ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Scuola di Scienze – Campus di Ravenna
Corso di Laurea Magistrale in Analisi e Gestione dell'Ambiente
Curriculum Climate-KIC

Key factors regulating energy transition and repercussions on supply, demand and decarbonization: a causal loop diagram based on Italian dynamics

Tesi di laurea in Sistemi di Gestione Ambientale, di Politica ed Economia Ambientale

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Presentata da
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Sessione Straordinaria Anno Accademico 2021/2022

ABSTRACT

International policy seeks a transition to a more sustainable and secure energy system based on renewable energy and end-use electrification.

Despite energy transition being extensively covered in literature, few studies address the topic considering cause-effect multisectoral interdependency. This work fills this literature gap and develops a logical-conceptual model of the energy transition by means of a system dynamics approach; in particular, the causal loop diagram representation (CLD) is used as a modelling technique. The model, based on an extensive literature review in the main sources on the subject (e.g., TERNA, IEA, IRENA), provides an overview of the energy transition, considering technical, socio-political, economic and environmental issues, focusing on the Italian energy panorama.

The system is divided into two main functional domains: energy production and energy consumption.

Within the two domains, 22 variables and one constant were identified and the causal relationships between them were explored. Some relevant feedback mechanisms emerged, one of which, seen in the "Limits to Growth" archetype, underlies the behaviour of the system. Namely, it was found that the diffusion of renewables triggers a self-reinforcing mechanism due to advances in the sector, leading to an acceleration in renewable capacity that is successively slowed down by a balancing mechanism, triggered by the gradual reaching of a limit.

A similar mechanism is conceivable for the consumption domain, driven by electrification.

Six exogenous variables were identified, some of which can be addressed as leverage points. The model was compared with related studies, and several mechanisms were confirmed. Finally, the work was discussed with 7 experts to collect comments, opinions, and criticism.

Further investigation of the system should be performed quantitatively by implementing mathematical simulations in the model.

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1. INTRODUCTION

1.1. The importance of energy transition

First, it is important to define the concept of "energy transition". According to the European Union (EU), “Energy transition is a long-term structural change in energy systems aimed at developing a secure, affordable and climate friendly energy system better able to manage and balance dynamic patterns of supply and demand from a national and European level right down to a local level.” (European Commission, 2013). The deadline for achieving the strategic energy transition goals required by the EU to the national governments is 2050, so a time horizon of about 30 years is set.

The energy transition is more urgent than ever, due to three current macro phenomena that underscore the need to abandon the current fossil fuel-based energy structure and shift to a renewable energy-based energy system (Tiribuzi et al., 2023). An overview of these three macro-phenomena is outlined in the following chapters.

1.1.1. Depletion of fossil sources

Fossil fuels are by definition non-renewable; therefore, their continued use leads to their gradual depletion. Their depletion began almost 35 years ago, so much so that in 2008 the International Energy Agency (IEA) itself declared that the most economic category of petroleum had passed its peak of production (IEA, 2008). The ever-growing demand for oil has so far been met by introducing into the market categories of oil that are increasingly expensive and difficult to extract, and often of lower quality (Hughes, 2021). With current demand, it won’t be long before fossil sources phase out, with devastating repercussions on demand, which to meet supply will be destroyed through sudden and painful cost increases (Tiribuzi et al., 2023).

This trend applies to all categories of fossil fuels, but some are more abundant (or easier to extract) than others. Compared to petroleum, natural gas seems poised for a less precipitous decline because there are still large enough reserves and, because it has approximately half the CO_2 polluting effect compared to other fossil fuels (Stephenson et al., 2012), it is considered by many as a "transition fuel," i.e., a low-carbon substitute for other more polluting fossil fuels, reducing GHG emissions in the short to medium term, until the penetration of renewables into the energy system is sufficient to cover the entire sector safely and sustainably. (Gürsan and De Gooyert, 2021). However, natural gas is by no means emission-free, as methane is a greenhouse gas 28 times more potent than carbon dioxide, and the inevitable leaks that occur during extraction and transportation are not negligible. In addition, natural gas deposits are often mixed with large amounts of CO_2, which is also frequently released into the atmosphere due to the absence of stringent control measures. (Tiribuzi et al., 2023).

In any case, fossil fuels clearly must disappear from the energy scene, and they should preferably be replaced by renewable energies before they are exhausted - also independently of environmental aspects.

1.1.2. Climate change

Five economic sectors were identified as the main drivers of GHG emissions: energy production, industries, buildings, transportation, and AFOLU (Agriculture, Forestry and Other Land Uses). The largest share of emissions in 2018 came from the energy systems sector (34 percent; 20 $GtCO_2eq$), followed by industry (24 percent; 14 $GtCO_2eq$), AFOLU (21 percent; 12 $GtCO_2eq$), transport (14 percent; 8.3 $GtCO_2eq$) and the operation of buildings (6 percent; 3.3 $GtCO_2eq$) (Lamb et al., 2021).

Except for AFOLU, the GHG emissions of the other sectors are related to the energy sphere, in which two main domains can be identified: firstly, emissions generated by energy production; in the second place, emissions generated by energy consumption, namely transportation, industrial processes, and the operation of buildings. It is evident, therefore, that the introduction of renewable energy sources (RES), coupled with effective electrification of processes, can take a significant role in mitigating GHG emissions in several aspects.

The GHG emissions from electricity generation depends on multiple factors, which can be grouped into four main categories:

- emissions generated upstream, related to the supply chain of fuels, their extraction and refining, and transportation to power generation facilities;
- emissions related to plant construction, including the extraction of raw materials, the manufacture of components and their transportation to the plant site, as well as emissions related to construction operations;
- emissions related to power plant activity, directly caused by fuel combustion;
- emissions related to downstream processes, caused by the disposal of process waste and eventually by the decommissioning of the plant and the restoration of the area.

Of these four, fuel combustion in power plants is the main cause of GHG emissions from electricity generation; in fact, according to Scarlat et al. (2022), in the EU27, the emissions associated with gross electricity production reached 296 gCO_2eq/kWh electricity, of which 251 gCO_2eq/kWh are related to fuel combustion, 36 gCO_2eq/kWh are related to upstream fuel supply and 9 gCO_2eq/kWh electricity are related to the construction and decommissioning of electricity plants.

Renewable energy plants, while not exempt from emissions related to manufacturing and installation processes, or downstream processes such as decommissioning, do not have emission factors related to fuel supply and combustion, which leads them to take a central role in decarbonization. Figure 1 provides a comparison of GHG emissions in EU27 from different energy sources, with the contribution of each of the four categories of emission factors described above. The graph shows the clear difference in carbon intensity between renewable sources, where the main emission factors (the only ones in the case of PV, hydro, and wind) are related to construction and decommissioning, and fossil sources, where combustion-related emissions are dominant.

