse – or even diffuse – knowledge on the same topic. Thus, this thesis should be looked at as a small step on the road to coherently representing energy transitions and, especially, those fully based on variable renewable energy sources[4]. The lack of social aspects in energy planning has been a shock to my mind in not a few situations; while I have been pleasantly surprised in cases where anthropological research is found, focusing the attention on the role of energy in societies.

Here in GEEDS, I have met colleagues with similar worldviews and interests in the modelling of how we understand the energy system as a principal agent of the social metabolism, and how it is responsible for the current anthropogenic impacts of humans on nature.

Objectives

Founded on this context, the doctoral thesis has been promoted to achieve the following objectives.

Objective 1. The development and validation of a statistical model to analyse the variability of renewable energy sources in the power system.

The accessibility to real data has allowed the statistical analysis of hourly, daily, and seasonal variability in Spain. Imports/exports, pumped hydropower storage and curtailment are common options to make the balance between supply and demand more flexible. How these may progress over time will show a first analysis of the consequences of installing new

[4] Variable renewable energy sources (VRES) define five technologies: solar photovoltaic, wind onshore, wind offshore, run-of-river hydropower (without storage), wave and tidal marine power.

capacities of wind and solar power technology. This objective aims to answer the following questions:

- Can statistical distributions be justified to represent the energy variability in the Spanish power system?
- What would happen if solar and wind technologies were taken on by 2050 in Spain?
- Given the traditional options to manage such variability, how relevant are they in the Spanish energy transition by 2030, 2040 and 2050?
- If a metric is applied to measure system performance, how would it vary over time during that transition?

Objective 2. Analysis of the energy system in Spain through the EnergyPLAN tool.

EnergyPLAN is an energy simulation model that emerged from the concept of *smart energy system* in Aalborg University. It provides a broad set of sector-coupling options to face higher shares of energy variability. This model has been used for several case studies around the world. We validate the model for Spain as a case study (calibration of 2017) so as to then explore a novel way to assume input values in the coming years of the transition (2030 and 2050). The energy policies applied to the scenarios make up a list of policy recommendations for this country that complete the flexibility gap of the statistical model (objective 2). The collective effort carried out through EnergyPLAN will answer the following research questions:

- How are the official reports conceptualizing the Spanish energy transition?
- Which data sources are useful to justify the inputs of EnergyPLAN?
- How can energy policies be transparently introduced into the analysis?
- Which are the best flexibility options for the transition in Spain?
- What facilities should Spain install, and when?
- What limitations may arise for government energy transition plans in Spain?

Objective 3: experimentation with methods to represent the impacts of variable energy sources for integrated assessment models.

The thesis reviews and tests integrable methods for IAMs. The hourly energy system software named EnergyPLAN is used to extract analytical equations for the capacity factors of key technologies in the transition (solar and wind), and to conceptualize a complete linking between this tool and an IAM (further work). The first solution generates inputs and outputs that are linearly correlated.

- What are the advantages of integrating the variability in the models?
- What temporal scales reproduce plausible results in the simulation?
- How can modellers extract information from an hourly energy model to reproduce hourly effects statistically in IAMs?

Structure of the thesis

This doctoral thesis is structured as depicted in Figure 1. After this introductory chapter, next Chapter 2 briefly contextualizes the role of energy throughout the history of humanity, emphasising the energy transitions with specific literature. This will help the reader to understand the historical situation we are in nowadays, i.e., which phenomena have brought changes in the energy system and what are the consequences for social relationships. Although the energy point of view is obviously partial, it is a partial explanation to why our economy is as it is, as well as for the anthropogenic climate change.

The experimental contribution of this thesis is related to systems running entirely on the exploitation of renewable energy sources. Chapter 3 frames the current energy transition and reviews the references with the greatest impact in the challenge of 100% renewable energy systems.

Chapter 4 analyses three strategic scenarios of increasing variability for Spain. The model reproduces the hourly variability through kernel probabilistic distributions. Assuming the current power system, the results of this experimental exercise bring troubling situations to light; estimating the requirements of storage, international interconnections, and a general performance of the power system. It has been published as an article in a peer review journal: Parrado-Hernando, G., Miguel-González, L. J., & Frechoso-Escudero, F. (2021). *Analysis of the variable renewable energy in the Spanish power system based on kernel probabilistic distributions*. Dyna (Spain), 96(2), 179–185. https://doi.org/10.6036/9892

Chapter 5 contributes in three ways. First, it provides an approach to study the energy transition in Spain towards a 100% renewable system. Second, it conceptualizes a link between an hourly energy model (EnergyPLAN) and a yearly integrated assessment model (MEDEAS). Finally, it proposes a policy agenda for Spain, in line with the official report (NIECP, PNIEC in Spanish). This chapter has been published in a peer review journal as: Parrado-Hernando, G., Antun, P., Fernando, F., Luis Javier, M. G., & Neven, D. (2022). *A novel approach to represent the energy system in integrated assessment models*. Energy, 258 (December 2021), 1–21. https://doi.org/10.1016/j.energy.2022.124743

Chapter 6 is the result of a collaborative work between the International Centre for Sustainable Development of Energy, Water and Environmental Systems (SDEWES) and GEEDS. The work contributes with a novel perspective to introduce hourly information into integrated assessment models based on the parametrization of multiple linear regression models. The chapter has been published in a peer review journal as: Parrado-Hernando, G., Luka, H., Antun, P., Iñigo, C. P., Ilija, B. B., Neven, D., Fernando, F. E., Luis Javier, M. G., & Vladimir Z, G. (2022). *Capturing features of hourly-resolution energy models through statistical annual indicators*. Renewable Energy, 197 (December 2021), 1192–1223. https://doi.org/10.1016/j.renene.2022.07.040

Finally, Chapter 7 summarises the principal findings of this thesis and the future research lines to follow in the ongoing analysis of the energy transition.

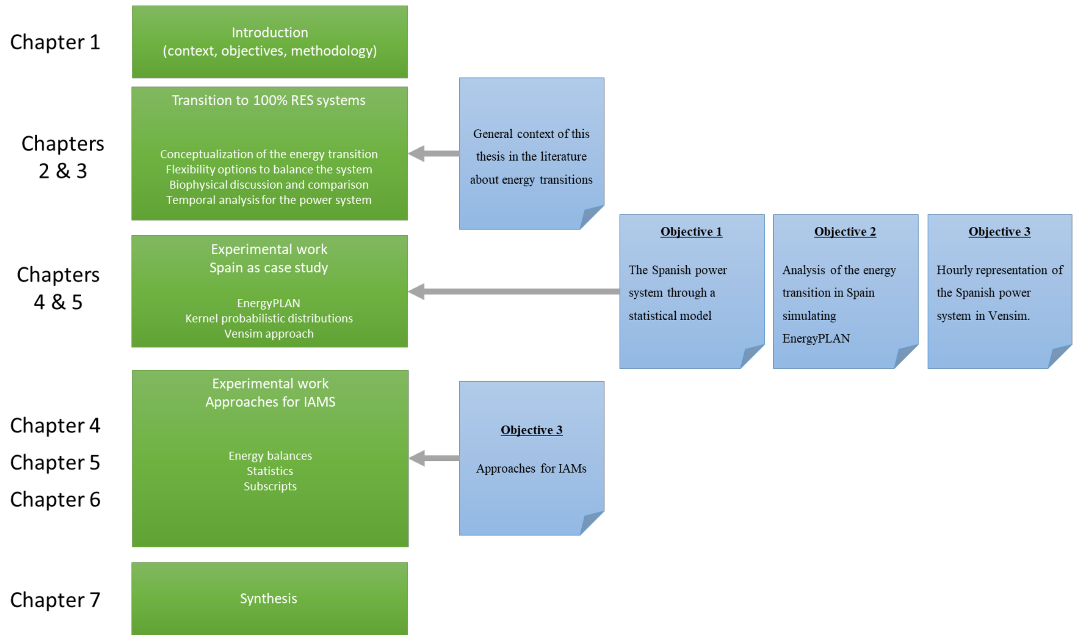

Figure 1. General structure of this doctoral thesis.

Methodology

Academic research starts with a review of the past and present literature on the topic of interest, and this work is no exception. The theory of social metabolism is presented first to build upon a useful narrative for energy planning that adequately frames the biophysical theory GEEDS puts into practice with IAMs. A historical view that explains the current energetic situation of our society is set out using that narrative, from general knowledge to specific facts available in the synergetic energy-anthropology literature. In addition, the literature review carefully assists the specific question of the biophysical limitations of 100% renewable energy systems, which are special cases of increasing relevance under the urgency to mitigate climate change.

Our experimental work therefore focuses on this relatively novel field, strongly linked to the issue of energy variability, emphasizing the penalties and technological requirements needed to cover the demand in such special cases. The contribution to the topic is carried out through three principal programmes: EnergyPLAN, Vensim DSS, and Matlab. The conceptualization, data collection, modelling, model calibration, and validation of the results are the main steps in this stage of the methodology. A PhD stay in Zagreb facilitated the international collaboration in one of the tasks of the Locomotion project, linked to EnergyPLAN; as well as the study of a 100% renewable energy system in Spain with the same energy planning model.

For a more detailed explanation of the steps that compose the methodology, we encourage the reader studying the "Methods" section of chapters 4, 5, and 6.

Finally, the conclusions are set out and policies, reflexions, and future developments recommended based on the previous results. Accessible official reports are therefore introduced to compare and check for incoherences and agreements.

Chapter 2
Brief history of energy transitions in human societies

Nowadays, humanity is aiming to tackle an uncertain future in the face of dramatic climatic disturbances through a deep reconfiguration of the energy mix and consumption patterns. However, this is not the first energy transition human beings have gone through to enhance the economy, no matter which logics were ruling at the time, no matter the complexity of the society.

Following this chapter, the reader gets introductive information to comprehend the multidisciplinary perspective that GEEDS supports to analyse the energy transition, from anthropology to thermodynamics. Consequently, the policy recommendations or scenarios tested in the experimental work related to the objective 2 of this thesis are better understood after reading it. Furthermore, this part recognizes the relevance of the technology to convert energy from one to the other to achieve such transitions, and a temporal perspective of the time consumed in past transitions to organize the changes in the scenario over time.

This chapter is structured as follows. First, the explanation of a framework for energy analysis of societies as alive organisms in nature. Second, a scientific history of the relation between the use of energy and social development. Finally, an explanation of the principal world problem nowadays that links to potential solutions in the next chapter, the anthropogenic impacts on nature.

A suitable analogy for energy analysis

As we shall explain, engineering can be understood as a feature of creation and analysis that society has for enhancing and mutating specific economic processes. The goal of this subchapter is not to develop a theoretical framework, but to introduce few concepts so that the reader can understand the biological perspective we often follow in this document; a biophysical approach that sees the economy in terms of flows of energy and materials, as a subsystem inside a larger physical system.

Metabolism refers to physical and biological processes that occur in living organisms and imply the use of energy to modify the structure of matter. The cellular metabolism presents elementary examples of metabolic processes for the analogy with higher levels of complexity. In net energy terms, the conclusions of the analysis in compound processes are the same. Breathing, temperature regulation, digestion of food and nutrients, waste disposal and functioning of the cerebral activity are possible due to multiple sub-processes working as a network at the same time; when accounting with the bounds of the organism, the balance results into a net consumption or supply quantity of energy and a higher or lower matter complexity.

The idea for the reader is therefore to generalize the concept of metabolism for all human and non-human activities that make up the so-called economy or *social metabolism*[5] (Figure 2). The concept has been one of the most robust instruments for understanding biophysical explanations in complex dynamics of the economy since the 1990's; a useful methodology for analysing the relations between society and nature from its material bases. The origins, approaches, and main developments of this socioenvironmental theory were studied in (Molina & Toledo, 2014). Some examples are introduced to show the parallelism between different scales, from the cellular to the biosphere.

Energy[6] and complexity of matter are the principal actors in this biological analogy. Thermodynamically, a catabolic process brakes chemical bonds to release energy, simplifying the complexity of the matter structure while increasing the entropy of the organism. On the other hand, an anabolic process uses available energy to build more complex chemical structures. Anabolism reduces the entropy of the organism. Ludwig Boltzmann expressed the following remarkable insight in his popular lecture of 1976: *"The*

[5] First introduced in the third volume of the famous book *"Capital"*, written by Carl Marx (Hall & Klitgaard, 2018). Nowadays, (Molina & Toledo, 2014) generalized it as follows: *"The idea of societies being similar to living organisms was accompanied by still another analogy: the laws of behavior and evolution ruling living organisms also apply to human societies"*.

[6] At the cellular level, adenosine triphosphate (ATP) is the – chemical – energy currency of metabolic processes. Some similar examples highlighting the relevance of energy in living things were introduced during the symposium (J. H. Brown et al., 2022) by some of the principal authors of the biophysical theory nowadays.

general struggle for existence of living beings is therefore not a fight for the elements – the elements of all organisms are available in abundance in air, water, and soil – nor for energy, which is plentiful in the form if heat, unfortunately untransformably, in every body. Rather it is a struggle for entropy that becomes available through the flow of energy from the hot Sun to the cold Earth. To make the fullest use of this energy, the plants spread out the immeasurable areas of their leaves and harness the Sun's energy by a process that is still unexplored, before it sinks down to the temperature level of the Earth, to drive chemical syntheses of which one has no inkling as yet in our laboratories. The products of this chemical kitchen are the object of the struggle in the animal world" (Schuster, 2009).

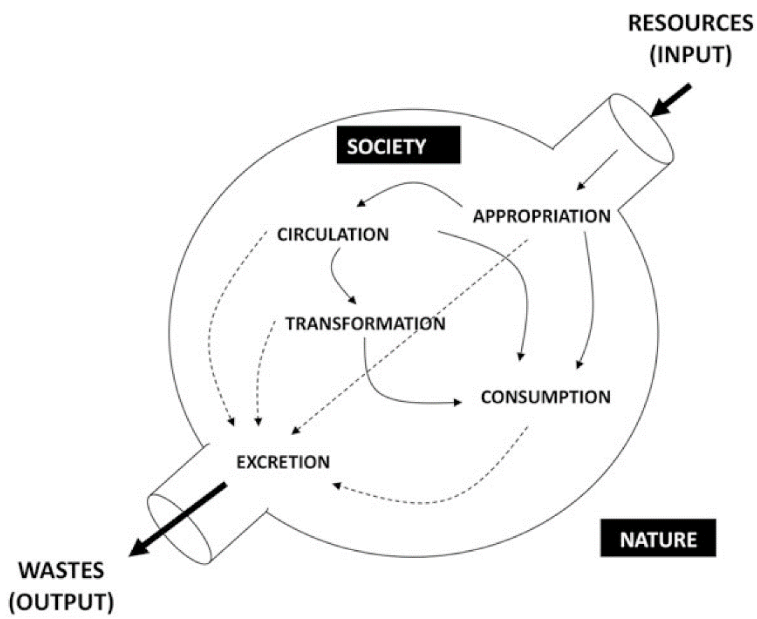

Figure 2. General diagram showing the five main metabolic processes and the relationship between society and nature. Source: (Molina & Toledo, 2014).

Here a quick example of the analogy. One of the vital functions of the human organism (social metabolism) is glycolysis (production of fuels) (Castrejón et al., 2007). Cells activate transporters and facilitators (humans and technology, e.g., oil wells) to capture glucose from the external environment[7]. Once the glucose is inside the cell, enzymes oxidize it (refineries) to obtain simple and more useful and simple elements like the ATP (energy carrier, i.e., a high-quality fuel), as well as other secondary products such as pyruvate, water and carbon dioxide, which are used in other processes or eliminated by the organism (recycling and waste). This process involves catabolic and anabolic sub-processes; however, the net effect is catabolic.

In engineering, the boundaries of the system are defined according to the research questions, whether it be a specific process, the economy, or the entire biosphere[8]. The social metabolism is also an open system exchanging energy and matter with the rest of the biosphere. All the energy sources gathered from nature to the organism are accounted as primary energy (e.g., oil, coal, wind power, solar power accumulated in biomass like agricultural products). This flow is used by humanity in two ways: i) to maintain the species (endosomatic metabolism of humans and livestock, including reproduction); and ii) to transform the materials (exosomatic metabolism) that are then supplied to cover the economic demand, which include all the assets we can imagine, infrastructures, instruments, engines, and high-quality energy carriers (electricity, gasoline, kerosene, pellets, etc.) [9].

What happens from the consumption of glucose to play a guitar is a good example to illustrate the generalization of thermodynamics in the analogy. *"During muscle contraction, chemical energy (glucose) is converted to mechanical energy when ATP is hydrolysed during cross-bridge cycling. This mechanical energy is then distributed and stored in the tissue as the muscle deforms or is used to perform external work"* (Ross et al., 2021). So,

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[7] In further detail, this subprocess is based on sodium (Na^+). The ion of Na^+ supplies the driving force for the movement of glucose. The chemical gradient of Na^+ is sustained by *pumps* of Na^+ and K^+ (ion potassium), a process using energy (ATP) called gill Na^+, K^+ ATPasa. In the analogy, electricity can be used in machines to sustain a rotatory system that generates a gradient of pressure to extract the oil from the field.

[8] An approach that considers the biosphere as a complex organism can be followed in (de Castro Carranza, 2013).

[9] Chemical energy in gasoline is transformed into heat and mechanical energy inside the combustion engine of a vehicle.

this process splits up the glucose to increase the availability of ATP as a net catabolic task, and since the efficiency of muscles is not perfect, a portion of the energy is released in the form of heat (again, a net catabolic result). Consequently, all the physical activity is essentially catabolic, from running to play a guitar. On the other hand, cell reproduction and growth of the mineralization of bone expend energy to build complex organisms from simple elements, so they are anabolic processes.

Consequently, social catabolic processes are related to the satisfaction of social demands, whether they are necessary or not. For example, burning gasoline, playing music, enjoying life, and supporting the social structures. Across all these activities, the energy embodied in products is degraded so the entropy of the system increases[10].

Finally, there is another catabolic function representing the natural degeneration (population, livestock) and *depreciation* (lifeless assets). For example, a diesel engine is not useful by itself. Humans install them into vehicles to drive and speed up mobility between locations (enhancing a function of the organism). The process of building the engine requires energy, materials, knowledge, workforce, and time; however, the usefulness for the economy is to move people (e.g., leisure and space trips) and products (e.g., railway transport) from one place to another[11]. Without such technology, the actual economy could not exist (in other words, it would suffer a paralysis, and without any help, it would become a simpler organism). If the diesel engine is not installed in a vehicle, its entropy increases and, after some time, becomes so high that it can never be used to transform chemical energy into mechanical power (lifetime).

The energy return on (energy) invested (EROI) is a metabolic indicator mentioned throughout this thesis. It is the *"ratio of how much energy is gained from an energy*

[10] Following an example, we transform chemical energy into mechanical energy in a combustion engine to move a vehicle (end use) until the fuel deposit is empty and the second law of thermodynamics stops it (transformation into heat due to the friction with air and elements). The whole process is a vehicle going from a low-entropic state (potential work stored) to a high-entropic state.

[11] The concept of *usefulness* is abstract. For some people, driving a car on a closed track at high speeds to win a race is an essential activity in their life.

production process compared to how much of that energy (or its equivalent from some other source) is required to extract, grow, etc., a new unit of the energy in question"(Murphy & Hall, 2010). Equation 1 shows the calculation of the indicator and the relation with the net energy available.

$$EROI = \frac{energy\ returned}{energy\ invested} \rightarrow Net\ energy = energy\ returned \cdot \left(1 - \frac{1}{EROI}\right) \qquad \text{Equation 1}$$

When applying the idea to compute an "EROI of the society"[12], the numerator and denominator change in the literature. This discussion can be read in (Capellán-Pérez et al., 2019), where the formula changes according to which metabolic processes are being considered within the bounds of the system to measure the indicator:

(1) Useful (end-use) energy delivered to society[13].

(2) On-site and off-site energy requirements to build, operate, maintain and dispose of the goods and products traded in the economy. Off-site refers to the energy invested in extracting and transporting, e.g., oil to on-site (imports).

(3) Additional energy requirements to effectively manage a variable output in the power grid. This term is related to the variability of demand and renewable energy sources.

(4) Energy used for the transport and distribution of energy (losses).

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[12] Atomic Detail Structural Models (ADSM) have been developed under the concept of EROI at the cellular scale to permit quantitative comparison between chromatophore and photovoltaic systems in the cell doubling process (Hitchcock et al., 2017).

[13] The literature does not agree on which is useful for the society (Pahud & De Temmerman, 2022). Would mobility be end-use, or just mobility related to leisure trips or freight transport (necessary for social metabolic processes)? Surprisingly, a technical indicator becomes the object of philosophical research to clearly establish the end of the energy chain.

(5) Embodied energy requirements in the machines and infrastructure required to construct the machines and infrastructure which allows the energy investments (2), (3) and (4) (i.e., indirect energy costs) to be made.

The authors reported three formulas of EROI: static (Equation 2), point-of-use (Equation 3), and extended (Equation 4).

$$EROI_{system}^{st} = \frac{(1)}{(2) + (3)} \qquad \text{Equation 2}$$

$$EROI_{system}^{pou} = \frac{(1)}{(2) + (3) + (4)} \qquad \text{Equation 3}$$

$$EROI_{system}^{ext} = \frac{(1)}{(2) + (3) + (4) + (5)} \qquad \text{Equation 4}$$

How should the EROI of the social metabolism be interpreted, therefore? Figure 3 paints an abstraction of this indicator over time. Until point 1, the society would come from a stable period of self-maintenance, in which energy has been used to sustain it. From 1 to 2, the envisioned society has invested huge amounts of energy (inflow increases) to modify metabolic processes (new energy infrastructure for an energy transition, higher population, more services than so far). From 2 to 3, that society recovers the invested energy[14] (e.g., using the engine in a vehicle). Finally, we can imagine that the society hypothetically finds energy scarcity before point 3; so even if it tries a return to a self-maintenance situation (with a higher complexity level, i.e., a wider system), the increase in effort to obtain the same quantity of energy, and the higher entropic process of degradation (higher

[14] Actually, this kind of situations is the reason why EROI does not guarantee fair conclusions by itself. For example, instead of recovery energy processes, the increase in the EROI may be due to a lower population (generating lower levels of services; so, for the rest of variables being constant, more energy is available). However, a reduction in the population implies a loss of complexity within the society, so the unfair *"advantage"* is not clear.

maintenance), would lead to a depletion process. Of course, there are other processes that may balance out the situations. One example could be a better energy efficiency in the engines used by the organism, which would help to sustain more complexity without any additional energy penalty (green line at the end of the figure).

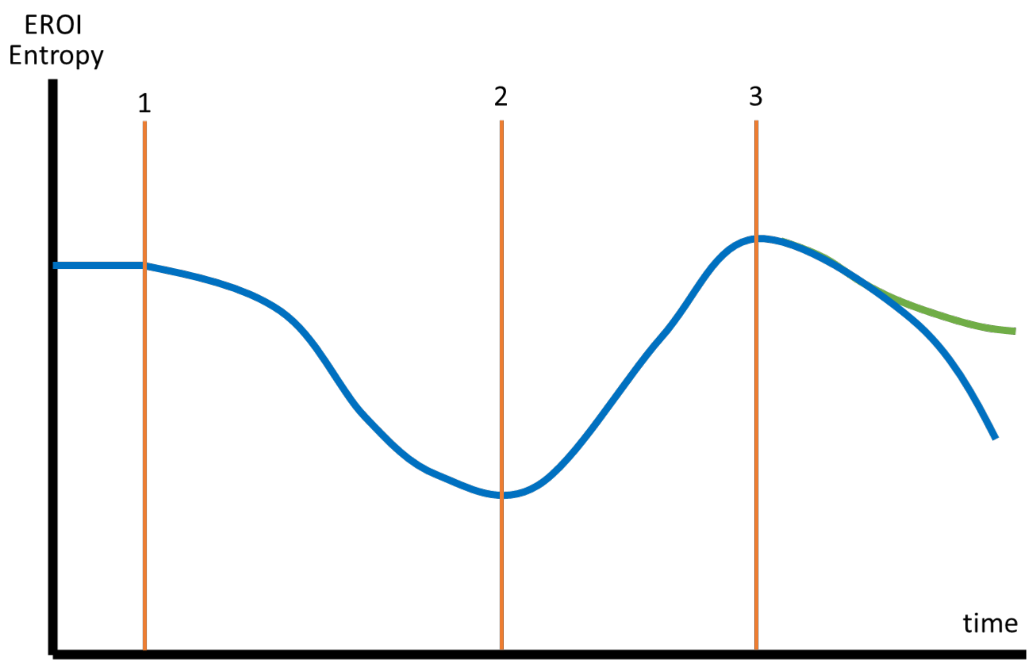

Figure 3. Conceptualization for a dynamic social metabolism. EROI and entropy are defined in the same axis due to their mutual connection, i.e., the higher the EROI is, the higher level of equilibrium the thermodynamic system will be in operation. The green line represents an alternative pathway. Own elaboration.

At the end of the day, the idea set out here agrees with (Jarvis, 2018) in the sense that expansive social metabolisms such as Capitalism would require an ever higher accumulation of entropy, with a similar trend in the inflow of energy to the system. Following this idea, energy transitions would clearly show depletions in the EROI. An approach reflecting this effect has been partially implemented with the dynamization of the static EROI by (Capellán-Pérez et al., 2019). Capellán-Pérez et al. assume coupling between energy consumption and economic development. In this assumption, the application of technological improvements on energy efficiency immediately drops the net consumption, saving energy in the same system; however, this gap is recovered after a while due to a variety of behavioural and economic responses. The net result is therefore to reduce the energy savings relative to a counterfactual scenario in which those responses do not occur (Brockway et al., 2021). This phenomenon is known as the *"rebound effect"*. Brockway et al. concluded that, even accounting with the multiple limitations, *"evidence base is growing in quality, quantity and diversity"*, and highlight that integration of this effect is the vital importance for integrated assessment models.

So, even if the final energy[15] is considered for computing the indicator in the study of Capellán-Pérez et al., the rebound effect is captured over time. This suggests that the final energy already accounts for most of the social metabolism in the industrial economy nowadays, independently of how society spends and distributes the remaining useful entropy at the end-use point.

Energy transitions in the past

"During most of human history renewable energy has been the only energy option available. Only during the last few centuries has fossil and lately nuclear energy sources been used in a non-renewable way". (Bent Sørensen, 1991).

The fossil fuels era (after 1850 CE) covers a very small part in the history of humanity. The problem of climate change had already been present as a natural phenomenon for humans

[15] Generally, final energy is defined as the one supplied to the consumers, in order to be finally converted and used at the end of the transformation chain (e.g., lighting, mobility, heat).

up to that date. However, just two centuries ago, very recently, the imbalance between the sources and sinks of the carbon cycle increased with the massive use of fossil sources, exacerbating the anthropogenic climate change. This is a dangerous path that puts ecosystems in danger and threatens species, including humankind.

Our ancestors used energy sources to accommodate themselves in nature, expanding the ecological niche with tools, techniques, and social structures under unstable conditions. However, other drivers, such as brain development and daily life experiences, fostered fruitful practices that emerged from the realm of creativity.

The relationship between *homo sapiens* and energy is presented as a double-sided agent of climate change, both problem and solution. To state that the exploitation of renewable energy sources can completely substitute fossil fuels is a technical reductionism, very far from multidimensional proposals that could effectively make the difference and bend the curve of greenhouse gas emissions.

In terms of evolution, how humankind has been organized in society influences the level and pattern of energy consumption. From a group of small, independent communities based on caring and mutual aid that were spiritually connected with nature, to modern Western society, which is virtually connected through the internet-of-things and based on individualism and the consumer society. The latter deprives nature of its essence, measuring it as part of the global market. This introduction aims to highlight the relevance of anthropological research on the role of energy in the evolution of society, to clarify the level of complexity possible, given the sources available, in the *social* or *industrial metabolism*[16]. Certainly, energy is only one determinant among many in history. However, the link between history and politics, and the study of social metabolism, is being systematized to provide new insights (Fischer-Kowalski et al., 2019).

[16] Society requires a permanent inflow of material and energy needs for the production and reproduction of its physical stocks. After their lifetime, materials are stored and then discarded or recycled (Krausmann, 2011).

Let us go back in time to understand where we are going. Not back to recent events, but to the times of previous societies. The book *"En la espiral de la energía"*[17] (Fernández Durán & González Reyes, 2018) is actually an anthology of the history of energy in the development of human societies (but not only that). In this thesis, this book has been used as a foundation from which additional references are used as support for key pictures of this brief history.

Human beings have a great capacity to capture exosomatic[18] energy to broaden potentialities of doing new activities. The energy surplus has been transformed by humans into terms of available time to play, think, communicate, and work on new knowledge. In their book, the authors considered three requirements or historical constants for using an energy source: i) the existence of converters (technology); ii) the availability of energy in the place it is needed (transport or in-situ resources such as rivers); and iii) the availability of energy at the moment it is needed (storage or, we add, behavioural change). Furthermore, work (high quality to move and transform matter), heat (low quality to heat and melt matter), and light were considered as the three fundamental uses of energy in societies.

Forager societies[19] operate mostly thanks to mutual aid, are non-hierarchical, and have simple relational structures[20] to survive in the hostile conditions of a narrow natural niche (Glowacki & Lew-Levy, 2022). The fact that the principal energy source came from themselves merges the feeling of security and cooperative manners in small but manageable (low complex) subsistence communities (IV, (Hernando, 2012)). As a consequence, individuality is very weak or even inconceivable.

The mobility of forager societies may be classified into those who: i) do not save provisions, displacing few logistics; ii) displace materials but are not territorial; iii) defend a territory;

[17] The title could be translated from Spanish as "In the Energy Spiral".
[18] Etymology: exo- + somatic. Of or pertaining to outside of the body (source: Wiktionary).
[19] The term *"forager"* is an adaptation of *"hunter-gatherer"* to cover not only feeding but all the consumptions involving energy, in this case, food and biomass.
[20] The book (Fernández Durán & González Reyes, 2018) mentions the coexistence of four types of societies; however, the analysis is focused on those considered a majority, for the sake of simplicity.

iv) are sedentary and save resources (Rowley-Conwy, 1999). The gradient between areas of abundant and scarce resources determines most of the mobility in these communities. It is a cyclical pattern very linked to seasonality. This behaviour verified the maxim of using the minimum effort to assure subsistence, so minimizing extraction to naturally store the resource. Symbolic language and cerebral development could facilitate the creation of new tools and *ways to do* hunting, gathering, caring, learning, etc. Both together facilitate the expansion of the natural niche for these communities. Tools arose around 2.5 million years ago with the purpose of minimizing energy consumption, while allowing a higher capacity of work and access to energy sources (e.g., larger animals and colder latitudes) (pg. 51, (Fernández Durán & González Reyes, 2018)).

Less than 200,000 years ago, the use of fire was generalized (James et al., 1989), 100 additional watts to the power that humans themselves can provide, estimated at 50-80 watts on average (Prieto, 2010). After the Neolithic period, humans started to save and transport increasing quantities of energy. Around 50,000 years ago, a secondary source of useful energy stored in the air and water started to be exploited. Navigation over rivers, seas and oceans became a reality ((James et al., 1989), cited in (Fernández Durán & González Reyes, 2018)). Energetically, transportation across land was limited by the lack of infrastructure and the feedstock consumed by draft animals on the way[21]. So, the heavier and bulkier the product, the smaller the market radius would be (chapter 7, (Wrigley, 2016)). It conditions the dynamics of ecosystems, including the availability of fruit, animals and wood (Krausmann, 2011).

We can assume that forager societies satisfied their needs with a low energy and material consumption. The EROI[22] of this society has been calculated to be around 4-10:1 ((Pimentel

[21] The energy needed to transfer a load of grain in a wagon drawn by four horses 23 miles cost around 6.25% of its value (chapter 7, (Wrigley, 2016)).

[22] Energy returned on energy investment. As explained before, the boundaries of the system we want to analyze determine the formulae of this indicator. In this chapter, the lack of EROIs for the social metabolism means we have to use proxies such as "$EROI_{soc}$", conceptualized by (Hall et al., 2009); the equivalent formulae are called "Final EROI" in (Galán et al., 2016) and "standard EROI" in (Murphy & Hall, 2011). The indicator is usually presented as "X:1", where X is the number of units of energy returned per unit of energy invested.

& Pimentel, 2007), cited in (Fernández Durán & González Reyes, 2018))(Hall et al., 2009)(Hall & Klitgaard, 2012a). In *"The global metabolic transition: a historical overview"* (Krausmann, 2011), the author argues that, since Palaeolithic times, humans have multiplied the per capita material consumption in parallel to the population growth. This is a synergy that has led to an exponential extraction of resources from nature and shows an imbalance in the several orders of magnitude (around 50,000 times) between the endosomatic capacity of the human metabolism, and the exosomatic system of the human economy.

The emergence of agriculture and domestication – around 10,000 years ago – meant the concentration of biological solar panels (plants) and bioenergetic transformers (animals) to improve the conversion from solar energy to useful human end-uses, allowing a higher surplus of energy to develop social complexity (Fred Spier, (Fernández Durán & González Reyes, 2018)). This period occurred at the beginning of the Holocene (12,000 years ago), the most stable period of climate in the last 400,000 years.

Where agriculture is assumed, population dramatically shifted the dietary pattern, i.e., the endosomatic metabolism. Foraged and hunted food is replaced by domesticated plant and animal by-products[23], gradually selected to increase productivity, while the entire ecosystem is conditioned to simplifications (Wells & Stock, 2020). This step forward in the way to achieve energy has been interpreted as a safe passage in a period of scarcity in regions with a high demographic density and decreasing natural resources.

There are three possible factors responsible for the increment in reproduction. First, in contrast to foragers, farmers are more susceptible to any ecological stress, due to their dependence on land productivity. Second, vector-borne diseases are propagated faster in

[23] In humans, the new diet implied slower childhood growth due to the lower level of protein intake, but higher levels of fat storage. The adoption of dairying may have buffered the lack of protein, an aspect that may have led to the north-south gradient of body size in Europe (Wells & Stock, 2020).

settlements of concentrated populations[24]. And third, the critical amount of potential harvesters[25] ((Boserup & Chambers, 2014), cited in (Fischer-Kowalski et al., 2019)).

Harvesting requires time and work that are not compatible with forager societies. It implies a deeper specialization, deforestation, and promotion of specific species (loss of biodiversity), as well as novel relations with nature and our fellow men, inherent in sedentarism. Nor is it by chance that patriarchy, the State, war, and exploitation started in the origins of agriculture and sedentary settlements (Lough, 1999)(Miller, 2015). The beginnings are characterized by the emergence of hierarchies in fertile areas of high population density that promoted a social division of work. The privileged elites were able to perpetuate a disbalanced access to higher levels of energy sources (slavery and use of animals). That cession may have been possible due to the loss of autonomy through the process of specialization.

The expansion of the State throughout fertile regions of the planet was not unencumbered of internal and external resistances from previous existing living standards and social norms and from dissenting political movements[26] (pg. 78, (Fernández Durán & González Reyes, 2018)). Individualism appears here as a driver of this new civilization, leading to domination of our fellow men and nature; where the State appears as the mechanism through which dominant elites organize the control and expansion of the territory; empires to control land, and in the end, energy.

Commerce was diversified to enhance food security (annual crop imbalances) by connecting new nodes in the market; although, as mentioned before, with the penalty of a higher energy consumption due to transport costs (less expensive through navigation).

[24] Longevity in agricultural societies decreased by about 30-40% (Miller, 2015).
[25] In agrarian societies, 80-97% of the population have to work on the land (Fischer-Kowalski et al., 2019).

[26] The evolution of the State has determined other core elements of societies, such as religion (Ira M. Lapidus, 1996)(Coulborn, 2018), but also as tax collector for the State (Coşgel & Miceli, 2009).

The main sources of energy in agricultural societies were land products (photosynthesis stored as chemical energy), and human and animal labour (mechanical energy) (Wrigley, 2016) ((Smil, 2007), cited in (Fischer-Kowalski et al., 2019)). Anthropologists estimated this energy regime to be 300 watts per capita of power (Prieto, 2010).

The EROI seems to become more widespread than in foraging societies, being estimated to be between 1.03-37:1 (Galán et al., 2016) ((Pimentel & Pimentel, 2007), cited in (Fernández Durán & González Reyes, 2018); pg. 121, (Rappaport, 2017); and pg. 93, (Hall & Klitgaard, 2012b)). It is a long discordance in the indicator, which may be due to the diversity of territories, more or less suitable ecosystems for agricultural activities. Similarly, the lack of flexibility to change from one society to another suggests that forager societies could have survived under very precarious circumstances (EROIs close to one), or living in comfortable conditions (EROIs close to 10 or even higher). Energetically, vegetal coal was the key to improving combustion in that period, thanks to a higher specific heat capacity with respect to bioenergy (wood and waste)[27].

The transition to Western modernity and Capitalism emerged in Europe around 1,500 CE. This system unfolded in just three centuries, very fast in comparison to previous economic transitions. To explain the social transformations generated with the new regime, we have respected the reasoning of the dialectical materialism shown in (Fernández Durán & González Reyes, 2018), i.e., the Marxist theory of the *primitive accumulation of capital* (Marx, 1976).

Merchant and artisan classes (the nascent bourgeoisie) were restricted to a fragile position because of the higher uncertainties of obtaining profits. To fix that insecurity, they started to invest in innovations for transport, means of production, logistics, and business; overcoming energy and political barriers to evolve from a local market (mainly dominated by the aristocracy) to an international commerce (open and flexible). Capital was accumulated in

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[27] However, very inefficient. By the early 18th century, a typical English furnace produced around 300 tons of pig iron per year, feeding the process with 12,000 tons of wood. 8 kg of charcoal per kg of iron, and 5 kg of wood per kilogram of charcoal (Smil, 2004).

urban areas known as city-states (Medina del Campo, Ambers, Genoa, Milan, Florence, Venice), configuring a flexible and dynamic custom-made competition. Novel governments were interested in the power of commerce and money instead of taxes. Later, improvements in the techniques and knowledge of marine transport connected new markets[28] (new opportunities to reproduce capital[29]), which had an explosive effect since the Iberian sailing expeditions to East Indies, America, and the circumnavigation to the planet (Portugal and Spain) at the end of the 15th century. Thereafter, the system has been expanded and covers the entire world.

The bourgeoisie is pragmatic, focusing attention on controlling the capacity to reproduce capital, and is able to do so with less military control over the territory. This change created a more efficient dominant class in opposition to the traditional feudal aristocracy. A second reason can be found in the Marxist concept of surplus value, which undervalues slavery and non-productive care work. Therefore, specialization was deepened by region, social class, and gender to achieve new levels of knowledge and techniques. Consequently, the situation led to conflicts for the control of power in society ("bourgeoisie revolutions" or "liberal revolutions"), in which the bourgeoisie acquired the control of the State in order to impose the new paradigm, i.e., a market society in which the new working class, dispossessed from the means of production, needs to sell their work (paid work) to get goods.

Psychologically, the idea of progress in Western modernity projects a utilitarian view of the environment, seeing it as inert resources to be exploited for the reproduction of capital. It is said that materials are *produced* and not *extracted*, since the latter imply the idea of scarcity, and thus a limit to growth. The progress of capital accumulation creates a metabolic rift in the organic connection between humans and nature (Hall & Klitgaard, 2018). The logic of Capitalism requires continuous growth and expansion that, in turn, imply rising consumptions of materials and energy. Wealth lost its natural dimension, i.e., finances

[28] Maritime trade between China and Portugal started from the end of the 15th century, in Macau (Wu et al., n.d.).
[29] Money and infrastructure employed to reproduce new money and infrastructure through the production of assets, goods, and services.

allowed the increase of power in a fictitious, unlimited growth of capital, without physical global consequences. This controversy was discussed through the evolution of science. For example, physiocracy (18th century) was a scholarly movement that has been pointed out as the origin of biophysical/ecological economics. It proposed that natural resources, and agricultural production in particular, were the source of material wealth (Cleveland, 1999). The economic process, they argued, is subjected to certain objective laws (Newtonian), independently of humans.

Surprisingly, energy was moved from the centre to a secondary role in the economy; likewise the caring of women and the surplus value in production. So, if the power in previous hierarchical societies was rooted in the control of high-density and fertile areas (energy susceptible to being accumulated to expand the territory); in Capitalism, power is rooted in the capacity to sustain and foster the causal loop that moves capital to produce and sell goods and services that, in turn, enables new investments, independently of where they are located. Such a capacity dynamizes commerce and improves competitiveness, a positive driver for creativity and productivity. The size of the world-system is dependent on the technology and energy available for mobilizing capital (transport). So, despite significant advances being made, especially in marine modes of transport, an energy revolution was required to overcome the physical limitations in time cost.

> *"The transition from a traditional agrarian to a fossil fuel based energy regime began before the industrial revolution and is still ongoing"* (Fischer-Kowalski et al., 2019)

Until the Industrial Revolution (second half of 19th century), the basis of Capitalism was mainly agrarian, gathering energy from the same sources as previous societies, i.e., intermittent solar energy and its accumulation via photosynthesis as biomass[30].

[30] Theoretically, the maximum solar energy conversion (photosynthesis) efficiency at 30 ºC is 4.6% for C3 plants and 6% for C4 plants. Nowadays, biotechnology could reach 8.8% of efficiency if the oxygenation reaction (i.e., avoiding the respiration process in C4 plants) is completely removed (Zhu et al., 2008). In nature, hydrogen generation in microorganisms has been demonstrated with an efficiency of between 5-10% (Reisner, 2011), while 14% was achieved for an artificial process (May

Urbanization was promoted to centralize the auxiliary services of production into poles. The urbanization process in Western countries further separated nature from the centre of economic and cultural imaginaries. In terms of energy, the limitation of collecting the real-time flow of intermittent solar energy (transformed during decades into biomass, disperse and complex to store) was overcome by exploiting a stock (fossil fuels transformed over centuries to millions of years, easy to concentrate and store). In agreement with (Fernández Durán & González Reyes, 2018), fossilist Capitalism is a false and temporal emancipation from biology. The economic development of this society brings with it a non-linear relationship with the energy requirements. As with the behaviour of energy losses when a vehicle speeds up (change in velocity for a laminar flow and the squared velocity of turbulent flow for two objects, e.g., vehicle and air), the economy nowadays is not able to escape from the energy chain.

So we have a well-known question: why were fossil fuels revolutionary? M. Fisher-Kowalsky et al. point to the scarcity of wood in the surroundings where the economic production took place and to the extraction of peat and coal to become more efficient (labour hours per energy unit)(Fischer-Kowalski et al., 2019). Furthermore, there were five crucial advantages with respect to previous energy sources (pg. 256, (Fernández Durán & González Reyes, 2018)):

- Accessible energy in abundance. They do not rely on meteorology or seasons, making the temporal independence of humans from solar energy possible. Limitations in the capacity of extraction of energy materials are geographical and geological.
- Higher energy density[31].
- Application to a wide set of end uses (in parallel to chemistry developments).

et al., 2015). However, the regenerative process of plants is included in the use of energy from photosynthesis, an ability that is lacking in efficiency calculations and human designs (self-reproduction).

[31] In the case of oil and natural gas, between 4-5 times more than wood (table 5.1 of (Fernández Durán & González Reyes, 2018)).

- Fossil fuels can be used anywhere (in parallel to transport developments).
- Fossil fuels are easy to store, so they can be used when required.

Figure 6 of the review written by (Pahud & De Temmerman, 2022) summarizes the EROI of fossil fuels and renewables. Fossil fuels showed a clear advantage: 70:1 for oil in 1930; 110:1 for coal in 2003; and 205:1 for gas in 1948. However, all of them are decreasing from those peaks and, nowadays (2020), the values are around 10:1 for oil; 65:1 for coal; and 80:1 for gas. So, industrial capitalism is able to reach higher EROIs than preceding societies. If we assume the EROI of all fossil fuels as a proxy for the EROI, the values have increased over time from around 20:1 in 1850 to 64:1 in the 1970s. The great surplus of energy would release more hours per capita for non-productive work (production of energy), such as services and research, music, and military activities.

However, Andrew Jarvis is against that proxy for estimating the EROI of an industrial society. He suggests that such a long-term growth rate in the global primary energy use (around 2.5%/yr) would be associated with an equilibrium in the EROI of 2:1 (Jarvis, 2018). Energy have continuously been invested into the energy sector to extract increasing quantities of primary energy along an exponential positive trend[32], very visible in Figure 4, where biomass is not substituted by fossil fuels but the last added to the first. For some authors (York & Bell, 2019), this trend implies an addition rather than a transition, since fuels are not substituted.

[32] The idea may be generalized for technology. Each improvement in a technology has been generally developed with higher investments of energy, material, intellectual and experimental workforce, and time, in comparison with older versions of that technology.

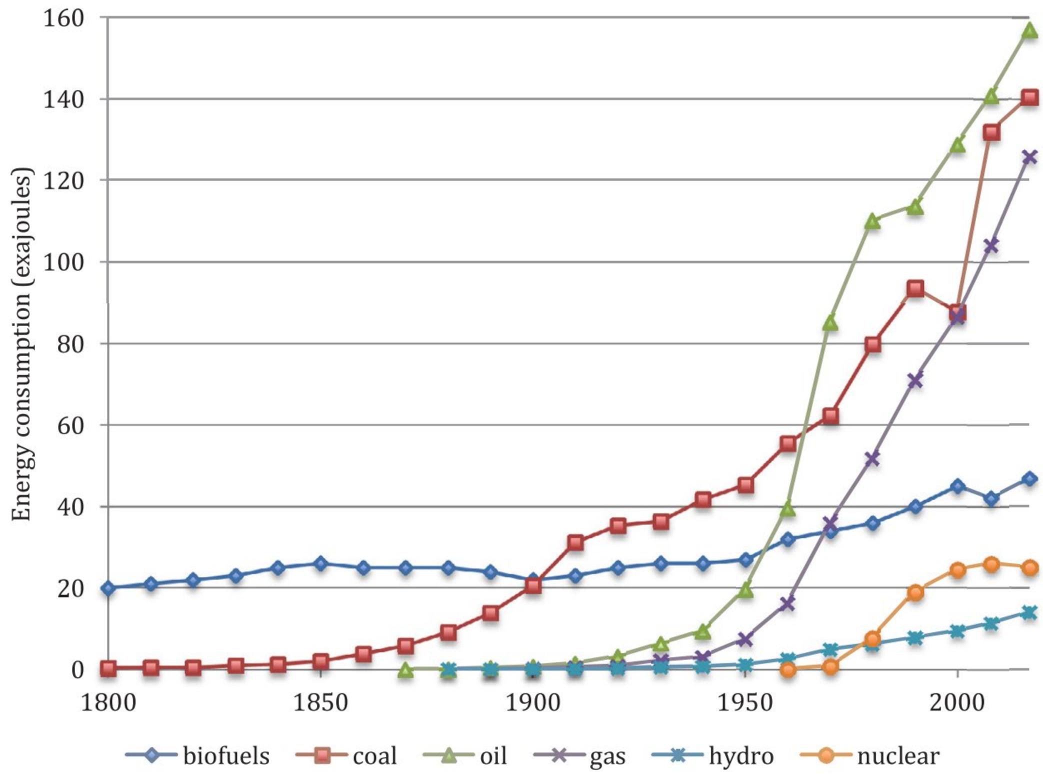

Figure 4. Global energy consumption by source from 1800 to 2017. Units in exajoules (York & Bell, 2019).

On the other hand, (Dupont et al., 2021a) estimated the societal EROI (net) to be 8.5:1 by 2018 worldwide, based on a macro-economic model of two aggregative sectors (energy and the rest). They also found that the energy sector self-consumed 11% of the final energy production for that year.

Currently, the sharply declining $EROI_{st}$ of fossil fuels (20:1) explains why renewables are being boosted. The post-industrial energy regime, characterized by a turning back to the exploitation of renewable energy sources, the massive use of information and communication technology, and the global culture of man-made consumption, is running with an EROI of between 20-64:1 (Table 2).

Table 2. Metabolic profiles of societies (table 1 from (Haberl et al., 2011), and EROI values cited in this chapter.

	Unit	Forager societies	Agrarian society (18th century)	Industrial societies
World population	Millions of people	6	50-250	1,600-8,000
Energy consumption	10^6 calories/day	30	600-6,500	123,000-1,656,000
Total energy use per capita	[GJ/cap/yr]	10-20	40-70	150-400
Use of materials per capita	[t/cap/yr]	0.5-1	3-6	15-25
Population density	[cap/km^2]	0.025-0.115	< 40	< 400
Agricultural population	[%]	-	> 80	< 10
Total energy use per unit area	[GJ/ha/yr]	< 0.01	< 30	< 600
Use of materials per unit area	[t/ha/yr]	< 0.001	< 2	< 50
Biomass (share of energy use)	[%]	> 99	> 95	10-30
Final EROI	X:1	4-10	1.03-37	2.5-64[33]

The use of fossil energy sources liberated human labour power for other activities, allowing the expansion of such phenomena as urbanization (Wrigley, 2016), research and innovation, and control. The combination of fossil fuels and machines introduced unconceivable levels of power (Prieto, 2010) and energy (Christian, 2012). The energy conversion from heat (low quality) to mechanical power (high quality) gained importance; from 0.1 kW (human) to 10,000 kW (steam turbine) at the beginning of 20th century (Prieto, 2009). The steam turbine was invented around the middle of the 19th century (Smil, 2019), a discovery that inspired the hydraulic revolution, which allowed higher scales of exploitation of the potential energy between head sites in a more efficient way.

[33] As mentioned above, the EROI of the industrial society as a whole could be around 2.5:1 (Jarvis, 2018).

The new industry of electricity, together with the internal combustion engine and the chemical industry, completed the wave of innovations in engineering (1898-1924), the so-called "Second Industrial Revolution" (from the 19^{th} and beginning of the 20^{th} centuries). These developments that were heavily dependent upon advances in science over the last century (Rosenberg, 1998). Electricity was especially relevant for the emerging dominant economic power, the United States of America[34]. The share of electricity in the end-use energy mix of manufacturing industries increased almost 20 points in the first 40 years of the 20^{th} century in the United States of America (Figure 5). New heat-to-power converters where connected to power-to-mechanical converters (the induction motor and the transformer, invented by Nikola Tesla) to enable the generation, transmission, and distribution of electricity over long distances.

In parallel, the human population grew to enlarge the workforce and apply power where machines were not able to substitute them. Despite that substitution, the total capacity has followed a net additive effect, a composite value of both human and machine contributions. Such substitution was present in applications requiring higher performances. For example, steam machines substituted draught animals and humans in agriculture, and then internal engines practically substituted steam machines to increase the specific power in labour activities (reduction of time cost).

In short, extraction is incremented to satisfy the demand of food and materials (appropriation). Cheaper and faster transport moves goods from the origin to the destination (circulation). Finally, population growth and a lifestyle linked to the new era carried higher levels of matter and energy demands (consumption).

The emergence of fossil fuels and the industrial revolution "depends upon and requires major systemic socio-political change" (Fischer-Kowalski et al., 2019), i.e., a drastic reconfiguration of society, a finding that opens up multidisciplinary research on social development. Their analysis concludes that social revolutions occurred in the early phases

[34] In 1900, this country was already the first industrial power around the world (figure 5.5, (Fernández Durán & González Reyes, 2018)).

of the transition to fossil fuels, when the economy was crossing a critical phase between 0.47 and 7.71 GJ_{FF}/cap/yr [35], a range that covered from two generations (e.g., Australia's revolution covered just 14 years) to centuries (e.g., The United Kingdom and The Netherlands, i.e., the global forerunners of the fossil transition), depending on available technologies, human learning, and accumulated experience. After the critical period ends, the Authors reveal an acceleration of the energy transition, reaching 50 GJ_{FF}/cap/yr in less than two generations (48 years with a standard deviation of 11 years). So, statistically, social revolutions did not affect either the speed of the transition or the industrialization. This last conclusion suggests that, independently of the ideology, fossil fuels were looked at as positive for the development of the desired society and/or an opportunistic way to control the power.

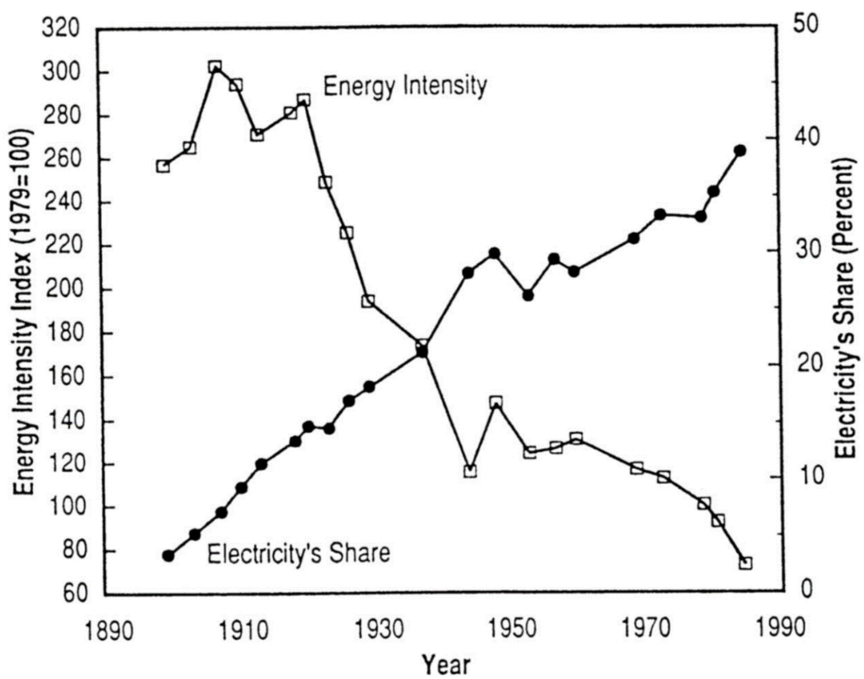

Figure 5. Energy intensity and electricity's share of US end use: manufacturing 1899-1985 (Rosenberg, 1998). Original source: pg. 116 of Schurr, Sam et al. (1990). *Electricity in the American Economy*. Westbank, Conn.: Greenwood Press.

[35] GJ_{FF} refers to the intensity of primary energy used from fossil energy carriers.

The power system has the following advantages:

- Electricity can make use of many energy sources (fossil fuels, solar sources, hydro, nuclear) (Rosenberg, 1998).
- Electricity can be transported instantaneously over long distances. Sources of carbon emissions are therefore placed where the power plant is located, improving health insurance in jobs and allowing the decentralization of industrial activity (Rosenberg, 1998).
- Broad range of power for efficient uses, lighting[36], mechanical work[37], low-temperature heating[38]. The energy intensity is reduced from final energy to end-use energy stages, as shown in Figure 5.
- Electricity enables automatic control, electronic digital computers, precision instruments, reprogrammable manufacturing technologies, etc. Electricity could be "packaged" in almost any size (Rosenberg, 1998).

Investments have been crucial in energy transitions throughout history. They mobilize efforts to put the economy into safer and more profitable situations. For example, the capital accumulated via slavery in sugar plantations was key to investment in mining and industry (Moore, 2013). The construction of the railway infrastructure consumed around 15% of all gross private domestic investments in the 1850s, and 18% in the 1870s and 1880s ((Hacker, 1940), cited in (Hall & Klitgaard, 2018)); while the iron industry consumed 25% of the total coal extraction in 1842 (Hobsbawm, 1977). Investments in energy infrastructure have not only been oriented towards improving the performance and speed of supply, but also to

[36] Light-emitting diode provides 2,600-2,800 lumens with 25-28 watt, delivering lighting with an efficiency of around 100 lumens per watt (Ayan & Turkay, 2017). Approximately, an open fire (wood) has an efficiency of 0.00235 lumens per watt, while a lamp (whale oil) has 0.1346 lumens per watt (Nordhaus, 1996).
[37] From 0.1 kW of humans to ultra-high-power electric arc furnaces (900-1000 kVA per ton of steel available in the transformers) (Cavaliere, 2016).
[38] Energy factors (efficiency) from 0.59 (gas boiler with storage) up to 3 (heat pump with storage) (Keinath & Garimella, 2017).

strengthening the hierarchy of the surplus value in Capitalism. For example, as Mitchell points out (pg. 406, (Mitchell, 2009)), oil pipelines were justified in part to reduce the coal workforce in Europe and therefore to undermine the political power of miners in Europe. The social metabolism was deeply shifted.

The natural delays between carbon emissions and global temperature increase partially answer the question of why the concern over scarcity and the climate change issue became international at the end of the 20th century (first report of the Intergovernmental Panel on Climate Change), and more specifically, after the publication of "Limits to Growth" in 1972 (Meadows & Randers, 2004).

The next-to-last indicator between energy and society is shown in Figure 6. The human development index (HDI)[39] of 40 world regions has been correlated to the total primary energy footprint[40]. The results show a statistically relevant relationship, with an R-squared equal to 0.8912 (Arto et al., 2016). As can be seen in the figure, energy explains more at lower levels of development. Another conclusion is the non-linear saturation in *developed countries*, which could not achieve higher human development index for amounts of primary energy consumption beyond 300 GJ/year per capita. The decoupling evidences the limitations of energy policies to develop social welfare. The results also show a clear inequality. On the one hand, regions responsible for an ever higher energy footprint are not achieving higher rates of development. On the other hand, regions with the lowest values (which are also the most populated) are consuming levels of energy under the recommended value of 0.8 (considered as "high development"). The non-linear trend concludes the impacts

[39] The HDI is an indicator introduced in the first Human Development Report (1990) by the United Nations Environment Program to simplify development as an average of achievements on health (life expectancy at birth), education (adult literacy and school enrolment), and income (Gross National Product per capita as the proxy for the standard of living). The HDI uses a scale from zero to one, where zero indicates the lowest level of human development and one the highest (for further information on the HDI consult (Klugman et al., 2011)).

[40] The footprint enhances the indicator by adding the embodied energy consumed worldwide to produce the goods and services demanded by a country. Note that it takes into account the globalization process (specialization and relocation of production, among other factors), thus accounting for the internal and external energy burdens of production (imports and exports).

of inequality, i.e., regions on the left could sharply grow with the few increments of energy consumed by regions on the right that do not need to increase their social indicator. Finally, it reveals how globalization indirectly transfers energy towards dominant countries through production[41], a historical constant of hierarchical societies.

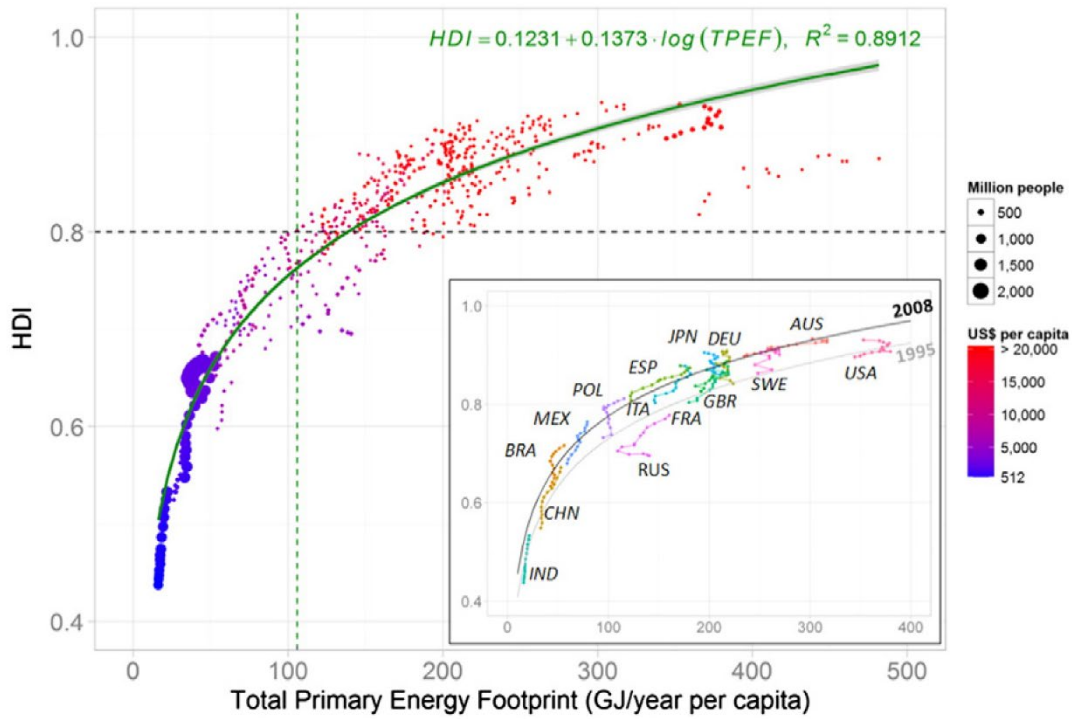

Figure 6. Human development index (HDI), total primary energy footprint per capita, population and GDP per capita of countries in (Arto et al., 2016).

[41] The amount of energy used by emerging to developed economies grew from 6.6% to 13.8% (relative to the total primary energy demand, TPED, of developed countries) between 1995 and 2008. TPED is the aggregation of the consumption of the energy sector, the losses during transformation and distribution of energy, and the final consumption by end users (Arto et al., 2016).

Finally, the minimum final energy consumption for a decent living energy[42] in a post-industrial society has been estimated to be within a range between 13-18.4 GJ/cap/yr for 119 countries (Millward-Hopkins et al., 2020). Currently, real consumptions are from under 5 GJ/cap/yr to over 200 GJ/cap/yr, revealing the aforementioned energy inequality across regions.

History has not been homogeneous, as different types of society have coexisted at the same time up to the present. However, the so-called globalization is, indeed, a living process to hegemonize advanced industrial Capitalism, a process which imposes a logic, praxis, and metabolism in practically all the regions of the world. The next section looks at a major issue created by humans, and the following chapter considers how we are trying to go back to 100% renewable metabolisms while still keeping our social complexity.

Climate change emergency

The climate on the planet Earth has changed over millennials, creating, expanding, and destroying the optimal conditions for an infinite number of ecosystems. Human beings were born and have developed their history in the period known as the Holocene, within a niche with specific climate conditions that have allowed the development of the uniqueness of our self-consciousness and developed reason. As a *sui generis* species, the fact that this climate niche is currently being modified by us implies our civilization is moving along a highway towards collective suicide.

The decoupling between natural and anthropogenic climate forcings has been thoroughly justified several times by the Working Group I of the Intergovernmental Panel on Climate Change. Their last contribution for the sixth assessment report (2021, (IPCC, 2021)) constitutes 2391 pages of human-driven climate change evidence. In the literature, the global surface temperature (annual average) is usually cited as a climatic indicator to reflect the climate decoupling since the pre-industrial era (1850 AD). Both trends can be seen in Figure

[42] Consisting of eight dimensions: 1) nutrition; 2) shelter and living conditions; 3) hygiene; 4) clothing; 5) healthcare; 6) education; 7) Communications and information; 8) mobility (Millward-Hopkins et al., 2020).

7, where the human-induced effect exponentially increases from the beginnings of the 20th century, and become dramatic after the 1990s, while the natural trend would remain roughly constant. In short, scientists conclude in chapter 3 of the report, that *"the likely range of human-induced warming in global-mean surface air temperature (GSAT) in 2010-2019 relative to 1850–1900 is 0.8°C–1.3°C, encompassing the observed warming of 0.9°C–1.2°C, while the change attributable to natural forcings is only −0.1°C to +0.1°C."*

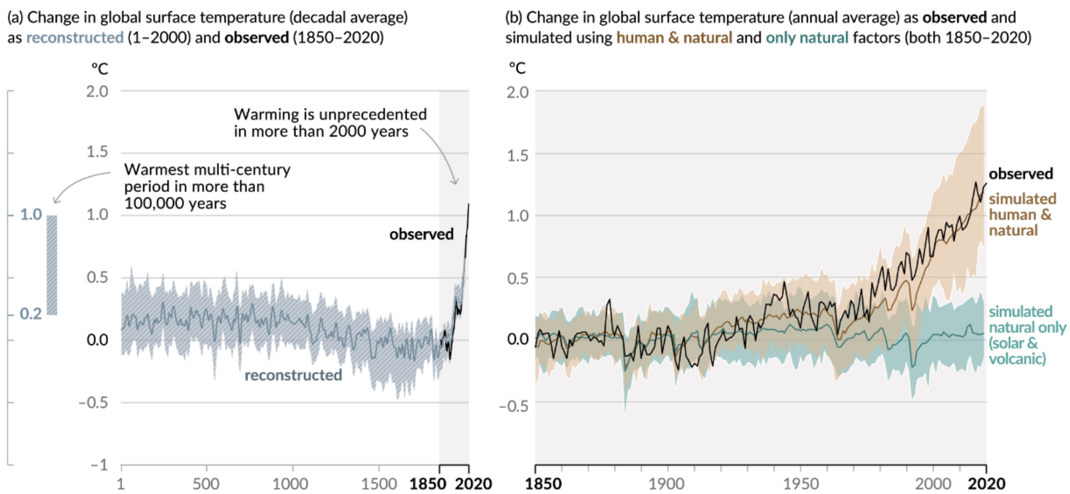

Figure 7. Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives. Panel (b) changes in global surface temperature over the past 170 years. Source: Intergovernmental Panel on Climate Change (IPCC, 2021).

The ongoing climate change will have moderate or high risks in almost every category of human systems and economic sectors, as well as in non-human ecosystems, by the end of the 21st century (Magnan et al., 2021). Today, confidence levels reveal a very high risk in corals and moderate risks in another ten systems, but a worsening situation is expected in the coming years, suffering very high risks in 16 of the 25 systems analysed in the study

(RCP8.5[43]). However, not only climate change is a hazard for the ecosystems; the coloured pie chart of Figure 8 represents the degree of human modifications in nine planetary boundaries (PBs) which *"demarcates a global safe operating space for humanity based on Earth system dynamics"* (Wang-Erlandsson et al., 2022). The lower panel illustrates how the anthropogenic pressure increase in the risk factor for the Earth system resilience. One may appreciate how the biochemical flows and biosphere integrity are extreme today, much more severe than climate change. However, the rest are not negligible, so the situation is very serious.

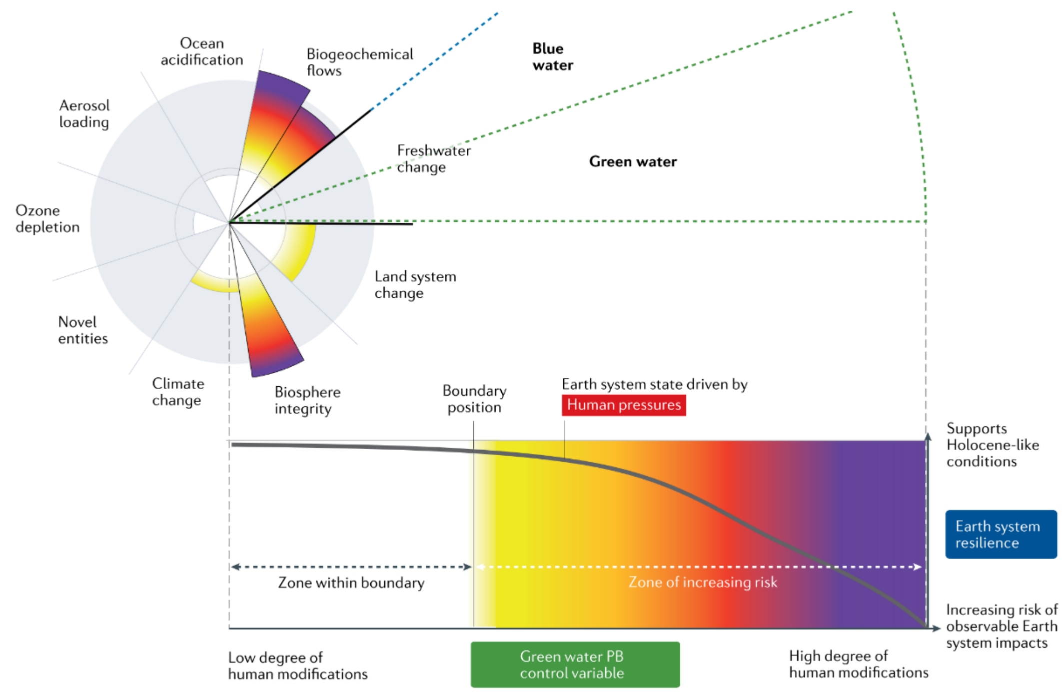

Figure 8. The nine global planetary boundaries illustrating the relationship between the degree of human modification of the green water and Earth system resilience implications. Source: (Wang-Erlandsson et al., 2022).

[43] Representative concentration pathway (RCP) in the 21st century. RCP8.5 is the worst pathway depicted by the IPCC and corresponds to a radiative forcing value of 8.5 W/m^2 for GHG sources (except CO_2) released to the atmosphere.

The risk range goes from a severe heat-related mortality (Vicedo-Cabrera et al., 2021) to catastrophic scenarios[44] through a cascading of positive amplifying feedbacks leading to a global climate failure (Kemp et al., 2022). So, what position is Academia adopting on this matter?

The supporters of Malthusianism and techno-optimistic environmentalism seem to continue a similar debate to what has gone before, without a general agreement concerning the consequences of a collapse of our civilization as we know it today (Gleditsch, 2021). Meanwhile, a *new* anthropological-based thinking, the so-called *degrowth*, holistically researches the human system as part of the evolution of nature, finding contradictions in the history of Capitalism and demanding radical modifications in the paradigm of human relationships – which are also economic – to live in a healthier relation with fellow human beings and nature (Crownshaw et al., 2019; Perrett, 2020; Shao, 2020).

Whatever the political system is, any kind of society unfolds an energy regime to sustain basic needs and social structures, from relatively simple hunter-gatherer communities to greatly complex societies such as the current one (Alexandre et al., 2022). We use energy in harvesting, hunting, cooking, heating, in mobility, and to get a higher energy supply from nature, among other things. Nowadays, all economic activities require energy to produce goods and services. Life is, in fact, a realm of continuous energy flows.

As has been demonstrated, the anthropogenic increase of greenhouse gas emissions has been warming the atmosphere, ocean, and land since pre-industrial times. However, which economic sectors are these emissions driven by? According to Lamb et al. (Lamb et al., 2021), the energy sector is in the first position. However, the human economy is complex and has intense trade across sectors, so we should distinguish between direct and indirect emissions. The direct emissions comprise all those produced by owned or controlled sources,

[44] In this context, a scenario is the quantification of a justified narrative that explains totally or partially an uncertain future.

while indirect ones refer to emissions associated with imports for the generation of electricity and heat in the local energy system that are then consumed in other sectors. Two examples could be, heating materials in furnaces to produce steel and space heating in buildings to produce comfort.

The energy sector developed a major role in the period 1990-2018, being responsible for 34% of the total direct emissions in 2018 (20 $GtCO_2eq$[45]), followed by industry (24%), AFOLU[46] (21%), transport (14%) and buildings (6%). In particular, basic material production (metals, chemicals, and cement) accounted for 37% of the total industrial emissions. In the AFOLU sector, land use change and management accounted for 47% of the net emissions. Road transport of passengers and freight represented 73% of the transport sector, followed by aviation (15%). In buildings, 66% came from power generation and commercial heat. Finally, the rest would come from direct consumption on end-use appliances such as boilers and lighting devices.

As we shall see later, this thesis highlights the concept of *smart energy systems* in deep decarbonization[47] pathways. This concept aims to cover as many generations and consumptions as possible to create new forms of flexibility in the energy system and so effectively reduce the carbon burden of the economy in the atmosphere (Connolly et al., 2016; H. Lund et al., 2012, 2017). In principle, it could be stated that all the direct and indirect greenhouse gas emissions of the economic sectors could be partially or totally removed from the energy system. However, there are specific chemical processes that are

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[45] Equivalent dioxide emissions (CO_2eq) is a metric measure to compare the emissions from various greenhouse gases according to their global-warming potential (GWP). All the values are translated as dioxide emissions.

[46] Agriculture, forestry and other land uses.

[47] *Decarbonization* denotes any reduction of GHG emissions from energy and industrial processes to decrease the average carbon intensity of primary energy production over time. In this sense, *full decarbonization* of the global economy means zero unabated emissions (Rogelj et al., 2015).

still far from this ideal situation. Some have been researched in the discussion section of (Parrado-Hernando, Pfeifer, et al., 2022), Chapter 5.

Given the relevance of the energy system in the anthropogenic contribution to climate change and the new, possible levels of penetration in the economic production; the following chapters address the concept of renewable energy and the impacts of the research on 100% renewable energy systems and global integrated assessment, focusing on technical issues at different temporal scales.

Chapter 3 Variability of renewable energy sources in decarbonized economies

The previous chapter highlighted the principal role of energy in the metabolism of societies, and the urgency to move forward with decarbonization pathways. In this chapter, the international proposal of *energy transition* is unfolded, highlighting the expansion of *sustainable* capacity to exploit *renewable* energy sources (*concepts* discussed along this chapter).

To focus more on the current energy transition, its characteristics are identified in this chapter, a synthesis of the up-to-date discussion about 100% renewable energy systems, as well as the difficulties inherent to removing fossil fuels from the economy in such scenarios.

- What are the main goals of the current idea of a 100% renewable energy system?
- Which are the different perspectives in the literature to deal with it?
- Which models and tools are being used to plan it?

The number of articles about the energy transition has followed an exponential behaviour in the Academy (Figure 9). Interest speeded up over the 1980s and 90s, experimented a sharp rise after the fourth IPCC[48] report (2007), and reached 1397 publications just in 2021. In 2021, 597 publications were found when searching for both "energy transition" and "renewable energy" by topic, title or abstract (Web of Science).

[48] Intergovernmental Panel on Climate Change. This institution is closely related to the field of integrated assessment models since the official scenarios are simulated in six of them.

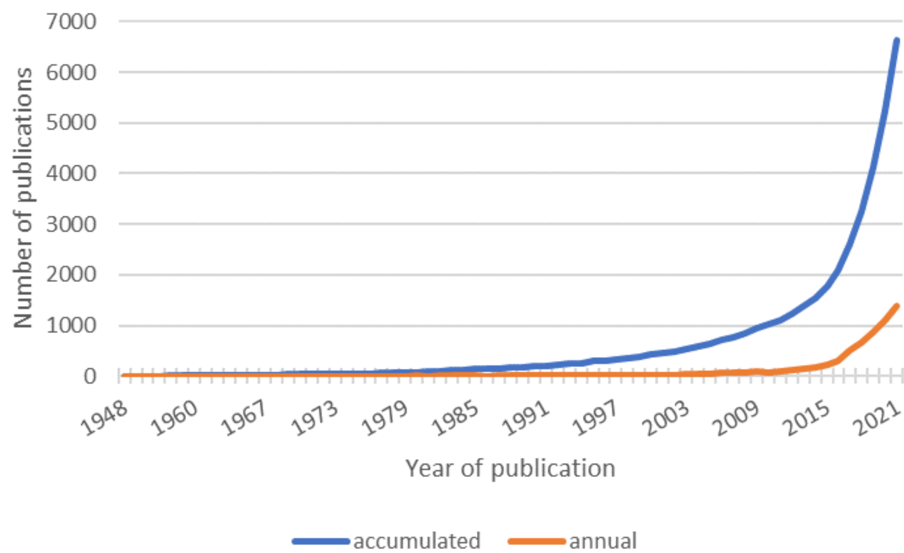

Figure 9. Number of publications over time containing "energy transition" within the topic, title or abstract since 1948 (first publication) to 2021 (both included). Source: Web of Science.

However, what do *renewable* and *sustainable* mean?

(Harjanne & Korhonen, 2019) have reviewed the etymology of the concept *renewable energy*. It was first defined as a contrast to fossil fuels in technical literature in the early 1900s. Later, after an intensive academic debate around the report "Limits to Growth" (published by the Club of Rome in 1972, (Meadows & Randers, 2004)), counterculture and environmental movements pressured for a more concise definition, in line with the ecological consciousness: *"renewable energy is a conceptual alternative to perceived dehumanizing, environmentally destructive centralized energy sources"* (Harjanne & Korhonen, 2019). This definition records nuclear power in the list of *non grata* sources. More recently, a new update of the old term has been done in the following terms: *"energy derived from natural processes that are replenished at a faster rate than they are consumed"*, which include wind, solar, hydroelectric, tidal, geothermal, biofuels, biomass, and part of waste. The latter is the current mainstream definition, in agreement with the International Energy Agency and other official institutions, such as Eurostat, IRENA, and the Organisation for Economic Co-operation and Development, among others.

Nevertheless, Harjanne and Korhonen, quite rightly, set out two maxims before their proposal. First, *renewable* does not mean *sustainable*, another definition that may be summarized as a process that meets the needs of the present without compromising the ability of future generations to meet their own needs and social development (chapter 6, (Enríquez Sánchez et al., 2020)). Societal aspects that have also been integrated in the concept recently; for example, impacts from the competition for water and agricultural land between biomass and food production, which increases the risk of higher food prices (societal unrest), soil degradation, loss of recreational value, and groundwater pollution. Second, thermodynamics dictates that the total entropy in an isolated system can never decrease (second law), so energy itself cannot be renewed in the strict sense[49].

A basic requirement for sustainability is the ability to function without destroying the resource base and without exceeding the environmental capacity to absorb the outflows of the social metabolism (pg. 75, (Krausmann, 2011)). All together, these requirements set down necessary but hidden dimensions that are avoided in the mainstream *sustainable development* (Kerschner, 2010), marking the steady-state economies as unattainable if it is not defined as *"a system in dynamic equilibrium within its containing, sustaining, and entropic biosphere"* ((Daly, 1990), cited in (Kerschner, 2010)).

Finally, they propose a carbon-combustion quadrant to structure the energy systems according to the level of carbon content of the fuel on the one hand, and the combustion requirements on the other. However, social affairs were excluded from the proposed quadrant. In short, an agreement based on technical and political criteria for the literature and policy agendas is a pending task.

[49] In fact, the planet Earth can be considered an open system in the global energy balance, and an isolated system in the material balances (assuming as negligible the inflow of meteorites).

The main contribution of our research has not been etymological. So, considering the current way of speaking about energy policy, and the concerns about nuclear energy (the quadrant is purely technical), the definition of "*renewable*" that best fits this research follows the IEA et al., i.e.:

"Energy derived from natural processes that are replenished at a faster rate than they are consumed. This includes wind, solar, hydroelectric, tidal, geothermal, biofuels, biomass, and part of waste".

In turn, renewables are here sorted into dispatchable and non-dispatchable. The difference lies in the level of control to accommodate the output to the demand. Although the criteria of sustainability are not implicitly reflected, they are analysed afterwards, in the discussion of scenarios that propose a great deployment of technology to collect energy from renewable sources.

A roadmap for the energy system

Historically, social metabolisms based on a 100% renewable energy system were very present until the expansion of fossil fuels. In order to drastically reduce our impacts to the planetary boundaries, Figure 10 depicts a mainstream future transition that would radically transform the metabolism of the society. A depletion of nuclear, coal, natural gas and oil that lets renewable energy mostly contribute to a stable or even decreasing consumption of energy in the long term (2100 AD). On the right, this figure summarizes a sensitivity analysis that reveals a non-uniform growth rate of new installations to exploit solar and wind renewable energy sources based on what moment of the energy transition the system is to supply a per capita power at the end of the transition (2100 AD).

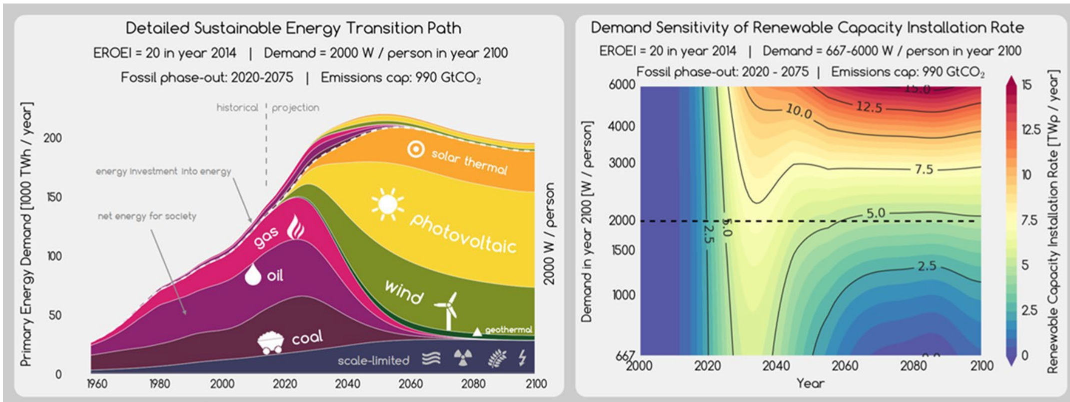

Figure 10. Detailed physical trajectory for the idea of energy transition. The energy resource distribution for offering net 2000 watts per capita (left) and the required installation rate of solar and wind per year to achieve variable levels of net power demand per capita (right). Source: figure 1 in (Bardi & Sgouridis, 2017).

We may imagine a higher or lower peak of energy consumption, faster or slower rates installing new capacities, or a different renewable mix at the end. However, there is agreement on two findings. First, after the peak, the system cannot continue the exponential – even slight – growth, supporting a decline and stabilization of the energy consumption. Second, fossil fuels must disappear, while renewable energy sources emerge to cover the gap.

Unfortunately, we cannot find a similar situation in the history. Bardi et al. expressed that *"making a veritable energy transition literally involves providing our energy in ways that were never employed at such scale before"* (Bardi & Sgouridis, 2017). Intermittent solar energy has been used in the past; however, the scale is multiple times greater to sustain a complex grid of economic and social nodes. The current industrial economy is more sophisticated, but its purpose is to allow the continuation of Capitalism, as it was in the fossil-fuel revolution of the19th century.

In general, the transition towards a 100% RES system shares two similarities with previous energy revolutions. First, we should see how investments are re-oriented to promote the new infrastructures of the future. Second, what has been called 'The Sower's Path' (Sgouridis et al., 2016), i.e., *"we need the energy from fossil fuels to transition away from their use"*; fossil fuels to extract and refine materials, to transform and assemble products, to transport them, to design and install new generators, new converters and new infrastructure (the *seed*), to utterly sustain the economy just with renewables (the *harvest*). So, what is different when facing this new energy revolution? Information, knowledge, and technology.

The transition can only be possible if the new energy system meets the three constant criteria in history (pg. 27, (Fernández Durán & González Reyes, 2018)): i) the existence of converters; ii) the availability of energy in the place it is needed; and iii) the availability of energy at the moment it is needed. A fourth criteria can be introduced from the concluding corollary in (Georgescu-Roegen, 2011), who stated that *"although all the processes included in any technology must be feasible, not every technology is necessarily viable"*. This means reproducibility, i.e., solar photovoltaic panels would be viable if we can construct them based (only) on electricity from such devices. Converters have been improved over time and their existence in the market allows a great range of possibilities, from enhanced steam turbines and internal engines (heat to power) to efficient heat pumps (power to heat)[50]. The electricity grid and biofuels, in combination with storage technologies, could match the other two requirements.

However, a holistic overview of the energy transition would not be complete without considering of economic and social analysis. Any limitation on both sides would imply additional barriers to the biophysical boundaries. For example, the inclusion of the term *just*[51] in the concept of energy transition enriches the energy guidelines by avoiding inequality and promoting distributive policies to effectively reduce poverty during the

[50] In 1910, a novel combustion gas turbine of 147 kW run of about 14% of efficiency (Yudin, 2022). The first large heat pump was tested in the UK in 1945, reporting a seasonal efficiency ratio of 3.42 (Valancius et al., 2019). According to the Danish Energy Agency (2020 data), the heat efficiency of fossil-fuel boilers is between 0.78-1.01, while heat pumps reach values between 2.15-5.40, depending on the configuration. Modern combined-cycle gas turbines can produce electricity at an annual-average efficiency of 56%; utility-scale ground mounted photovoltaic solar panels do so at 23% (single axis tracking); and an oil engine can produce electricity at 35% (annual average).

[51] A review of this concept was carried out by P. García-García et al. (García-García et al., 2020).

transition, which implies more than biophysical and economic issues. Although both spheres of knowledge fall outside the scope of this thesis, a quick overview is presented below to highlight the relevance of interdisciplinarity in this field.

(Jackson & Jackson, 2021) have researched the energy transition from the viewpoint of biophysical economics. They have recently developed a conceptual model to see the environmental effects of two scenarios of energy transition in the economy, including finances (high and low investments). In summary, the efforts of financial investment for the energy and capital sectors increase employment significantly at the beginning of their scenarios. Prices increase due to the higher wages in households and markups of firms. The increasing prices lead to an increase in the input costs by firm sector, which leads, in turn, to a cost-price spiral that causes a significant spike in inflation (2027 according to authors). Inflation adjusts the consumption patterns of agents (households and firms), so the real wealth (income) of households falls. This situation generates a declining trend in consumption, and thus a constriction of investments across sectors, except for renewables. Consequently, the feedback negatively impacts employment, resulting in an economic recession from 2028 to 2031 (low capital scenario) or 2033 (high capital scenario). The expansion of unemployment and capital intensity leads to a larger share of profits, while the wage share is falling, placing downward pressure on household consumption (so final demand). Afterwards, the recession ends, and the economic system grows, following oscillatory trends caused by the initial conditions (investments). In the low capital scenario, there would be a period of negative growth from 2032 to 2051. However, in the high capital scenario, that period of crisis would be shorter (2034-2042) but then another recession would appear from 2043 to 2051, finalising with another period of recovery from 2052 to 2079.

To complete this section, (Vanegas Cantarero, 2020) developed a holistic approach, considering social institutions as political actors that can accelerate the energy transition in developing countries (Figure 11). On the proposal, energy consuming sectors are defined at three levels: technological, social, and institutional. According to the authors, this framework can help in any region, developing or developed, to promote the energy transition. Escaping from Eurocentrism, the authors highlight the fact that countries enclosed in the global South face some challenges that must be tackled first in order to make the energy transition possible:

1. The enduring predominance of traditional unprocessed biomass in the energy mix (charcoal, animal waste). When households get richer, they usually switch to safer, more efficient fuels (Daioglou et al., 2012).
2. The population experiences energy poverty, which leads to system inefficiencies and deepens social inequalities (Sovacool, 2012)(Oyewo et al., 2021).
3. Size-constrained and unreliable power networks and systems. Extreme weather events, climate change impacts, and the security of energy supply are common concerns in the sub-Saharan countries, as highlighted in a review on the status of 100% RES system studies for such developing countries (Oyewo et al., 2021).
4. Reforms, privatization, and financial instability for the power sector. A process that does not lead to a higher capital utilization, except where it is coupled with the existence of an independent regulator (Zhang et al., 2008).
5. Poor quality or lack of data.
6. Fast development of transport fueled by fossil energies. A phenomenon closely linked to economic growth.
7. Inequity, a weak democracy, and a low participation and perceived level of knowledge of citizens in regard to energy-related issues.
8. Expressions of neo-colonialism and imperialism from fossil fuel corporations and their government allies. Imposing manners to influence the extraction of resources in former colonies.

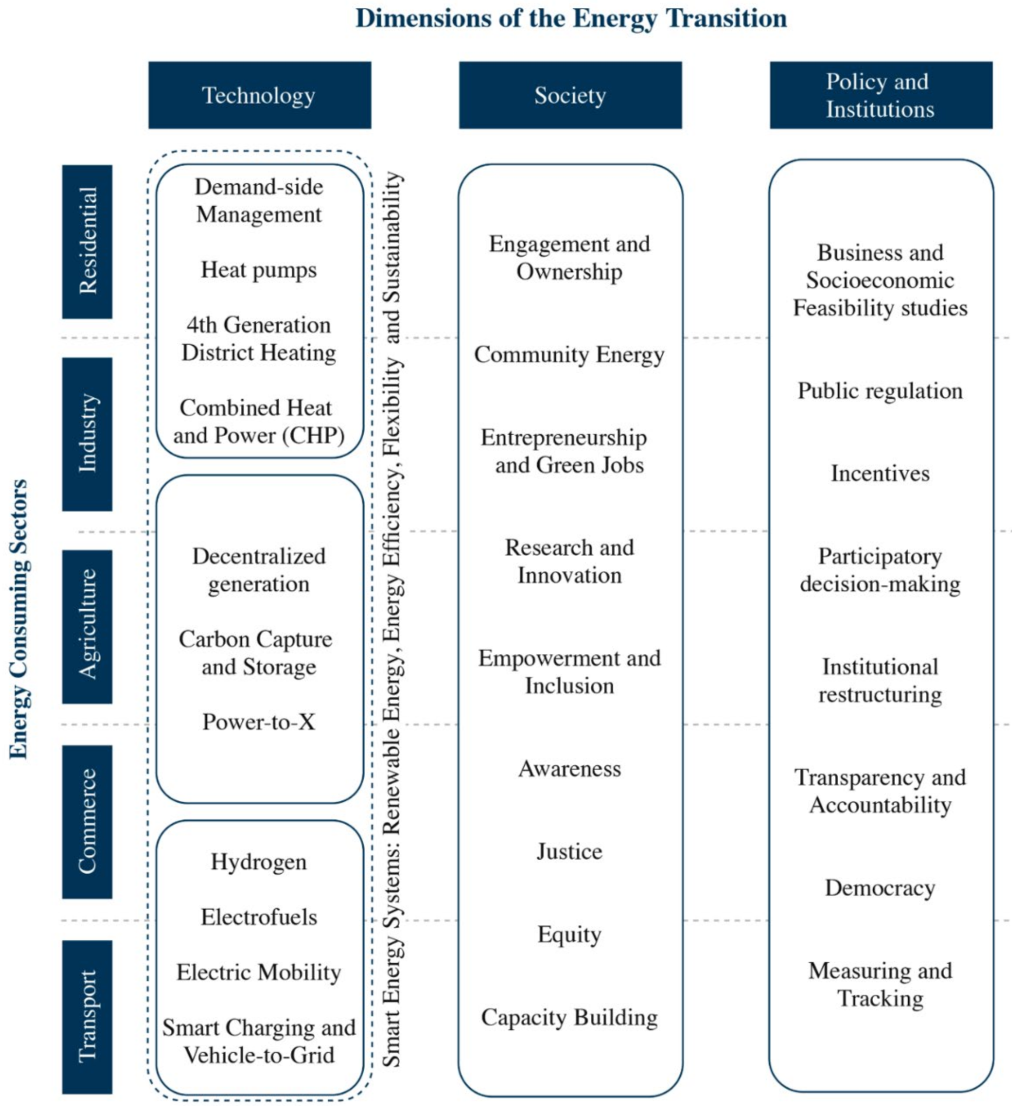

Figure 11. Roadmap for accelerating the energy transition in industrial societies. The proposal covers energy end use consumers at the technological, social, and institutional levels (Vanegas Cantarero, 2020).

Why do we need energy planning?

Beyond a certain number of interactions, the structure of a system cannot be formalized with mental models. Integrated assessment models exist to provide, at least, general answers on the big questions of our times, assuming dynamics with high degree of complexity. Beyond dimension of relationships, making impossible to be understood by humans. Energy systems require the processing of huge amounts of information and calculations in a multi-level framework. The consequences of ad-lib long-term policies are similar to driving a car with our eyes closed. The future society relies on a right analysis and assessment. Therefore, we need to imagine and build up a plan before applying a policy agenda, where synergies across active agents, opportunities, weaknesses, strengths, and threats are considered.

Modern energy planning is supported by two pillars: scenario analysis and modelling. Scenario analysis has been regarded as adequate to manage *deep uncertainty*[52] in unclear but possible future pathways. This analysis offers two advantages; first, the orientation and discussion of different futures; second, it supports decision-makers on strategies for overcoming short- and long-term challenges (Cao et al., 2016). Furthermore, a scenario is material itself for further investigations.

Suffice it to say here that transparency is a basic requirement to be applied. However, as (Cao et al., 2016) pointed out, transparency is an insufficient condition for a valuable and reproducible scenario study. Stakeholders and policy makers should comprehend and offer the possibility to reproduce the conclusions of the scenario. The authors proposed to follow the conceptual framework shown in Figure 12. Methods are reported step by step, as well as the empirical data gathered, assumptions and hypotheses, inputs and outputs of the models, and the post-processing of results, conclusions, and recommendations. They concluded that

[52] Concept developed by Lempert et al. (Lempert et al., 2005). Deep uncertainty is what analysts do not know, or the parties to a decision cannot agree on, (1) which conceptual models are appropriate to describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes.

a high degree of transparency, in consonance with scientific standards, is still pending in model-based energy scenario studies. This criticism has been considered when applying policies to build up the scenario of Chapter 5.

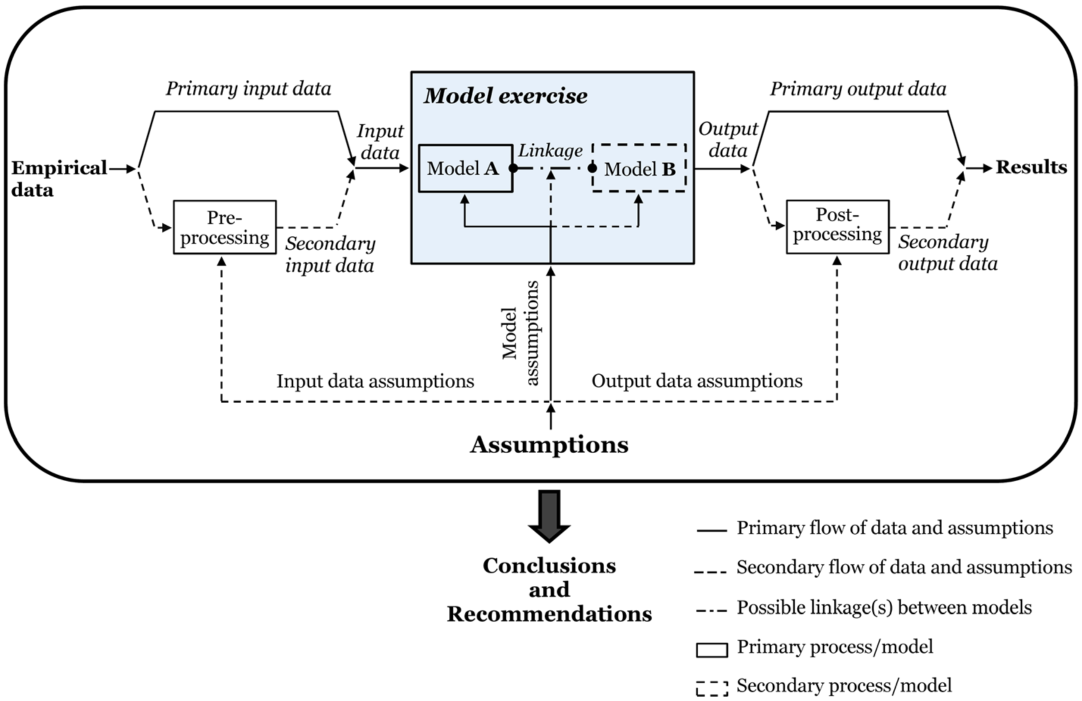

Figure 12. Conceptual framework of information flow and data processing proposed by Cao et al. (Cao et al., 2016) for model-based Energy Scenario Studies (ESS).

The field of energy planning has developed several frameworks and tools to achieve a deep understanding of the energy system. It is a very dynamic sector in which improvements are in the daily agenda to continually assess policy options better.

Regarding energy modelling, the first division is usually founded on how a modelling community frames the system. The *holistic top-down approaches* (e.g., integrated assessment models) are focused on representing the entire system. So, the complexity dwells in the links between elements, including feedback loops. On the other hand, *technical* *bottom-up approaches* analyze the components and interconnections in detail within the specific energy system to assess the positive impacts provided by technologies.

(Prina et al., 2020) have identified four key resolutions in energy modelling: a) temporal, b) spatial, c) in techno-economic detail, and d) in sector coupling. Together with transparency, a model could achieve enough to contribute to the topic under discussion. The best short-term models of their review were Oemof and Calliope (medium resolution in techno-economic detail), and PyPSA (medium resolution in sector coupling). Specifically, PyPSA (T. Brown et al., 2018) has been highlighted *"as one of the promising open source tools, best validated for energy transition analyses for Europe, but it is not yet available on a global scale"* (Breyer et al., 2022). From the holistic modelling field, the best long-term model (5-year time step) would be the LUT model (Sadiqa et al., 2018), though it lack resolution in techno-economic detail (medium) and transparency (medium).

The temporal scale in energy analysis

"Imagination to power" and *"Be practical, do the impossible"*, slogans embodied by French students in May 1968. A complete renewable energy system was not included in the list of claims then; however, the first two 100% RES studies were published not long after that year, in Denmark (B. Sørensen, 1975) and the United States of America (Lovins, 1976). Later, the research on these systems increased exponentially over time. According to the Web of Science[53], 244 articles were published in 2021. A review on the historical evolution of 100% RES systems can be found in (Breyer et al., 2022).

One of the main concerns in the literature is the issue of *intermittency* and *variability*. These two terms are equally defined in the literature, but in general, intermittency refers to power fluctuations while variability to energy fluctuations. In short, intermittent energy sources provoke drastic changes in the input of local power plants that imply, after energy conversions, systemic energy variability.

[53] Keys: {"100" AND "RES" and "system"} AND {"100" AND "renewable" AND "system"}

The integration of the intermittency of the so-called variable renewable energy sources (VRES, i.e., solar photovoltaics, onshore wind, offshore wind, marine, wave, and tidal technologies) requires a sizing of the flexibility requirements for operating the power system in a cost-effective and reliable way, across all time scales (Pitcher, 2015). Figure 13 illustrates impacts of this variability at different time scales of the power system operation, as well as possible solutions for them.

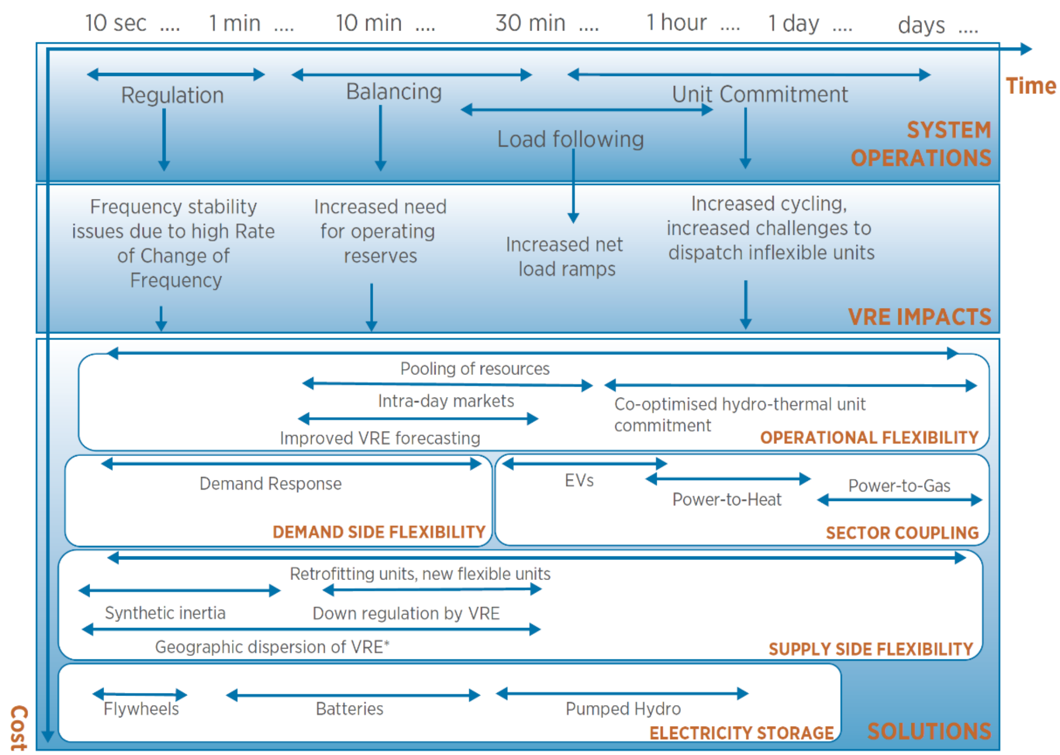

Figure 13. Impacts from renewable variability integration and possible solutions in the power system (Pitcher, 2015).

The issue of variability is not only linked with the fossil fuel consumption required in balancing units (e.g., combined cycle of gas turbines), but also, for instance, to which capacity of reserves is needed, an important aspect to calculate the economic value of load-following services (Mohandes et al., 2019). Last but not least, the feedback to capacity expansion would open up the disparity of material intensities in the assessment of lifecycle analysis (Tokimatsu et al., 2020).

Four limitations can be pointed out in literature when looking for the appropriate temporal scale in a model.

- Overlapping dynamics that occur at different scales. The spaciotemporal resolution limits which processes can be appropriately integrated into systems with a large share of variable renewable energy sources (Ringkjøb et al., 2018).
- Data availability. In (Dai et al., 2017), limited data are mentioned that represent short-term effects in batteries, stating that the *"power sector model could be improved by the use of a more reliable dataset covering more regions"*. In the same way, the scarcity of data has been found when trying to reproduce the impact of wind power in the size of primary, secondary, and tertiary reserves (Brouwer, van den Broek, et al., 2014). As a rule of thumb, more detail requires more data to disaggregate the problem.
- Computational effort. Potential downscaling brings more expensive memory and computation tasks (McCollum et al., 2017). (Huppmann et al., 2019) highlighted *"potential trade-offs between more advanced approaches and computational complexity , and explicitly caution against including too much detail when this is not pertinent for the research question at hand"* in a novel framework to develop the integrated assessment model named $\text{MESSAGE}_{\text{ix}}$. (Huppmann et al., 2019). Again, the endless discussion between accuracy and practicality.
- Epistemic uncertainty[54] from one's own methods used in the analysis. Some examples could include: (Ludig et al., 2011) concluded that the *time slices* method poorly renders dimensions of the power system, e.g., high percentages of the

[54] Source of uncertainty in engineering modelling for risk and reliability analyses. Epistemic uncertainty can be reduced by the modeller if more data are gathered or the model is refined (Kiureghian & Ditlevsen, 2009).

> variability were lost in demand, solar energy, and wind energy, with 96 slices of 1 hour length. (Welsch et al., 2014) compared two energy models, OSeMOSYS (12 time slices) and the soft-linked TIMES-PLEXOS (in two configurations, 12 slices and 8784 hours). The Irish power system delivered 21.4% of wrong dispatch allocations in OSeMOSYS, underestimating the investments required by 14.3%.

The real operation of national power systems may be analysed in two steps. First, forecasting delivers a first shape of the future dispatch in the market (merit order). Second, solving the short-term capacity allocation of reserves based on operational criteria. The fact that the energy transition covers not only electricity but the supply of primary energy to the whole economy, i.e., heat, electricity, solids, liquids, and gases, is again highlighted. Consequently, the future energy system would be more complex than today. Engineers can try to optimize the operation to synchronize the system to the weather conditions and demand profiles.

Integrated assessment models are not inattentive about the temporal scale. The introduction of Chapter 5 sets out the challenge for the holistic tools, suggesting a minimum resolution of 8 hours for the analysis. An extensive analysis of the temporal scale in IAMs is then developed in Chapter 6, specifically, in the introduction with appendices (e.g., table A.1 summarizes this information), evaluating different methods applied in the history of energy modelling.

Flexibility options

In the biological analogy, flexibility options are metabolic energy converters that facilitate energy sources to the organic functions and increase the efficiency of the processes. They include synergies from the electricity sector to others such as transport (electric vehicles), heating systems (district networks), or fuels (electrolysis). Storage, for instance, is an option at any facility to delay loads over time. Their interest in planning is the macro-effect rather than the fine detail of operation. Technical and economic details by technology are avoided so as to focus attention on the systemic flexibility needed in the energy transition. Some authors have delivered a first, rough estimation of general flexibility requirements in 10% of the installed renewable capacity (Gonzalez-Salazar et al., 2018). However, each region, economy, or society always has special characteristics and capacities. Generally, flexibility options consist of existing technologies with new active regulation strategies to take advantage of new situations; or specific technologies created to exploit an assumed future electricity overproduction from such effects as the duck curve[55], while also covering a market to substitute fossil fuels.

As we have seen above, supply and demand have to match at each point of time to operate the power system properly. 100% RES systems are based, in general, on high shares of variable power generation that require *energy system flexibility*, additional measures that can fall on either the supply side (time response of power plants) and/or the demand side (planning and control) (P. D. Lund et al., 2015). Flexibility is here sorted into local and systemic. We refer to *local flexibility* as the ability of a power/heat plant to adjust the output for the grid. When scaling the additive local flexibility into the whole region, it reaches systemic effects. So, we refer to *system flexibility* as the ability of the power/energy system to balance the energy demand and supply in the economy.

(Huber et al., 2014) found three pragmatic metrics to measure the system's flexibility in the literature: ramp magnitude, ramp frequency, and response time. Although the last two measures fall outside the scope of this thesis, the maximum and minimum power/heat ramps are crucial to planning short-time procedures for ancillary services and schedules (e.g., the intra-day market). The consequences of insufficient flexibility were analysed in China (Li et al., 2022):

- Rising curtailment in centralized renewable power plants.

[55] Self-consumption of solar electricity is increasing in homes and businesses, and it takes place directly at source or in the immediate vicinity. Following the sun's irradiance, the net demand shapes a pattern similar to a duck bill, intense in the midday hours on sunny days. The effect is partially accentuated by the fact that solar generation reduces the energy transmission from power plants. The grid operator has shown a growing concern about the stress ramping in late afternoon required to deal with the loss of solar generation after sunset, just when peak demand begins. The duck curve pattern appeared in California, and is now common in countries worldwide, making the duck curve even fatter (Colmenar-Santos et al., 2019).

- Falling reliability to meet load demand. It may cause serious concern since the economy and social welfare is highly dependent on electricity supply.
- Increasing costs in the operation of the power system.

What would the general picture of the energy system look like at high levels of renewable integration? Again, it depends on the regional conditions. From the EnergyPLAN's framework, six technologies were combined in simulations to estimate *flexibility potentials* for Bulgaria (Pfeifer et al., 2021). In descending order, industry decarbonization (combination of electrification and promotion of hydrogen) was highlighted as the best option to flexibilize the system, followed by the smart electrification of transport, the reduction of the minimum load required in power plants, and the massive use of power-to-heat technologies. On the other hand, demand side management did not contribute significantly.

The next subsections briefly explain the flexibility options considered in the experimental stage of the doctoral thesis.

Ancillary services

Reliable electricity should incorporate both *adequacy* and *security*. Reliability can be defined as *"the ability to supply loads with high level of probability for a certain time interval"* (Bompard et al., 2013). A reliable power system delivers electrical energy to all points of utilization within acceptable standards and in the amounts desired continuously. Adequacy, in the same reference, is the *"ability to supply power to customers in various conditions, taking into account operational constraints"*. Finally, security means *"the ability to withstand imminent disturbances or contingencies"*, e.g., short circuits or unanticipated loss of system elements.

Table 3 defines some of the most common ancillary services in the power sector. Traditionally, agreements between the power system operator and the private energy sector through specific ancillary service markets have managed the reliability task. High-inertial power plants, responsible for assuring technical security and enough capacity to meet the demand (P. D. Lund et al., 2015). These services deal with critical uncertainties from the real time operation to the day-ahead schedule (Gonzalez-Salazar et al., 2018).

Table 3. Grid ancillary services.

Very short duration: Milliseconds to 5 minutes	
Service	Description
Power quality and regulation	"Power quality and regulation is a power-intensive ancillary service that is characterized by a rapid and frequent response and very short duration. It is used to balance fluctuations in network frequency and voltage that arise from variations in wind and solar generators' output, along with their distributed nature. A too sharp deviation can damage equipment, lead to tripping of power generating units, or even to a system collapse" (P. D. Lund et al., 2015).
Short duration: 5 minutes to 1 hour	
Service	Description
Spinning, non-spinning and contingency reserves	"Spinning reserve refers to online power generation capacity synchronized to the grid having a short response time for ramping up but allowing several hours of use. They are generally used in contingency situations such as major generation and transmission failures. Spinning reserves are restored to their pre- contingency status using replacement production reserves that should be online 30–60 min after the failure. Non-spinning reserve is similar to spinning reserve, but without immediate response requirement. However, these reserves still need to fully respond within 10 min" (P. D. Lund et al., 2015).
Black-start	"the starting-up of a power plant after a major grid failure. The startup process requires some initial power input before the plant begins sustaining itself, and therefore a temporary external source of power is needed…some generators may need to be black-started themselves" (P. D. Lund et al., 2015).
Intermediate duration: 1 hour to 3 days	
Service	Description
Load following	"Load following is a continuous grid service that is used to obtain a better match between power supply and demand." (P. D. Lund et al., 2015)
Load levelling	"Load levelling with energy storage refers to the evening-out of the typical mountain and valley-shape of electricity demand. As with load following, energy is absorbed during periods of low demand and injected back to the grid during high demand" (P. D. Lund et al., 2015)

Transmission curtailment prevention / transmission loss reduction	"Transmission curtailment prevention and transmission loss reduction are ancillary services that temporarily reduce the amount of current flowing in certain parts of the power grid, increasing the efficiency of transmission and preventing production curtailment due to power line limitations." (P. D. Lund et al., 2015)
Unit commitment	"Unit commitment service refers to energy reserves that are used to manage errors and uncertainties in the predicted wind and solar output. For example, there might be an unforeseen shortage of wind for several days, requiring substitutive power to be supplied by discharging an energy reserve." (P. D. Lund et al., 2015)
Long duration: several months	
Service	Description
Seasonal shifting	"In seasonal shifting, energy is stored for up to several months. Seasonal shifting is most useful in systems with large seasonal variations in power consumption and generation." (P. D. Lund et al., 2015)

The level of flexibility is usually limited by the thermal stress in the thick-walled machinery. In one minute, the ramping rate (% full load) of a hydro reservoir is around 15% to 20% higher than the case of a simple cycle gas turbine. Nevertheless, geothermal is slower and can ramp at around 5%, while nuclear does so at around 2% (Gonzalez-Salazar et al., 2018).

In 100% RES systems, large steam turbines fuelled by geothermal, biomass, and biogas could provide *inflexible generation* in the baseload operation, sustaining the control of electricity quality (fast response and secondary). On the other hand, other designs of start-up and ramping operations are rare and time consuming for these plants. However, other thermodynamic cycles, configured in flexible gas turbines (biomass gasification, biogas), and solar CSP, are able to produce *flexible generation* for levelling down the time response of the output, very appropriate in the management of load variations and starting at short notice (mid-merit power stations). Finally, *highly flexible* power plants usually have very low marginal costs to sharply ramp up/down their output. Reservoir hydro, combustion engines and aeroderivative gas turbines are good examples of this category. Other examples are flywheels (very short term, 1 ms-5 min), flow batteries (short term, 5 min-1 h), or pumped hydropower energy storage and compressed-air energy storage for intermediate and long-term regulations (1 h-months) (P. D. Lund et al., 2015).

Power quality is a power-intensive service to flexibilize the response for a short duration, while load levelling is an energy-intensive service to satisfy the medium- and long-term demand response. Figure 14 summarizes common implementations at the local and system levels.

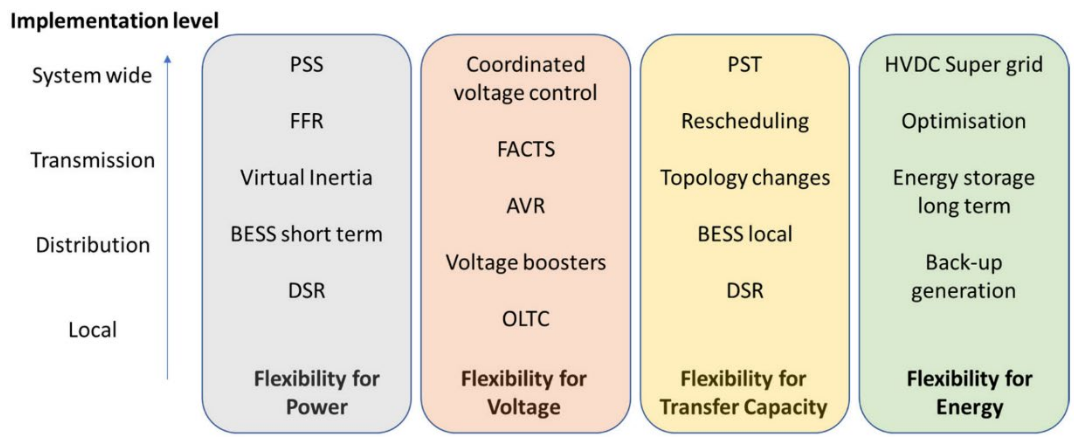

Figure 14. Ancillary services to add flexibility from power plants. PSS: Power System Stabiliser; FFR: Fast Frequency Response; BESS: Battery Energy Storage System; DSR: Demand Side Response; FACTS: Flexible AC Transmission System; AVR: Automatic Voltage Regulator; OLTC: On-Load Tap-Changer; PST: Phase-Shifting Transformer. Source: (Hillberg Antony Zegers et al., 2019).

Assessing electrification policies in IAMs requires specific analysis, particularly critical for the power system, the biggest human machine. In any case, the validation of a scenario for the power system (and energy system by extension) is pending on such additional technical constraints as the power quality and power ramps. If we review the scope of IAMs[56], they actually need to represent the structural changes[57] in the annual energy balances to generate feedback to other modules (economy, materials) in order to depict a realistic inertia of the

[56] Integrated assessment models operate at a global scale over many decades, integrating energy, environment, economy, and feedbacks between them.
[57] For example, the inertia of the capital stock and the electricity market (Pietzcker et al., 2017).

general dynamics of the social metabolism. However, the power analysis may be endogenous or exogenous for the model to complete the assessment in the specific sub-system.

Demand side management (DSM)

According to (Finn et al., 2011), there is a broad set of potential measures to follow the supply side of the energy system with an active role of the demand. DSM has the potential to be completely energy efficient since it does not require any intermediary conversion of energy. The promotion of DSM may be imposed or financed via incentive or price. Figure 15 depicts the effects provoked by five DSM strategies (P. D. Lund et al., 2015), in comparison with the flexible load shape as reference (table 2, (Alto, 1989)):

- **Peak shaving.** This effect reduces the peak of the load demand to avoid stressing high ramp loads for the suppliers. This strategy presents lower electric and fuel costs.
- **Valley filling.** This strategy is the opposite to peak shaving and increases the demand to homogenize over the top. This strategy presents no change to the electric cost but brings a higher fuel cost.
- **Load shifting.** This reschedules with intermediate storage and a utilization rate of less than 100% (e.g., intermediate storage of pulp in the paper industry). This option does not compromise the continuity and quality of the final services. It assumes around a 1% higher electric cost initially (lower later) and a lower fuel cost.
- **Conservation.** Measures oriented towards reducing the overall demand load. This strategy presents lower electric and fuel costs.
- **Load growth.** Opposite measures to conservation. This increases the load to match the supply. This strategy presents higher electric and fuel costs.

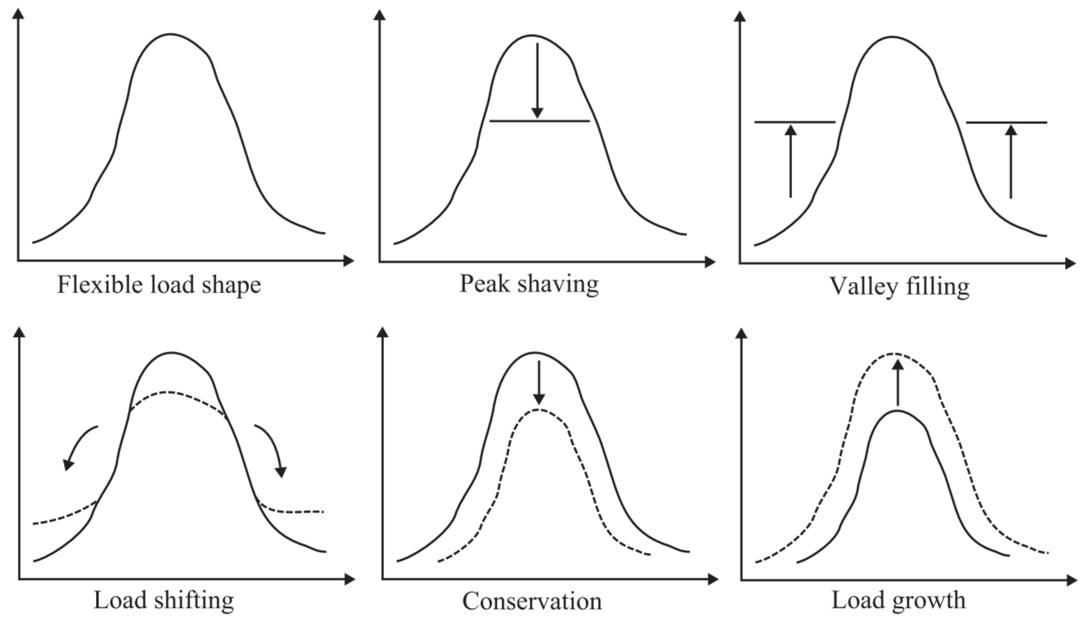

Figure 15. Different types of demand-side management effects (P. D. Lund et al., 2015).

DSM technologies and algorithms have found a good experimental benchmark and promotion in the field of microgrids, with relatively small power distribution networks, easy to isolate/grid-connect, controlling all kinds of elements (generators, storage devices, households appliances, etc.) to optimize the operation of the system (Kanakadhurga & Prabaharan, 2022). Scaling the control of multiple small loads can generate a great potential at the power system level. Additionally, the highest power burdens are placed in energy-intensive heavy industries, which can also contribute as ancillary services (Golmohamadi, 2022).

Power grid expansion

The expansion of power grids has at least three flexibility contributions (Li et al., 2022):

- Matching supply and demand geographically.
- Balancing special fluctuations over broader areas.

- Integrating different geographical markets through cross-border trade.

High-voltage direct-current grid interconnections were highlighted for reducing the total cost, while increasing the overall efficiency and credibility of the energy system (Aghahosseini et al., 2019). Their American study found that the levelized cost of electricity dropped 14% from a scenario of independent regions to the paradigm of interconnectivity.

(Jacobson, 2021) concluded that interconnecting Portugal, Spain, and Gibraltar would decrease the aggregate annual cost of a 100% wind-water-sunlight system by 4.3%, while shedding 8.6%. On the other hand, a France-Spain-Italy connectivity would not reduce the cost per unit energy, since it was already low. There are other examples of regional synergy in the same study. Norwegian hydropower reservoirs could fill the gaps in Denmark's depicted system, reducing the overall nameplate capacity of generators for both countries by 22.6%, decreasing their average energy costs by 20.6%. In China, most of the wind and solar resources are concentrated in northern and western regions, remote locations from the centres of consumption in the East and South. The control of the inter-provincial and inter-regional transmission capacity is an efficient flexibility instrument for this country.

An extreme and emerging case study is the modelling of an interconnected world (Brinkerink et al., 2018)(Brinkerink et al., 2021). However, a balance between time intensity and data accuracy is present, spending more than 24 hours per simulation for certain cases. Covering the world, other variables take relevance: migrations, socio-economic drivers and barriers (Hojckova et al., 2022), and international trade of primary energies, among others. On the other hand, some authors have reviewed the benefits, opportunities, risks, and challenges for a global grid (Brinkerink et al., 2019).

The isolation of Spain is studied in Chapter 4 of this thesis.

Storage

From a system point of view, storage is a way to save a form of energy during a period, based on a charge and discharge process. There are a vast number of situations where storage is applied. Below, we have written a short introduction as a guide for the reader.

Mechanical energy storage technologies

The most deployed and mature technology to store mechanical energy is pumped hydroelectric energy storage, consisting in an exchange of water in reservoirs at different elevations connected by pipes and turbomachinery (Gallo et al., 2016). Energy is stored by pumping water from the lower to the upper reservoir. Later, water is returned to the lower reservoir through a turbine to restore energy (Chen et al., 2009). According to the characteristics of the turbomachinery unit, it can pump, turbine, or both (reversible pump-turbines) (Beaudin et al., 2010). A global storage potential of 23,000 TWh was found with geographical analysis for this technology (Stocks et al., 2020).

Compressed air energy storage is also a commercially mature technology. Its operation is able to compress large amounts of air (charge energy) by driving a compressor (electricity consumption) into an isolated system (e.g., salt mines or rock caverns). When required, the compressed air is heated before feeding it to a gas turbine to move its paddles (discharge process). The compressed air may be preheated with additional fuel use (generally natural gas or heat recuperator) to increase the enthalpy of the fluid, and then expanded in a turbine to generate electricity (Chen et al., 2009). Quasi-isothermal or quasi-isentropic processes are desirable to avoid wasted heat.

In a flywheel, the energy is transformed from electricity to rotational kinetic energy and vice versa, and then stored. An electric motor spins up the flywheel rotor (charge) to then turn the role of the rotor into a generator to produce electricity while decelerating the system (Chen et al., 2009).

Liquid air energy storage, based on liquefaction of air, is not yet at the commercial stage. In charging mode, a liquefaction cycle (electricity consumption) stores air in a thermally insulated tank. The discharge cycle, however, expands the liquid air to increase its pressure by passing through a heat exchanger to increase its enthalpy. The high-pressure air is used to generate electricity in a turbine (Gallo et al., 2016).

Pumped thermal energy storage is being using at the laboratory scale. Basically, a reversible heat pump engine is connected to two tanks for exchanging heat, moving a synchronous motor/generator. Electricity is consumed to produce high-pressure hot gas that is injected into a storage tank, while the cold gas is injected into the other storage tank. Hot and cold fronts are propagated from the gases into solid materials that fill the tanks. When required, the heat machine acts as a heat engine to discharge electricity from the temperature difference of both tanks. A shaft works to drive an electric generator (Gallo et al., 2016).

Electrochemical energy storage

This classification regroups different types of rechargeable batteries. A battery cell is composed of three main elements: two electrodes (positive and negative) and an electrolyte. An electrochemical potential is generated between both electrodes to induce the redox reaction that generates an external electrical current (discharge cycle in a closed circuit). Reactions are reversible, so batteries can be recharged by applying an external voltage (Chen et al., 2009). The response time is generally below one second, down to a scale of milliseconds (P. D. Lund et al., 2015).

There are many suitable materials whose chemical properties are useful to store energy. Conventional (lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion) and high-temperature batteries (sodium-sulphur, sodium-nickel-chloride, flow batteries, metal-air) are the most practical (Gallo et al., 2016).

Electrical energy storage technologies

The application of electromagnetism is another option to store electricity. Supercapacitors, for example, accumulate positive and negative charges, inducing a static electric field. They have a low energy density (2–10 kW h/m3), a moderate to high efficiency (60–85%) and a high self-discharge rate (over 40%/day) (Chen et al., 2009) (Beaudin et al., 2010)(Luo et al., 2015). On the other hand, instead of accumulating charges and inducing a static electric field, superconducting magnetic energy storage passes a current through a superconducting coil, thus generating a dynamic electric field (or a magnetic field) (Gallo et al., 2016).

Chemical energy storage

Power-to-gas and power-to-liquids, mentioned separately above, are chemical energy storage systems that have a holistic approach to the energy sector.

Solar-to-fuels comprises processes for the renewable production of synthetic fuels using solar energy, carbon dioxide and water. Such processes can be created from lifeless devices (*solar refineries*) or from biological organisms (*biorefinery*). The first is traditional in the sense that synthetic gas is obtained via power-to-liquid processes (solar photovoltaic and electrolysis) to feed the next fuel synthesis process (Gallo et al., 2016). The second is called metabolic engineering, an emerging field (laboratory scale) which uses the tools of synthetic biology to develop solutions in a symbiosis between nature and humankind (Ko et al., 2020). *"Hybrid biological−inorganic constructs have been created to use sunlight, air, and water as the only starting materials to accomplish carbon fixation in the form of biomass and liquid fuels"* (Dogutan & Nocera, 2019). A successful example (also closing the carbon cycle) was found with the *Ralstonia eutropha*, a bioengineered bacterium that drives the biosynthesis of poly(3-hydroxybutyrate), containing intramolecular hydrogen, to then produce isopropanol, isobutanol, and isopentanol (fuels). The energy efficiencies for fuels derived from the use of this bacteriums greatly exceeded the observed solar-to-biomass efficiencies of the most productive plants (typically around 1%) (Dogutan & Nocera, 2019).

Biomass is actually solar energy accumulated over time via photosynthesis into chemical energy. Surprisingly, although biomass is used in almost all the 100% RES system studies, missing its logistics is a major issue (Rentizelas et al., 2009)).

Thermal Energy Storage (TES)

These are storage solutions in which thermal energy (hot or cold) is the energy output form. The input to the storage may be waste energy, power-to-heat conversions. These systems may be classified by material and process: a) sensible heat thermal energy storage, b)latent heat thermal energy storage, and c) thermochemical energy storage (Chen et al., 2009)(Gallo et al., 2016).

Power-to-heat (P2H)

This flexibility option is the combination of technologies enabling an effective contribution for both renewable energy integration and decarbonization of the heating sector (Bloess et al., 2018). What provides flexibility in the power-heating system is the combination of three elements. First, an energy transformation process, i.e., consumption of electricity to generate heat. Second, a process of energy conservation, i.e., saving heat when excess is to be consumed later (thermal storage, not strictly P2H). Third, a carrier (e.g., water) to transport heat from the location where it is originally generated to where it is consumed or stored by the user. Obviously, P2H relies on the heat demand available in the region, and (Keiner et al., 2021) have estimated it for 145 mesoscale regions, reaching a global heat demand up to about 56,600 TWh_{th} in 2050, from about 45,400 TWh_{th} in 2012.

P2H applications (Figure 16) balance energy variability in the following ways (Maruf et al., 2022):

1. Reduce curtailments in variable renewable power plants.

2. Increase demand-side flexibility through load shifting.

3. Provide grid services via aggregators to optimize heating costs for consumers and provide grid balancing services to the national grid.

4. Increase self-consumption from local renewable-based generation.

P2H technologies can be classified according to the connectivity to the network (Figure 16), i.e.:

a) Centralized heating & cooling networks.
b) Installations on isolated/decentralized systems.

However, this general overview can be spread throughout a wide range of realities for both centralized and decentralized configurations, highlighting the relevance of heat pumps in low-carbon energy systems (Bloess et al., 2018). In agreement with (Maruf et al., 2022), the technology readiness level indicates that a fast development of P2H devices is possible, but the lack of infrastructure is a barrier to be overcome, an additional burden to fix.

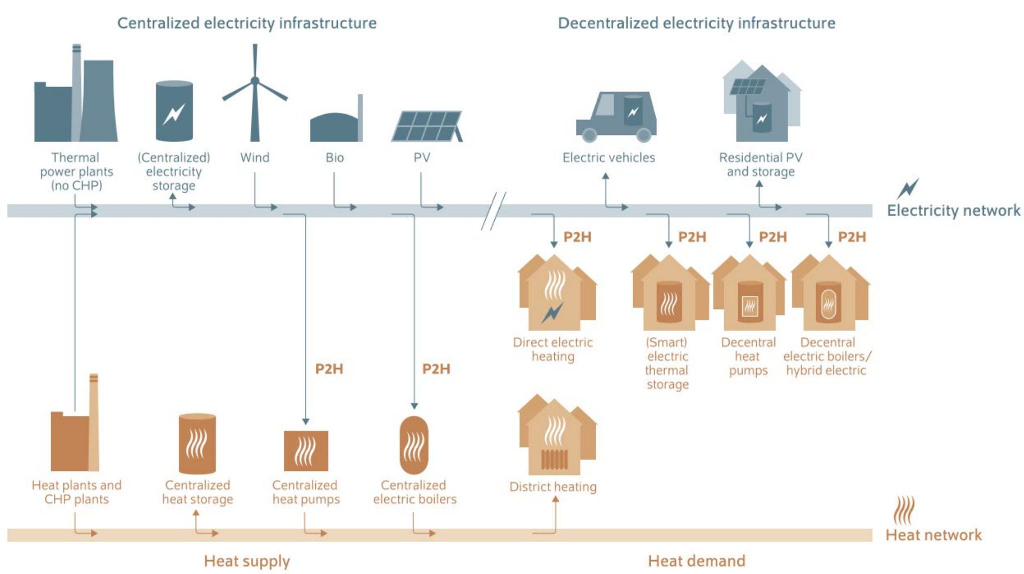

Figure 16. Different P2H configurations in the low- and medium-temperature economy (up to 1000 °C) (Bloess et al., 2018).

Power-to-gas (P2G) & Power-to-liquid (P2L)

P2G and P2L play with the same four components to decarbonize fuel markets: a) a carbon source; b) hydrogen and/or synthesis gas production; c) fuel synthesis; and d) fuel purification (Varone & Ferrari, 2015). The renewable version (Figure 17) of using the power-to-methane route via water electrolysis and then CO_2 methanization has shown a large potential in avoiding GHG emissions, while overcoming flammable and explosive problems in the processes (Qi et al., 2022). Applications go from offshore ship refuelling for marine transport (Bonacina et al., 2022) to evolutionary projections for defossilization in the steel industry (Lopez, Farfan, et al., 2022).

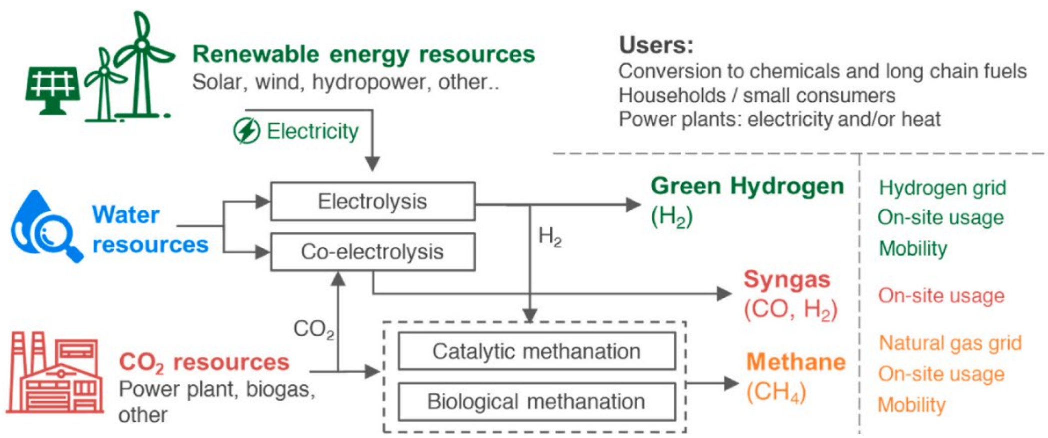

Figure 17. The renewable power-to-gas concept (Qi et al., 2022).

Figure 18 represents the technology using CO_2 emissions from industries or CO_2-free electricity (renewables) to produce an energy carrier (methane or hydrogen) that is then refined as fuel for end-uses. Infrastructures, such as gas pipelines, benefit from strategy (Fuchs et al., 2012). However, one limitation has been highlighted: hydrogen can only be directly injected into the natural gas grid for concentrations up to 4–5% (Gallo et al., 2016).

The P2G technology is currently under development. An alkaline electrolyser is the most mature and commercial form with a power-to-hydrogen efficiency between 43–66%. In the early commercial phase, those based on polymer electrolyte membranes have a higher efficiency of around 68–72%. Finally, the high-temperature solid oxide electrolyser seems to be promising, reaching an efficiency of up to 98% in the step of splitting CO_2 (Beaudin et al., 2010). The power-to-power application (electrolyser, storage device for hydrogen, and back to electricity in fuel cells or gas-engine/turbine) reduces the round-trip efficiency to 30-50% (25-35% if using methane). Thermodynamically, power-to-power would not be a smart option (Gallo et al., 2016), and generating hydrogen to integrate variable renewables is expensive for now (Beaudin et al., 2010).

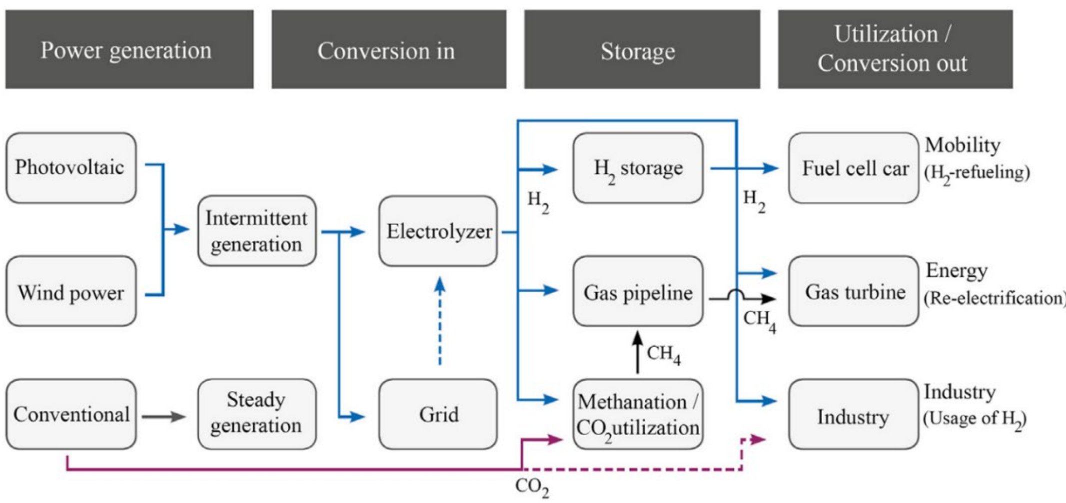

Figure 18. Power-to-gas flow schedule (Gallo et al., 2016).

Vehicle-to-grid (V2G)

To increase the utilization share of variable renewable energy sources, this option turns batteries of electric vehicles into storage for the grid. *Smart* (algorithm) power charge and discharge between grid and vehicles, using the latter as grid storage facilities (Mortaz & Valenzuela, 2018). Communities of electric vehicles can act as local aggregators to deliver a quick response that effectively accommodates demand, e.g., local peaks from wind/solar farms (Yao & Momoh, 2017).

Optimization for predictive energy management really becomes relevant for reducing the stress in batteries and performing a cost-effective operation with the grid. Artificial intelligence, Markov, the exponential decreasing model, and the telematics technique are some algorithms employed in the multi-source information platform shared among active agents of the power grid (Zhou et al., 2019).

The lifetime is additionally reduced because of the double function (to power the vehicle and as grid storage). Results in (Fioriti et al., 2023) suggest realistic lifetimes in the range of 10-20 years (200-300 10^3km) for V2G systems used by commuters for daily use of around 30 km a day. The lifetime drops with a heavier use of the battery (highway) to about 1-2 years (Fioriti et al., 2023).

A deep understanding of electric vehicles and their modelling in system dynamics have been advanced in the GEEDS papers (Pulido-Sánchez et al., 2021)(Pulido-Sánchez et al., 2022a). Our colleagues highlighted the rising awareness of the scarcity of critical materials in this sector, especially, lithium, manganese, and nickel. A concern also present in a European Commission report on this topic (Bobba et al., 2020).

Desalination

Globally, four billion people suffer water scarcity (Bond et al., 2019). This has been accentuated with the increase in water demand over the last few decades. Four direct anthropogenic factors, and one indirect factor, damage river hydrology: withdrawal of surface water from rivers and lakes, direct interception of catchment runoff, interception and regulation of river flows by dams, and alteration to surface-groundwater interactions through groundwater extraction. Anthropogenic climate change is the indirect factor.

(Ghazi et al., 2022) have reviewed renewable energy-based desalination. Wind, solar photovoltaic, and wave plants have been used to power electrodialysis and reverse osmosis. Wind coupled to reverse osmosis has become the main option to produce fresh water from seawater for drinking and agricultural purposes nowadays. An overproduction of electricity at certain hours (low prices) may benefit the market of desalinated water, playing an active balancing role from the demand side to match the supply.

Nevertheless, seawater desalination has a potential for adverse environmental impacts (pg. 716, (Elimelech & Phillip, 2011)). A priority for any society is to save and manage water reserves in a sustainable environment. Desalination of seawater could be an option to survive in water-stressed countries, but this strategy is wrong if we aim to support large-scale seawater desalination plants to irrigate new agricultural lands or to create golf courses in the middle of desertic areas. In short, planning should be conservatively placed within the ecological burdens of a region, mitigating the anthropogenic damage factors to water resources.

Some studies integrating desalination in 100% RES planning can be followed in Chile (Osorio-aravena et al., 2020) and Kazakhstan (Bogdanov, Gulagi, et al., 2021).

Curtailment

Centralized renewable power plants can restrict their power output when necessary to reduce mismatches between supply and demand. This is done following a specific strategy that varies according to the resource to be curtailed (Rossi et al., 2016). This option would be profitable at lower levels (less than 3% of the annual generation) if the cost of opportunity lost is lower than the marginal cost of increasing the output in dispatchable power plants (Li et al., 2022). However, this measure assumes wasted energy that may be used together with other flexibility options, such as sector coupling or storage.

When lacking flexibility, the exponential behaviour of curtailment generates a major concern beyond 30% of VRES installations in the mix (Brouwer, Van Den Broek, et al., 2014). A recent review of real curtailment has been done by (Yasuda et al., 2022). Figure 19 shows the successful and negative contexts for the integration of VRES. The authors highlight the fact that one or more of the following conditions are related to successful integrations (e.g., Spain or Shanxi): a) a strong domestic transmission grid; b) a high capacity of interconnectors to neighbouring countries; c) a high flexibility from conventional generators; d) implementations to operation-related adjustments (critical inertia limits).

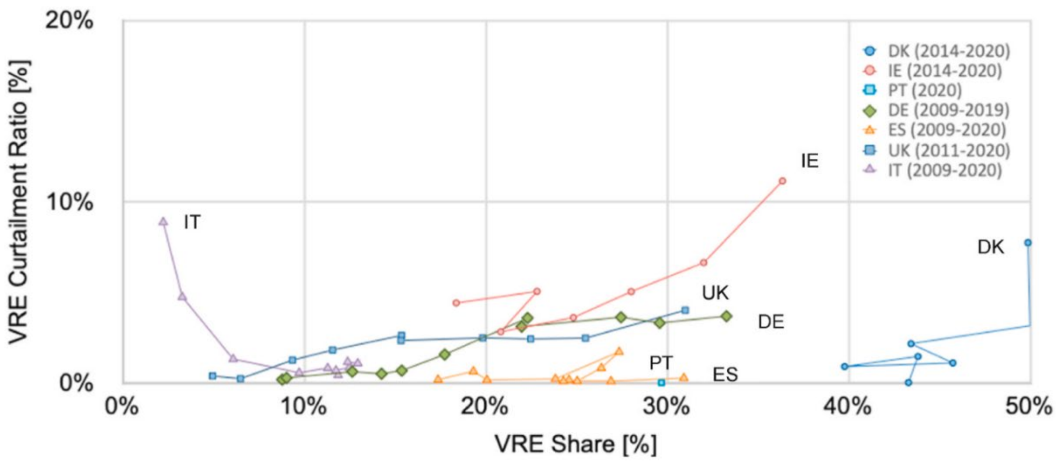

Figure 19. Curtailment of variable renewable energy (VRE) for some countries and share in the mix (Yasuda et al., 2022). DK: Denmark; IE: Ireland; PT: Portugal; DE: Germany; ES: Spain; UK: United Kingdom; IT: Italy.

Carbon capture and storage (CCS)

CO_2 capture technologies remove carbon emissions directly from carbon sources (power plants, gasification processes, etc.). Despite the disagreements and the lack of these technologies in the literature of IAMs (Jacobson et al., 2017), they have experienced a sharp growth over the last few years (Clack et al., 2017).

The IAM community presents CCS – and specially the most promising bioenergy generation with CCS, BECCS), common in scenarios of deep decarbonization elaborated by the Intergovernmental Panel on Climate Change – as part of the exploratory technologies in desired scenarios rather than a professional option that should really be considered (Low & Schäfer, 2020). In fact, a set of technologies was not considered when developing the MEDEAS model by our research group (GEEDS), but CCS was in the list together with another, highly financed, *'clear + clean'* solution, hydrogen (section 2.8.1, (Capellán-Pérez et al., 2020)). There were two criteria for removing CCS from the professional package of technologies in MEDEAS:

- A technology must be currently available, demonstrated, and commercial to avoid the inclusion of speculative technologies.
- Assure the technology will be a reasonable net energy contributor to society (i.e., it has a positive energy balance, EROI greater than 2).

(Child et al., 2019) revised the literature discussing CCS, and they concluded that it involves high costs and significant risks for only a relative benefit to society. In their words, *"CCS and nuclear power…appear on the verge of collapse as many nations see greater promise in renewable energy, as institutional investors seek to avoid risk through avoidance and divestment"*. From(Ram et al., 2017), Child et al. summarizes the following reasons why CCS is questionable:

1. CCS is more expensive than renewable technology.
2. Budget and construction further deteriorate the poor economics of CCS, which is not as yet a mature technology.
3. CCS is not carbon neutral, requiring efforts to manage the technology for generations.
4. CCS only manages CO2, so it is an incomplete solution to the impacts of fossil fuels, which have more harmful emissions, such as nitrogen oxide, heavy metal, and sulphur oxide.

Although science is always open to reviewing technologies when advances are demonstrated, and the current ongoing global model of the group (WILIAM, H2020 Locomotion project) considers this technology in power plants, we decided not to include CCS technologies in the modelling and analysis of 100% renewable energy scenarios for this dissertation.

Biophysical discussion in 100% RES systems

This section sets out the biophysical literature to discuss the limitations and gaps facing the challenging scenarios. Many studies have highlighted difficulties reaching 100% RES scenarios, especially due to three main concerns: a) the use of novel technologies based mostly on hydrogen (but also carbon capture and storage and flexible nuclear power plants); b) the omission of technical detail in the operation of energy plants (e.g., transients, harmonics, thermal stress); c) the omission of physical, social, and environmental barriers (e.g., mineral scarcity, acceptance of new large solar-PV plants, or damages to fauna and flora).

The bridging science called *biophysics* is the set of disciplines that applies theories and methods from physics to understand how our social metabolism works. In the topic of 100% RES systems, biophysics has been employed to estimate levels of extraction and payback from sources to sinks of nature, and to address indicators concerning planetary boundaries.

"The human economy…", as Kaufmann pointed out in 1987, *"…is consistent with physical laws; the organizational state of the economy increases while the organizational state of the universe as a whole decreases…the existence and reproduction of labor and capital depends on a continual input of low-entropy energy"* (Kaufmann, 1987). This logic may be extended beyond energy. Materials, knowledge, time[58], and space should be assumed as variables of the economic production[59]. Undervaluing the consequences of an unfair management of resources brings the concealment of drivers that explain social vulnerabilities in this disbalanced world economy. For example, the promotion of electric batteries and wind

[58] Time is a societal limit to be considered in the sustainability discussion. A global allocation problem among countries of the zero-sum game (Pérez-Sánchez et al., 2021).
[59] A reasoning that has been properly developed by ecological economists (Carpintero, 1999)(L. R. Brown, 2013). Biophysics has also proved that the Marxist tradition lacks physical restrictions in the analysis of the economy [61].

turbines should consider from where and how critical raw materials are going to be extracted, given that the activity has triggered crises[60] and internal armed conflicts[61].

There has been criticism of the mainstream economy since the very beginnings of biophysical research, but the strength of alternative policy recommendations for the energy transition has gradually grown over time, with regard to the following question: are energy planners also lacking biophysical restrictions? In modelling, (Bardi & Sgouridis, 2017) summarize a way forward as: *"Ideally, models should respect energy resource limitations, carefully articulate demand projections by the physical capital evolution by sector rather than trend extrapolations, and account for temporal variations, be it hourly or seasonal"*. The following paragraphs set out the discussion to avoid unfortunate recommendations.

(Heard et al., 2017) define four technical criteria to accept a 100% RES system:

- **Criterion 1.** The electricity demand must be consistent with mainstream projections.
- **Criterion 2.** The simulation must represent the matching between supply and demand at different timescales (five-minute, half-hourly, and hourly), including extreme climatic conditions.
- **Criterion 3.** Identification of transmission and distribution grid requirements, described and mapped to demonstrate how the electricity delivered by power plants reaches the end user.

[60] The international trade of strategic rare earths such as cobalt (Sun et al., 2022) or oil (Umar et al., 2022) are particular evidence of this severe situation, especially for key policies such as transport electrification (Pulido-Sánchez et al., 2022b). For example, the increasing interest of the European Commission in critical raw materials for strategic technologies and sectors is a clear symptom of economic vulnerabilities on physical restrictions (Bobba et al., 2020). The report highlights 7 minerals (lithium, graphite, cobalt, dysprosium, neodymium, nickel, and praseodymium) and 5 industries (batteries, fuel cells, wind turbines, photovoltaics, and e-mobility).

[61] As Lessmann and Steinkraus support (Lessmann & Steinkraus, 2019), the difference in the distribution of natural resources generates ethnic tensions through the induced rent-seeking behaviour, leading to income inequality. In short, *"resources are a blessing for resource-rich regions, but a curse for ethnically divided nations"*. It is fair in most of African economies dominated by extractivism (Greco, 2020).

- **Criterion 4.** Essential ancillary services must be maintained in the proposed system to ensure power quality and a reliable operation of the network, including distribution requirements.

None of the 24 studies analysed by (Heard et al., 2017) passed the four restrictive criteria. For the authors, none of them provide a convincing demonstration of the feasibility of their results.

Related to criterion 1, Heard et al. defined *viability*[62] to complete the justification of a scenario, based on, e.g., the historical maximums and minimums from real data. The maximum annual change in the energy intensity of the economic sectors is indirectly considering biophysical limits. Lacking more information, the assumption that such annual changes can be repeated in the future would be plausible. However, there are other assumptions that cannot be proved in the history. For example, higher rates in the electrification of cement, steel, refineries and hydrogen industries, or a transition in the market of the transport sector from gasoline, diesel and kerosene to electric- and hydrogen-fuelled mobility. These complexities are often missing in 100% RES studies (Jacobson, Delucchi, Bazouin, et al., 2015).

Both aspects of criterion 1 have been considered in Chapter 5 to reproduce our own scenario (2017-2030-2050), based on the historical energy intensities by economic sector and including the mentioned complexities. Regarding criterion 2, we only completed the hourly resolution. Similarly, criteria 3 and 4 fall outside the scope of this thesis, so they should be integrated into the future steps of this research line, so as to complete the justification of scenarios.

Appendix A in Chapter 6 reviews in detail the modelling of the energy variability in 8 integrated assessment models (Table A.1). However, biophysical dimensions were not

[62] *Viable* means, besides feasibility, the condition that the system is also realistically reproducing the socio-economic constraints in the scenario. Therefore, we can state that a technology can be technically feasible, but socioeconomically unviable (Heard et al., 2017).

included, so they have been included in this document so as to be able to further understand the state-of-the-art in the planning models.

Land and water

Land plays a limiting factor in energy plans that aim to unfold the exploitation of solar and wind power/heat plants. Energy-Economy-Environment models (a field very close to IAMs) integrate land as a biophysical domain of analysis to assess future pathways (Sgouridis et al., 2022). On the other hand, water availability is also a concern (especially in critical periods of drought) in the disruption of rivers and associated habitats, inflow for cooling at certain thermal power plants, reservoir levels in dam hydropower plants, and agriculture, among other uses.

On the side of 100% RES systems, (Heard et al., 2017) have highlighted a lack of land analysis in the field. For example, undervaluing the high land requirements of some 100% RES system scenarios for the United Kingdom and New Zealand, where latter seems to present enough hydrology of waterways to accept energy systems running almost exclusively with hydropower plants for about 4.5 million people that live on the island.

Different definitions are found, but most 100% RES studies follow the *land footprint* definition of (Jacobson et al., 2019), which means *"the physical area on the top surface of soil or water needed for each energy device…spacing is the area between some devices – such as wind turbines, wave devices, and tidal turbines – needed to minimize interference of the wake of one device with downstream devices"*. Consequently, (Jacobson, Delucchi, Bazouin, et al., 2015) estimated the potential area available for solar installations in rooftop and non-rooftop technologies. (Jacobson et al., 2019) further studied the impacts of 100% RES plans on grid stability, jobs, health, and climate around the world, finding a land footprint of 0.65% for the sum of the 143-country land area (rooftop solar installations were not included). However, the result did not come from a geographical analysis (note S44 in the supplementary material), and disposal of well-connected transmission lines and distribution systems was argued in order to validate the lack of land in small countries and islands. The same approach was followed in later articles, e.g., section 3.4 in (Jacobson et al., 2022). In general, geographical information system is usually used to accurately estimate the land requirements.

(Haas et al., 2018) considered the flow routing in the modelling of cascading hydropower supply (water-to-power conversion), as well as a water balance for pumped hydro storage. Biophysically, the natural inflow is considered in the study.

Oceans are shown as a source for new minerals and fresh water, rather than a limited resource that can constrain the deployment of certain power facilities. A clear example may be found in (Breyer et al., 2022) and the use of the LUT Energy System Transition model, where desalination is used to overcome possible water-stressing situations in the studies. Fortunately, cooling systems based on water are more intensive in Rankine (steam turbines) and Brayton (gas turbines) thermodynamic cycles, so water is not the first limiting factor for renewables. Similarly, in the studies of Breyer and Bogdanov, among others, available land is a constant upper bound, devoid of any dynamics.

(Capellán-Pérez et al., 2017) estimated the land requirements for expanding the capacity of solar electricity technology in two scenarios to cover 100% of the electricity mix and 100% of the aggregated final energy consumptions for the year 2009 in 40 countries (mostly Europe). The results suggest that a 100% solar electricity scenario could not therefore be feasible[63] in at least 16 of these countries, most of them in northern latitudes and consuming high amounts of electricity per capita. On the other hand, the authors also integrated the land competition and biodiversity into a national biophysical score. From this learning, for the IAM called MEDEAS, the authors later assumed an exogenous share of available rooftop in urban land for thermal solar and photovoltaic solar technologies (Capellán-Pérez et al., 2019).

[63] *Feasible* refers to *"possible within the constraints of the physical universe"*. The concept covers the whole electricity system, not merely the individual items of technology, such as solar panels or a wind turbine (Heard et al., 2017).

Other articles just mention how land and water might affect the energy transition in the introduction, discussion or conclusion sections. (Eyre, 2021) just mentioned that bioenergy is limited by land availability and the competition for other uses, such as food production. (Aghahosseini et al., 2019) proposed a grid interconnectivity across American regions on the basis of the land area available in the continent (only a single transmission line was marine). (Alves et al., 2020) and (Marocco et al., 2023) mentioned that islands have limited available space, so the valorisation of waste is crucial, indirectly linked to energy limitations. Surprisingly, water was not limited in either study, despite it also being a limited resource on islands and a barrier in the development of some types of power plants and electrolysis processes. Unfortunately, environmental impacts in biodiversity (fauna and flora) were also omitted in both case studies.

We have found literature from an energy-land-water perspective that could help to better integrate and represent the role of water and land in the energy transition towards a 100% renewable energy system (Price et al., 2018). In (Luderer et al., 2022), soft/hard-linking of several models has empowered the integration of both dimensions, water and land, to study low-emission scenarios. Alternative transformation pathways for land systems, environmental side effects from the competition of bioenergy, and non-energy uses for land and water (e.g., forests and land for rain-fed and irrigated crops) were some topics considered within the connection between REMIND (IAM) and MAgPIE (REgional Model of INvestment and Development, and Model of Agricultural Production and its Impacts on the Environment). Thus, the model Lund–Potsdam–Jena managed Land model (LPJmL) provided spatially explicit data on biophysical conditions, and the PREMISE framework (Ecoinvent database and ReCiPe method) to perform the life-cycle analysis of technologies.

(Turner et al., 2013) used the CSIRO model, which represents explicitly land, water, air, biomass, and mineral resources to assess the availability of water, materials (infrastructure) and fossil fuels on a transition to a 100% renewable power system (not the entire energy system) in Australia. For the sake of simplicity, they assumed both physically and economically available fossil fuels, but considering possible disruptions in the international market. In comparison to the business-as-usual scenario, material usage (glass, concrete, copper, and steel) experienced an increment of a factor close to ten for the renewable-based trend. The consumption of water in the renewable-based scenario did not suppose an issue for Australia, with the next disclaimer: *"if biomass is generated from specific additional forest plantations, the impact on river water resources can be detrimental"*.

Resource potentials (including their variability)

The literature defines two main categories of resource availability: variability observed in recent decades and variations coming from climate change (Breyer et al., 2022). Modelling futures would imply a stronger variability for wind and hydropower resource, and a marginal variation for solar resources. A beneficial exercise proposed by the authors to balance and adapt the energy system is the sharing of resources between neighbouring regions. For (Heard et al., 2017), however, the most concerning finding in the dependence of resources is biomass (potential estimation and consequences of exploitation). Biomass is a diffuse primary energy source that would generate conflicting effects in the ideal of the energy transition by increasing poverty, the ecological footprint and pollution, while also damaging the land conservation and therefore biodiversity and social justice for indigenous communities.

Traditionally, we have estimations from the specific literature of annual averaged capacity factors for technologies. More recently, the integration of resource-mapping studies within the methodology to estimate the potentials of interest are appearing.

(Jacobson, Delucchi, Bazouin, et al., 2015) estimated the annual averaged capacity factors for onshore and offshore wind turbines, as well as for hydroelectric power plants based on external information. The potential of solar generation was calculated by state in the United States of America. Relative information was gathered from other studies for geothermal, hydroelectric, tidal, and wave power capacity. Later, the same authors led the contribution of a model integrating gases, aerosols, transport, radiation, general circulation, mesoscale, and the ocean to capture extreme weather conditions and be consistent with the kinetic energy balance worldwide, based on 3 years of data at 30-second time resolution for 24 regions (Jacobson et al., 2019). In (Jacobson et al., 2022), new references are considered for the potential of pumped hydropower storage.

(Child et al., 2019) assumed generation profiles of solar photovoltaics, concentrated solar power, wind power (onshore and offshore) and capacity factors of suppliers. Rainfall was considered to estimate the capacity factor of run-of-river and dam hydropower units. A third set of calculations were done to estimate the potential of geothermal energy. Finally, biomass and waste energy were directly taken from other studies.

(Capellán-Pérez et al., 2017) used irradiance values, cell efficiency conversion, an average performance ratio over the park's life cycle, and a land occupation ratio to obtain the solar power density at country level. In another study, (Capellán-Pérez et al., 2019) assumed maximum techno-sustainable potentials for eight technologies to collect renewable energy from nature. The conceptualization of the IAM used (MEDEAS) did not represent the intra-annual evolution of variable renewables (solar photovoltaics, concentrated solar power, wind onshore and wind offshore) in the power system but implicitly considered impacts caused by their penetration in the electricity mix, from 0% to 100%. (Capellán-Pérez et al., 2019) modelled stylized damage functions based on own calculations from real data to estimate two key outputs. First, the reduction in the capacity factor of those units considered as *baseload* [64]. Second, the capacity factor of variable renewable power plants itself is reduced due to the wasted energy in over-productive hours (more energy than demanded). The approach would be realistic in traditional systems; however, they would not represent an actual smart energy system in which there is a great saving of renewable electricity overproduction available for other energy sectors. In short, flexibility options were not considered in MEDEAS.

[64] These technologies are characterized by high investment costs and relatively low variable operating costs. They are profitable when selling electricity during most hours of the year. They are also dispatchable in the sense that they can adjust output in response to demand. Typical technologies are nuclear and thermal power plants (Jonson et al., 2020).

Similarly, Dupont et al. (Dupont et al., 2021b) have quantified in detail the potential for wind (onshore and offshore) and solar energies as the major sources proposed in global 100% renewable worlds. Three types of solar power plants were considered: i) photovoltaic centralized power plants (two types of panels), ii) rooftop installations in the residential sector (two types of panels), iii) concentrated solar power plants (with or without thermal storage).

Most of the literature reviewed took the potential of renewable energy sources from existing resource-mapping studies (bottom-up approaches), such as (Haas et al., 2018)(Luderer et al., 2022)(Burandt et al., 2019)(Lopez, Aghahosseini, et al., 2022). Managing specific references, (Pfeifer et al., 2021) have gathered information about the potential of biomass, wind, run-of-river hydropower, and solar photovoltaic technologies. In methods, (Alves et al., 2020) limited the consumption of biomass in thermal power plants by the yearly resource available (value assumed from the specific literature of the case study). In tables 1-4 of the supplementary material of (Bogdanov et al., 2019), the authors show upper bounds in terms of full load hours for solar-PV, wind onshore, and hydro run-of-river technologies, as well as maximum annual potentials (TWh) of biomass. Additionally, the maximum installed is introduced for open-space solar-PV, concentrated solar power, wind onshore, dam hydropower reservoir, and run-of-river hydropower plants by subregion (145 in total), as part of the geographical description for the model. These values come from (Bogdanov et al., 2016), which, in turn, gather information from external data sources, for example, the assumption of a technical potential of 87.5–2770 PWh_{el} (solar photovoltaics) and 23.6–161 PWh_{el} (wind energy) worldwide. (Aghahosseini et al., 2019) calculated the hydropower resources from water flow data in 2005. However, the maximum potential of solar-PV, solar CSP, and onshore and offshore wind power plants are gathered from other studies and included as part of the method.

In Chapter 5, the biomass is considered as a limitation of the energy transition. The value is assumed from an official report. Furthermore, we mention the lack of endogenous fossil production in Spain, so imports could be constrained by protective political measures if the peak of these resources pressure the international trade, thus limiting the energy transition.

Materials and minerals[65]

Materials should also be considered in the energy transition. As (Deetman et al., 2021) highlight, *"the electricity sector will likely be responsible for a large increase in annual material demand towards 2050"*. Section D of the review made by (Breyer et al., 2022) considers criticisms of raw materials needed for the transition. In fact, as they point out, 100% RES research has promoted the investigation of material availability limits. However, to date, few studies really include this topic as part of the methods.

Junne et al. (Junne et al., 2020) studied four critical materials (neodymium, dysprosium, lithium, and cobalt) in six scenarios of global energy transition, two of them based on 100% renewable energy. These last two are presented as the most challenging in terms of materials.

Heard et al. (Heard et al., 2017) advised that, in developing countries, the energy transition needs new infrastructure concentrated around cement and steel. A challenge would remain in the logistics of fuel distribution, assuming additional intensive energy needs in the scenarios. On the other hand, (Capellán-Pérez et al., 2017) included two references to alert for possible material constraints during the emergence of solar technology, e.g., copper and silver.

Recycling rates in scenarios are high. (Junne et al., 2020) based the methods on the premise that a recycling infrastructure is well established and economically viable recycling processes to achieve 80% recycling rates.

Energy Returned On energy Invested

Looking back to EROI[66], we feel enthusiastic that this indicator has created a rich discussion in the foundations of the field under analysis. The discussion about EROI is currently not trivial in 100% RES systems. This indicator is linked to the net energy available for a society,

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[65] The European Commission has identified risks in critical raw materials (25) for strategic technologies (9) and sectors (renewables, e-mobility, Defence & Space) in the context of the energy transition (Bobba et al., 2020).

[66] The indicator has been already introduced in section "A suitable analogy for energy analysis" of Chapter 2 in this document.

and it draws a non-linear relationship known as the "net energy cliff". Figure 20 shows the estimated situations of different technologies nowadays. So, for example, biofuels would not be the best option to promote since society can only achieve 60% of net energy availability, compared to wind (95%) or solar (90%). In general, this would validate the large developments of solar and wind technologies planned by the Intergovernmental Panel on Climate Change and the literature reviewed.

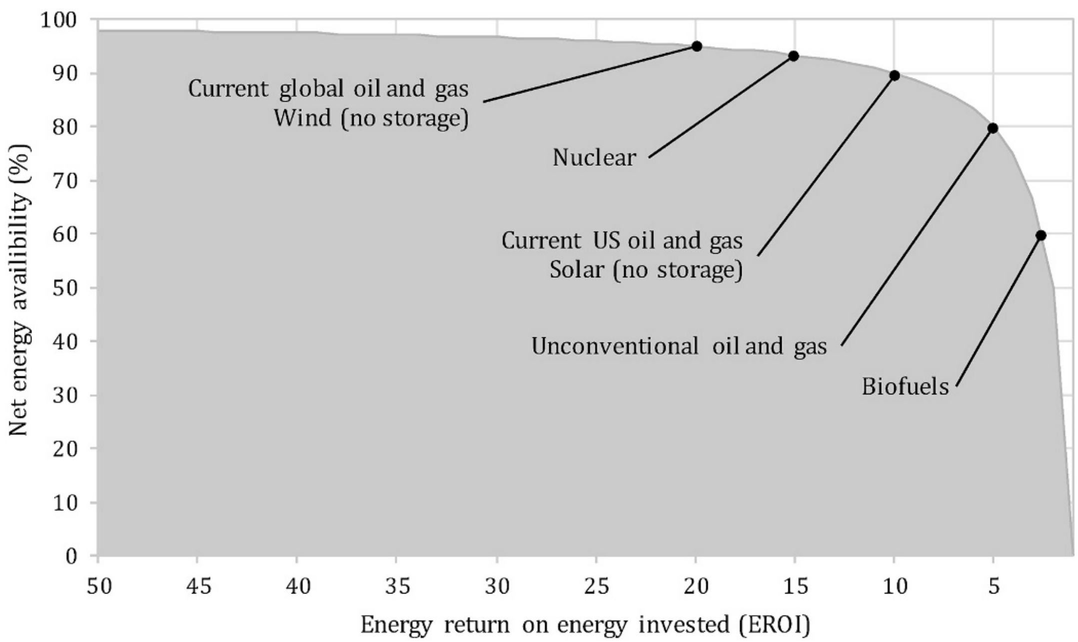

Figure 20. The net energy cliff, relationship between the net energy availability for a society and the EROI (Jackson & Jackson, 2021).

Supporters of 100% RES systems are aware of the limits. For example, Kenneth Hansen, together with professors Christian Breyer and Henrik Lund, two of the most-cited researchers in this field, wrote in 2019: *"Moreover, research priority should be given to combining the design of future 100% RE systems with the available resource potentials within and across regions"* (Hansen, Breyer, et al., 2019). Recently, Breyer and Lund have published studies including the biophysical insight to emphasize the limits. Regarding Lithium, Breyer et al. concluded in 2020 that *"in the century level cumulative analysis, existing resources supply the demand throughout the century only in few cases…for all other cases, supply deficits result in accompanying resource depletion before the end of the century"* (Greim et al., 2020). Both researchers recognized in 2022, together with another 21 co-authors (among them, Mark Z. Jacobson and Ugo Bardi), that the energy return on energy invested indicator, very common in modern biophysical economics, *"gives a fundamental insight into the practical viability of energy technologies from the point of view of the end user",* but alert that incorrect or partial applications of the famous indicator may lead to catastrophic conclusions, such as Georgescu-Roegen in 1971 or overestimations in the static final EROI of fossil fuels due to the fact that only processes at point of extraction are considered (section VI-A, (Breyer et al., 2022)).

The fact that the higher the complexity of a system, the more difficult its representation would be, leads to higher uncertainty about the output of interest. For example, (Breyer et al., 2022) argue that correctly framed EROIs of solar photovoltaics could reach values in the range of 15-60 and 20 for wind electricity. Radically different, these values fall very far short of the $EROI_{ext}$[67] delivered by (de Castro & Capellán-Pérez, 2020) (table 3) on large hydropower (6.5), wind onshore (2.9), wind offshore (2.3), solar-PV (1.6), and solar CSP (0.8). In fact, the EROI lower than one for concentrated solar power implies that the expansion of this technology should not be promoted, since we would be gathering less energy than we are investing.

Differences lie in the lack of a common framework to compute the actual energy delivered to society, and that the EROI is an indicator of estimations too complex to agree when attempting to assess a representative technology. EROI changes due to the learning curve of sub-technologies and regional conditions, e.g., meteorology and climate change in the case of solar and wind energy sources. However, as (Breyer et al., 2022) have written, *"despite*

[67] Final energy delivered to the final consumer (numerator) divided by both direct and indirect energy requirements to deliver the energy accounted in the numerator (denominator).

these methodological difficulties, correctly-framed EROI studies are still useful in allowing for the development of energy transition scenarios that are not based simply on the technical feasibility of a 100% RE-based society, but which also question the specific path that society needs to follow to carry out the transition before it is too late".

(Capellán-Pérez et al., 2019) dynamized the static EROI (equation 2), endogenous analysis in the IAM called MEDEAS-W, that further consider the lifetime of the technology, as well as the feedbacks from other spheres of human activities, such as the internal trade of the economy (input-output analysis and energy intensities), demography (population changes), and climate impacts. They reached a 100% renewable power system in which the dynamic $EROI_{st}$ of solar (PV & CSP) and wind offshore technologies exponentially grows at the end of the simulation (2060), showing very low values for most of the scenario, due to the initial energy and material investments (energy embodied as transformed matter). Wind onshore presented the highest values, with an oscillation caused by re-investment in the period 2045-2055. The energy transition depicted (green-growth-100% scenario) could cause a fall in the $EROI_{st}$ of the system to values lower than five in a period of 10 years (2050-2060), which is very dangerous for metabolisms of complex societies such as ours[68]. Capellán-Pérez et al. highlighted the fact that their results could be branded as optimistic, given conservative assumptions made along the EROI analysis. The evolution in the dynamic EROIst of renewable technologies (fast decline at the beginning followed by slow recovery) show similar patterns to the system EROI in (Jackson & Jackson, 2021), in opposition to the behaviour of the system EROI presented by Capellán-Pérez et al. in the mentioned reference. This may be caused by the lack of representation of non-renewable technologies, as well as methodological disagreements.

[68] According to Durán et al. (Fernández Durán & González Reyes, 2018), a complex society could be achieved with EROIs higher than 10. From the current point of view, the risk of losing social complexity, according to the $EROI_{st}$, would be: no risk (> 15:1), low risk (< 10-15:1), dangerous (< 5-10:1), very dangerous (< 5:1), unfeasible system (< 2-3:1) (Capellán-Pérez et al., 2019).

Social and political dynamics

There are other barriers that can constrain scenarios proposing a complete decarbonization. For example, (Capellán-Pérez et al., 2017) wrote *"geopolitical and economic barriers, as well as concerns over energy and food security will effectively pose significant constraints on the setting up of such large-scale intercontinental infrastructure"*.

In sociology, surveys are the principal source of information when searching for barriers. Unfavourable electricity prices, high initial investment cost, lack of acceptance by consumers, and lack of regulatory framework are some barriers to developing renewables, pointed out by (Rosso-Cerón & Kafarov, 2015). Educational institutions are projecting a collective worldview where renewables are presented as supporters of nature, advanced (complex) societies, and health. Renewable mega-projects break with the previous ideals, forcing people to accept severe exploitation on the land where they live. This is one reason why there is increasing opposition to energy mega-projects that are controlled by an external/international private company and benefits have no impact locally. (Jacobson, Delucchi, Bazouin, et al., 2015) pointed at wars and social opposition as sources of uncertainty when they planned roadmaps. In the subsequent related article (Jacobson et al., 2019), the economic cost to health and jobs were included in the social-cost analysis using social discount rates (notes S43 and S45 in the supplementary material). The authors insisted on the benefits of 100% renewable energy sources, in terms of the social costs of carbon dioxide (benefits for health), to reduce the *"limiting factor"* of social and political barriers in the transport sector (substitution of traditional vehicles by electrified vehicles). (Junne et al., 2020) alert that geopolitical issues derived from the unequal global distribution of resources is expected to rise.

(Alves et al., 2020) included a reference to social, economic, and environmental sustainability challenges faced by power systems in islands. However, they neither explicitly mention nor consider such challenges as limitations in the work. Social acceptance and political concern are usually mentioned to assume the lack of such uncertain aspects (social dynamics) of the energy transition in the techno-economic analysis, e.g., (Bogdanov, Ram, et al., 2021). Meanwhile, (Sgouridis et al., 2022) argue that approaches based on cost-benefit analysis interpret *efficiency* without possible social, environmental and political costs or the benefits from certain actions. Regarding scenarios, future energy demand projections strongly depend on social practice, economic and political choices, and demographic trends. The construction of the scenario becomes a set of value-laden assumptions.

Infrastructure and others

A challenging concern for modelling is that the energy transition may be limited. In the review of (Heard et al., 2017), it is said that *"no studies addressed the distribution-level infrastructure that would be required to accommodate increased embedded generation"*. Among the literature analysed, power transmission lines would be the most cited limiting infrastructure. Here are some examples.

(Aghahosseini et al., 2019) highlighted the fact that *"several technical, political and social barriers may slow down the progress of cross-border grid interconnections"*. Two examples are included; first, the opposition of residents to building transmission lines; second, the considerable energy losses of transferring electricity over long distances. These are arguments that agree with (Child et al., 2019), who reminded us of the uncertainty implicit in possible social resistance to new necessary high-voltage direct current transmission lines.

(Haas et al., 2018) modelled the power transmission infrastructure using a transport model (active power flows were considered, voltage phasors were not). They warned that *"planning transmission infrastructure usually involves other dimensions beyond costs, such as social opposition that results in delays and cost over-runs. These are being dealt with in more detail in an ongoing study"*.

(Jacobson, Delucchi, Bazouin, et al., 2015) mentioned the importance of energy-delivery infrastructure in the deployment of the transport sector. The creation of new infrastructure, they said, *"might result in a temporary, minor increase in emissions before emission are ultimately reduced to zero and might have minor impacts on energy use in the industrial sector"*.

(Turner et al., 2013) do not include biophysical barriers, but set them out for a 100% renewable energy system in Australia. The industrial metabolism, according to the authors, would change over the energy transition, demanding higher quantities of steel, copper, concrete, glass, and plastic, while building new installations that naturally involve energy use along with the labour burden.

In (Dorotić et al., 2019), the strong electrification of the transport sector assumes the EU 2050 goals on this matter. The installed capacities of the power sector would be increased greatly if they are not reached. They considered specific data on road infrastructure of the island depicted.

(Bogdanov et al., 2019) described the LUT Energy System Transition model, which integrates high-voltage alternative and direct current lines and converter stations as infrastructure needed to develop the power transmission capacity. However, (Bogdanov, Ram, et al., 2021) mentioned that, despite grid developments being considered in overall electricity T&D losses, the structure of the regional AC power grids inside the countries is not modelled.

Other authors are more holistic in their conclusions. (Breyer et al., 2022) write *"high bioenergy use may be in serious conflict with sustainability criteria, given that the global arable land is shrinking, ecosystems are under massive pressure, the world population is growing, and more food supply is required, while ongoing climate change impacts threaten even current food production...no more than about 27,800 TWh/yr of bioenergy can be supplied sustainably"*. In another study, (Luderer et al., 2022) represent the industry sector with four subsectors: steel (iron ore and secondary steel production, represented with a stock-flow model), cement, chemicals and other manufacturing. So, feedstocks and energy for infrastructures are included for both direct and indirect electrification of the economy.

Conclusions

The concept of energy metabolism and the field of 100% renewable energy systems frame the research of this thesis. Specifically, the modelling of variability in the energy system to consider new options that increase the term (1) by reducing the negative influence of curtailment in the EROI. Scenarios re-think how energy systems should evolve to achieve 100% renewable mix generations, considering biophysical limitations and Spain as the case study. On the other hand, there are two topics that are beyond the scope of this thesis. First, the calculation of energy and material intensities for technologies used to manage the variability, so the term (3) was not completed. Second, the complete assessment of all the biophysical criteria here reviewed, and the connection with economic and social feedbacks could not be achieved due to lack of information and time to integrate the specific modelling into a holistic integrated assessment model.

The complete modelling of the energy transition is a challenging task involving knowledge of multiple approaches that are not yet implemented. In order to compare the experimental work of this dissertation, we have reviewed 30 recent articles working on or discussing 100% RES power/energy systems. Premises, gaps and advances on this topic are summarized in Table 4, state-of-the-art in the features that energy planning models should include to work in the field of 100% RES systems.

Chapter 5 mentions some biophysical limitations in the methods used to study the Spanish energy transition. The lack of a more holistic approach makes the study partially incomplete. Climate change damage, EROI, and mineral scarcities are explicitly written into the article, but not considered within the methods.

Table 4. Premises, advances and gaps in the modelling of 100% RES systems.

Features modelled in the field of 100% RES systems	
Defossilization	The sources of energy to be exploited must be considered as entirely renewable in the last year of the scenario, verifying the full decommission of fossil fuels in the energy system. The capacity expansion relies on the regional conditions where the study is applied (Breyer et al., 2022).
Efficiency	Promotion of the energy efficiency wherever possible (Breyer et al., 2022).

Energy system re-design	Conversion of energy to save, transport (energy carriers), and flexibilize its availability at the end-use point, independently of the primary energy form extracted (Breyer et al., 2022).
Technological improvements	Assumption that modern hydrogen-based fuels (e-fuels[69]), third-generation biofuels, as well as power-to-X options[70] will be mature technologies in coming decades, able to substitute fossil fuel demands in those sectors that cannot be electrified before 2050. Common examples are long-distance aviation and marine transport, or industries producing cement and fertilizers (Breyer et al., 2022).
Demand	The energy services have to be fulfilled in the simulations (Breyer et al., 2022).
Applicability	Cases of study are applied to a wide range of geographical resolutions, from islands and smart grids to a unique World region.
Monetary requirements	Costs of technologies and fuels.
What is usually underrepresented in this research?	
Infrastructure	The enabling infrastructure to install such power-to-X technologies is omitted in the literature (e.g., materials to build power grid extensions and networks for district heating and hydrogen products) (Breyer et al., 2022).
Fossil feedstock	A complete elimination of fossil fuels as non-energy feedstock of the industry sector (steel, chemicals, pulp and paper, etc.) has not been modelled in these studies (Breyer et al., 2022).
Dynamization	Usually, scenarios are based on modifications of the historical year (calibrated), so dynamic effects are not considered from one year to the next in the scenario.
Demand patterns	The scope of 100% RES studies needs more detail about the supply side, assuming exogenous – or even better, endogenous – trends over plausible scenarios, including climatic conditions (Heard et al., 2017), different heating and cooling demand patterns of industries, and sub-disaggregation of Transport into different modes, linking the energy and feedstock requirements to the evolution of the economy (Breyer et al., 2022). All together, these are affected by the

[69] Use of electricity to generate synthetic fuels from hydrogen via electrolysis.
[70] Power-to-X refers to technologies able to convert electricity into another energy form. For example, power-to-heat (electric boilers and heat pumps), or power-to-hydrogen (electrolysers).

	underrepresented changes in the lifestyles of people (behavioural change and prosumers[71]).
Stability and quality constraints	Technical analysis of the stability, quality (frequency and voltage control) and security in the power system, e.g., power flow analysis, transient analysis, or simulation of black-out restoration processes (Heard et al., 2017)(Zappa et al., 2019). The assessment of the discussion about centralized vs decentralized systems is related to this topic, since it needs a detailed picture of the energy networks.
Feedbacks	100% RES systems need to represent coordinated and integrated elements in shared networks. This implies that, in addition to the other topics, feedbacks from one year of the simulation to the next should become widespread in this field, a lesson from integrated assessment modelling (Capellán-Pérez et al., 2019). For example, the feedback from the transformation of energy flows (primary to end-use energy) and the capacity expansion (energy plants, transmission lines, storage plants, etc.) to update the input-output tables (intermediate trade).
Risk-aware power balancing	The need to update the deterministic models and tools to the stochastic status, and to further develop probabilistic models (Kim et al., 2022).
Monetary requirements	The monetary value of changing the intermediate trade of the economy to supply all the necessary equipment for the transition (Bardi & Sgouridis, 2017).

The EnergyPLAN model used in next chapters is referenced through its documentation (cited in the peer-reviewed articles). Likewise, the assumptions with this model are presented in the appendices of such articles. For example, the conceptual differences between EnergyPLAN and the official energy balances used in the study are shown in appendix A of (Parrado-Hernando, Pfeifer, et al., 2022). The correspondence between the sectors of the model and those energy balances (table A.1 and table A.2), and the technical parameters assumed for the simulations (table A.3), as well as including the priority order for energy supply. Tables A.4, A.5, and A.6 in that appendix show the efficiencies and conversion

[71] Prosumer refers to agents that both consume and produce energy (Pena-Bello et al., 2022).

factors used. The rest of information in the same appendix presents the values assumed until 2050 for energy intensities.

Biophysical limits

In general, the literature on 100% RES systems has been more imaginative (proposals of flexibility options) than realistic (biophysical barriers). In some cases, the authors drag up old data about biophysical potentials, while others update sources or integrate the estimations within the methodology each time. The discussion has been written from the review, and summarized in Table 6 (located at the end of this chapter for comparison purposes).

As a result of the literature review, we can state that energy policy should be opened up to other disciplines that work with technical issues indirectly affecting resource supply. Accounting for, at least, critical raw materials would enhance the analysis. What is more, by implementing the modelling where "C" is found (Table 5), the results should cover most of the dimensions claimed in this thesis. One exception is biodiversity, which was not included in any of the articles, so it may be a potential research line from ecological engineering. The same may be concluded for social concerns, since there is a lack of modelling for social acceptance and barriers in the literature about 100% RES systems. Fortunately, it is a common concern, so exercises of modelling social acceptance should emerge soon from a novel multidisciplinary research line that, expanding the numeric analysis, links social perspectives within the theory of energy transitions.

From Table 5, we agree with section 3.5 in (Heard et al., 2017) concerning the lack of any detailed integration of ancillary services, even though these services are included – given that they were always present in energy planning.

Flexibility options

The literature review has revealed that all the flexibility options have been modelled across the literature, so they would be available, if necessary, by joining academic efforts.

Flexibility options used in the different articles are summarized in Table 5 (located at the end of this chapter for comparison purposes).

Ancillary services are taken into account in some way across the literature. However, none of the papers have integrated primary services around voltage and frequency stability, since this would require a power flow analysis. Obviously, transient analysis and other relative cycles and millisecond temporal scales fall outside the scope of the research on these energy system scenarios, at least, to our best understanding.

The literature agrees on the tight regulation of electricity and other energy prices to compensate for services provided by the flexibility options in such countries as China (Li et al., 2022). Fortunately, the willingness of governments to set up new legislative instruments to unlock flexibility means there is potential for further renewable integrations.

Appendix A in Chapter 6 reviews 8 IAMs in detail concerning the modelling of flexibility options (Table A.2), a key aspect in balancing the variability of renewable energy in the energy system. The experimental work of this thesis considers several flexibility options (Table 5). The study that integrates the most options is (Parrado-Hernando, Pfeifer, et al., 2022).

Ecological engineering in energy planning

In short, the biophysical discussion about 100% RES systems can be identified as a novelty from the perspective of ecological engineering in the field of energy planning. Such novel insights are causing an interdisciplinary dialectic similar to the existing discussion between the disciplines of neoclassical and ecological economics.

Ecological engineering[72] has coined several definitions (Xu & Li, 2012), summarized as *"the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both"* (Mitsch & Jørgensen, 2003). So far, the disciplinarity foundations

[72] It was first coined by Howard T. Odum in the 1963. It has been used extensively in North America, Europe, and China (where the father of this discipline was Ma Shijun) (Mitsch & Jørgensen, 2003).

refer to human interventions aiming to restore nature. Nevertheless, ecological engineering is presenting findings in relation to the biophysical limits of the energy transition. When engineering integrates ecology, "desired results" and "depends on the situation" become two measurements of an effective management representing the future energy system (Xu & Li, 2012). It is a common point in the attempt to overcome climate change.

Any economic activity entails an implicit environmental impact. The efforts of ecological engineering are traditionally focused on regenerative solutions, but there are few solutions in the energy system of the social metabolism to tackle anthropogenic climate change. If activities to design sustainable ecosystems are only beneficial for local ecosystems, this sector will continue with dependencies on other sectors of the economy. The end of the sentence *"for the benefit of both"* would therefore remain partial. The biological concept of *metabolism* is also shared by both disciplines. It leads to a more complete energy analysis by following a holistic overview of the processes involved in the system. EROI has been shown as to be a good example of this. So, extending ecological engineering to energy planning and IAMs can reinforce them and reach higher impacts.

Consequently, we may extend the definition of ecological engineering to include the field of 100% RES systems as follows:

"Ecological engineering aims to design a human metabolism in coherence with the sustainable levels of natural sources, sinks, and essential processes in the biosphere".

As argued by Bruno Latour (translated by Couze Venn), moral goals are proper to humankind, not part of motionless matter. In the same way, (Collins & Kusch, 1998) argue that technologies belong to the realm of means, while morality belongs to the realm of ends. A political problematization of the relation between ends and means is increasing nowadays because of the logic behind large-scale projects that aim to sustain unfair situations. This issue can be tackled in the 100%-RES literature by introducing biophysics and more detail, thus ethically going out on a limb.

This thesis does not define a political framework, but the extrapolation of the real data available in official databases, while the simulated impacts of comprehensive modifications in the quantitative scenario may support different qualitative narratives, politically interpreted under different – even opposing – ideologies or preconceived notions. For example, 100% renewable energy systems have been imagined as *desirable* realities to work for along this century. Consequently, one could easily fall into the ongoing bourgeois cultural revolution, i.e., support the idea that Capitalism as a system of perpetual growth in the reproduction of capital can avoid collapse by re-designing the energy system. In words of Fredric Jameson (Frederick, 1982), *"Capitalism demands…a memory of qualitative social change, a concrete vision of the past which we may expect to find completed by that far more abstract and empty conception of some future terminus which we sometimes call 'progress'"*. For the last few years, this sentence has perfectly defined what has been called "green Capitalism", a clear reference to a positive step forward from the still fossilist period. Another trouble spot in political ecology can be found in the relation between limits to growth and social justice, welfare or austerity (Gómez-Baggethun, 2020).

Table 5. Flexibility options used during the experimental work of this thesis, and others reviewed about 100% RES systems. AS: ancillary services; P2H: power-to-heat; P2G: power-to-gas; P2L: power-to-liquids; V2G: vehicle-to-grid; DSM: demand-side management; DES: desalinization; STO: storage; CCS: carbon capture and storage; IIL: international interconnection lines; CUR: curtailment. References "C" are studies considering the technology in the methods. References "M" are studies mentioning or discussing the technology but not included in the methods. Each item studies the whole energy system (ES) or the power system alone (PS). Time refers to the temporal resolution of the power/energy system operation (s: second; h: hour; y: year).

Article	**Time**	**AS**	**P2H**	**P2G**	**P2L**	**V2G**	**DSM**	**DES**	**STO**	**CCS**	**IIL**	**CUR**
(Jacobson, Delucchi, Bazouin, et al., 2015) (Jacobson, Delucchi, Cameron, et al., 2015) (Jacobson et al., 2019) (Jacobson et al., 2022)	30 s	C	C	C	M	M	C		C		C	
(Child et al., 2019)	1 h	C	C	C	M	C		C	C	C	C	C
(Capellán-Pérez et al., 2017) (Capellán-Pérez et al., 2019)	1 y	C				M			C			M
(Turner et al., 2013)	1 y	C							M		M	
(Pfeifer et al., 2021)	1 h	C	C	C	C	C	C		C			C
(Dupont et al., 2021b)	1 y	C							C			
(Heard et al., 2017)	Review	M							M		M	M
(Dorotić et al., 2019)	1 h	C	C	M	M	C	M	M	C		C	
(Alves et al., 2020)	1 h	C	M	M		C	M		C		C	C
(Aghahosseini et al., 2019)	1 h	C		C				C	C		C	C
(Bogdanov et al., 2019) (Bogdanov, Ram, et al., 2021) (Bogdanov, Gulagi, et al., 2021)	1 h	C	C	C	C	C		C	C	M	C	C
(Eyre, 2021)	1 y	C	C	C	C				M	M		
(Haas et al., 2018)	1 h	C		C	M		M		C		C	C

(Sgouridis et al., 2022)	Review	M		M	M				M	M	M	
(Breyer et al., 2022)	Review		M	M	M	M	M	M	M	M	M	M
(Luderer et al., 2022)	1 h	C	C	C			C	C	C	C	C	C
(Burandt et al., 2019)	1 h	C	C	C					C	C	C	C
(Lopez, Aghahosseini, et al., 2022)	1 h	C	C	C	C	M		C	C	M	C	C
(Holttinen et al., 2022)	Review	M	M	M	M		M		M		M	M
(Hansen, Mathiesen, et al., 2019)	1 h	C	C	C	C				C			C
(Marocco et al., 2023)	Time slices	C		C	M				C			
(Parrado-Hernando et al., 2021)	**1 h**	C							**C**		**C**	**C**
(Parrado-Hernando, Luka, et al., 2022)	**1 h**	**C**	**C**	**C**		**C**	**C**		**C**			**C**
(Parrado-Hernando, Pfeifer, et al., 2022)	**1 h**	**C**	**C**	**C**	**C**	**C**			**C**		**C**	**C**

Table 6. References highlighting biophysical limits in the discussion about 100% renewable energy/power systems. References "C" are studies considering biophysical limits in the methods. References "M" are studies mentioning biophysical limits or discussing those which are not included in the methods of other relative studies. Each item studies the whole energy system (ES) or the power system alone (PS).

References analysed	System	Land	Water	Infrastructure	Technical potential	Minerals/ materials	EROI	Biodiversity conservation	Social/Political
(Jacobson, Delucchi, Bazouin, et al., 2015) (Jacobson, Delucchi, Cameron, et al., 2015) (Jacobson et al., 2019) (Jacobson et al., 2022)	ES	C		M	C				M

(Child et al., 2019)	ES				C				M
(Capellán-Pérez et al., 2017)	ES	C			C	M		M	M
(Capellán-Pérez et al., 2019)	PS	C	M	M	C		C		
(Turner et al., 2013)	PS	M	M	M	M	M			
(Junne et al., 2020)	ES			M		C			M
(Dupont et al., 2021b)	ES				C		C		
(Pfeifer et al., 2021)	ES				C				
(Heard et al., 2017)	Review	M	M	M	M	M		M	M
(Dorotić et al., 2019)	ES			C	M				
(Alves et al., 2020)	ES	M			C				
(Aghahosseini et al., 2019)	ES	C			C				M
(Bogdanov et al., 2019) (Bogdanov, Ram, et al., 2021) (Bogdanov, Gulagi, et al., 2021)	ES	M		C	C				M
(Eyre, 2021)	ES				M				
(Haas et al., 2018)	PS		C	C	C				M
(Sgouridis et al., 2022)	Review	M		M		M			M
(Breyer et al., 2022)	Review	M		M	M	M	M	M	M
(Luderer et al., 2022)	ES	C	C	C	C	C			M
(Burandt et al., 2019)	ES				C	M			M
(Lopez, Aghahosseini, et al., 2022)	ES			M	C				M
(Holttinen et al., 2022)	Review			M					

(Hansen, Mathiesen, et al., 2019)	ES			M	C				
(Marocco et al., 2023)	ES	C			C				
(Parrado-Hernando et al., 2021)	**PS**						**M**		**M**
(Parrado-Hernando, Luka, et al., 2022)	**ES**	**M**			**M**	**M**			
(Parrado-Hernando, Pfeifer, et al., 2022)	**ES**				**C**	**M**	**M**		**M**

Chapter 4
Analysis of the variable renewable energy in the Spanish power system based on kernel probabilistic distributions (Parrado-Hernando et al., 2021)

Abstract

The development of renewable energies has been highlighted as a driver of the energy transition towards a more sustainable society. Despite the well-known benefits in health and regional energy resilience when those sources are leveraged, wind- and solar-based technologies bring about flexibility challenges in the power system. The variability in the generation of energy from renewable sources is probably its greatest weakness. This problem can be alleviated in different ways, but a detailed statistical analysis of the situation in each country is necessary to find the optimal solution in each case. This article analyses, from historical data and possible scenarios, some consequences that must be taken into account in the growth of electric power generation with renewable sources. Many assessment reports have been published to analyse high shares of the variable renewable energy supply (VRES) contribution in the electricity mix. This article aims to improve the accuracy in such reports through a novel analysis tool. Hourly timescale and the use of kernel probability distributions allow the well-represented supply and demand profiles necessary for an in-depth insight into electricity management. Spain offers multiple peculiarities which make our native region of interest for research activities. Here, an official report is analysed for three case studies: Spain as an energetic island without storage; Spain as an energetic island with storage; and Spain with both storage and international interconnections. According to this scenario, in 2050, the results indicate an underestimation of VRE generation (19% of renewable overcapacity) leading to very important challenges to the power system operator in the management of situations with 19 consecutive hours of electricity overproduction. In addition, a common output deserves attention: facing such scenarios with very high shares

of VRES, more flexibility is required in the power system in order to be efficient in progressive electricity development.

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Chapter 5
A novel approach to represent the energy system in integrated assessment models (Parrado-Hernando, Pfeifer, et al., 2022)

Abstract

The Spanish national energy and climate plan (PNIEC) has recently been published, leading the worldwide task of climate change mitigation towards a net zero-carbon economy by 2050. The objective scenario of the PNIEC expects to reach a renewable share in the power system of 74% by 2030. In this context, three contributions are developed: i) providing an analysis of how Spain is facing the energy transition; ii) conceptualizing the link between an hourly energy model (EnergyPLAN) and a yearly integrated assessment model (MEDEAS); and iii) proposing a transparent policy agenda for Spanish benchmarking in line with the official report. The results clarify the decreasing role such technologies as the combined heat and power facilities have, as well as the pressure surrounding biomass in Spain. Coherency in translating common variables in the energy chain of IAMs to the energy model is effectively reflected in the tables as an output of the research. Positive conclusions are found for Spain. The commitment of 74% might well be completed and the Spanish economy could run with a 100% renewable energy system by 2050, with requirements of sixteen and six times more installed capacity of solar-PV and wind onshore, respectively, by 2050 relative to 2017.

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Chapter 6
Capturing features of hourly-resolution energy models through statistical annual indicators (Parrado-Hernando, Luka, et al., 2022)

Abstract

Long term-energy planning has gradually moved towards finer temporal and spatial resolutions of the energy system to design the decarbonization of society. However, integrated assessment models (IAMs), focusing on a broader concept of sustainability transition, are typically yearly-resolution models and this complicates the capture of the specific supply-demand dynamics, which are relevant in the transition towards renewable energy sources (RES). Different methods for introducing sub-annual information are being used in IAMs, but the hourly representation of variable RES remains challenging. This article presents a method to translate the main dynamics of an hourly-resolution energy model into a yearly-resolution model. Here we test our method with the current European Union region (EU-27) by configuring and applying the hourly-resolution EnergyPLAN. Multiple linear regression analysis is applied to 174,960 simulations (set by varying 39 inputs by clusters and reaching 100% renewable systems), relating the adjusted capacity factors of the technologies as well as the variation of electricity demand and natural gas consumption as a function of the options installed to manage the variable RES. The obtained results allow the validation of the developed approach, which is seen to be flexible and easily generalizable enough to be applied to any couple of hourly and annual-resolution models and/or country.

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Chapter 7
Synthesis

The following points highlight the main findings and conclusions extracted from the three articles published on peer-review journals. They cover the objectives introduced in Chapter 1.

- Spain has proven to be a good case study for testing new energy planning methods. First, it is possible to cover most of the energy system over a sufficient time horizon thanks to the availability of hourly data and official reports. Second, the variability of meteorological conditions has revealed a wide range of situations on the supply and demand sides, reproducing challenges in the simulations carried out.
- With increasing rates of variable renewable penetration in Spain, all simulations have revealed an exponential growth in curtailment. The need for novel agents in the market and additional back-up requirements are findings that clearly points towards a more complex and interlinked energy system, focused on electricity. If any new measure is considered, the business-as-usual trend will negatively affect society, wasting huge amounts of electricity and therefore losing EROI and originating inefficient and expensive configurations of the energy mix. However, the global efficiency, developed in (Parrado-Hernando et al., 2021), could be improved by just considering mature storage and international power transmission lines, reaching a maximum in 2040. The next falling trend in that indicator demands additional flexibility measures, which have been applied for Spain in (Parrado-Hernando, Pfeifer, et al., 2022) to test a scenario of a 100% renewable energy system.
- Statistically, probabilistic distributions partially reproduce regional conditions, which is sufficient to identify and visualize the issue of intermittency and the need for planning. Multiple linear regression analysis has proven to be a feasible tool to condense EnergyPLAN results into analytical equations, integrable in IAMs.

- If the current trends of population and per capita energy consumption in Spain were maintained, we will face a Spanish population of 44 million in the year 2050. The annual final energy consumption per capita would be around 42 GJ/cap/yr (Parrado-Hernando, Pfeifer, et al., 2022), far higher than the level we need for a decent living standard[73] (13-18.4 GJ/cap/yr, (Millward-Hopkins et al., 2020)).
- Several options have been tested in simulations to tackle the issue of intermittency of renewable electricity sources in Spain. The order in which to promote them relies on how mature the technology is assumed to be. Until 2030: a) planning to manage and exploit sustainable potentials of biofuels and biomass; b) promotion of heat pumps in the space-sparse residential and service sector, while district heating is installed in high-density areas, including solar thermal; c) efficiency measures; d) reinforcement of grid stationary storage (pumped hydropower storage and batteries) and international transmission capacity; e) and industrial electrolysers to substitute natural gas in hydrogen-generation processes. However, the following set should be promoted from 2030 to 2050: a) synthetic fuels based on hydrogen in sectors with difficulties to be decarbonized; b) electric vehicles (according to the availability of minerals in the international market); c) reinforcement of the grid stationary storage; and d) expansion of the district heating networks and solar thermal technologies. PNIEC (Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), 2021), the most recent official report of energy planning in Spain, does not reach 2050, and the plan estimates lower levels of electrification but higher levels of renewable penetration and transport demand, in comparison to our results. For example, with reference to the conditions of 2017, +19.2% of wind, −17.5% of solar-PV, and −31.5% of solar CSP. In the energy transition, the main concerns Spain is facing are four: the evolution of the energy demand, social barriers derived from an inadequate installation of power plants, the potential scarcities of minerals (lithium, cobalt, nickel, manganese, graphite, and copper), and climate and human damages to biomass sources (including an appropriate management of forest).

[73] We recall here the decent living standard covers nutrition, shelter and living conditions, hygiene, clothing, healthcare, education, communications and information, and mobility.

- Flexibility options bring about two main benefits in the decarbonization process. First, a diversification that increases the number of agents on the supply and demand side, and therefore the potential to enhance the national energy security. Second, they open up new markets offering low-carbon energetic goods, an added environmental value much demanded by society.
- The hour, as the temporal unit of analysis, is enough for a general energy planning at national and world levels. Hourly results are accurate when comparing with historical data of generation and demand, so systemic barriers of the social metabolism can be assessed. Nevertheless, a higher resolution would capture more effects and technical barriers in specific technologies and sub-systems, especially in the power system.
- The methodology used in Chapter 5 enables the user to introduce ad-hoc policies to enhance the transparency of scenarios. However, the published article lacks the integration of biophysical constraints within the methods; a limitation that we hope to overcome in future steps of modelling.
- Although the Spanish power system operator has made data available to the public and Academia over the last decade, some specific physical characteristics of the power system such as voltage and frequency remain unavailable for the public analysis. The system operator is still a mandatory stakeholder in completing serious plans because of the unopened data collection required to reproduce operational scenarios in the power system.

Hereafter, additional considerations are summarized from the entire work set out in this document.

The following points are extracted from this doctoral thesis, to be considered in energy planning for the current energy transition:

- There is no unique way to make the transition towards a 100% RES system. Regional conditions determine most of the variability affecting energy plans. Flexibility options are being developed in many places to adapt the system to the regional conditions, with the aid of both mature and promising technologies.

- We believe that studying single years in simulations will soon be obsolete. The evolution of energy research is focusing attention more and more on the dynamics of the elements involved in the energy transition, which allows researchers to obtain synergic and feedback effects over years and decades, as has been shown when analysing the variability of renewables over hours during the year. System dynamics can have a good performance in the future if the development of the software allows for an external code enabling connectivity and modularity with other bottom-up and top-down approaches, not just to enhance the information available in the coupled model, but also for comparison purposes.
- Although the estimation of the maximum potential capacities has been the most cited biophysical limit, others have also been considered and omitted.
- Our studies should include the EROI indicators in the planning of the economy, so as to assure the optimal configuration while also achieving the desired level of complexity, or that allowed by nature, from infrastructures to connect activities of high-EROI to supporting low-EROI activities (even less than one, e.g., music and culture).
- The field of integrated assessment models (IAMs) has been proven suitable to consider energy transitions holistically. The interdisciplinarity develops conceptualizations by integrating several factors, focusing the attention on the feedbacks rather than specific technological details. The literature review has shown advances in models that reflect the trend towards mixing frameworks, in parallel to advances in computation machines to assume higher computational costs.

This thesis expands the knowledge of specific situations of decarbonization pathways and options to better integrate renewables in energy plans. The scope is now open to further work and collaborative tasks for the following steps in modelling the energy transition, i.e., the integration of the methods presented in the IAMs developed by the research group GEEDS. Below are some points to be considered:

- We would like to stress the importance of the connection between the energy transition and industrial production. This relation should be further studied to dynamically determine the evolution that the energy transition itself brings in the material production of the economy.
- In Chapter 2, we have described how new configurations of the energy system triggered new forms of social behaviour. Social barriers against the energy transition might be strong. This social opposition has not yet been modelled in scenarios of the 100% RES system, but only mentioned as an uncertain risk factor. The integration of social barriers and acceptance facing new installations in the energy mix will allow for a more complete panorama and dynamics when applying specific policies, thus enhancing the assessment. Similarly, modelling impacts on biodiversity have not received enough attention in the literature we reviewed. So, additional environmental impacts can contribute further along this line.

Final considerations

Energy transitions have led to social phenomena. First, when a society achieved higher energy levels, a surplus of energy was available to substitute the labour force in processes, which led to migrations that provoked economic, political and social tensions. Second, a higher complexity has historically required a higher concentration of population. Urbanization facilitates the organization of daily life for the population's increasing toned of production, thus increasing interactions between people and thus, the likelihood of developing new visions for society.

Historically, societies have sustained different degrees of social complexity. Freedom, serfdom, and slavery have coexisted in societies of low EROI. In theory, mutual aid and collaborative communities (small groups) could structure an efficient complex society with low energy investments for the activities. The internet-of-things and philosophy are central axes for a desirable society. Ethics and a re-designing of social structures based on ecology should be the key to reconnecting our lifestyles to the ecosystems that support life. Nevertheless, the feasibility of a complete evaluation of energy and the material requirements remains uncertain. What seems clear is the fact that lower levels of energy consumption are unavoidable.

I hope to continue working in GEEDS to bring the methods set out here into IAMs, as well as other links required to better understand the energy transition and the implications of energy policy.

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APPENDIX A. Peer review articles published in an indexed journal.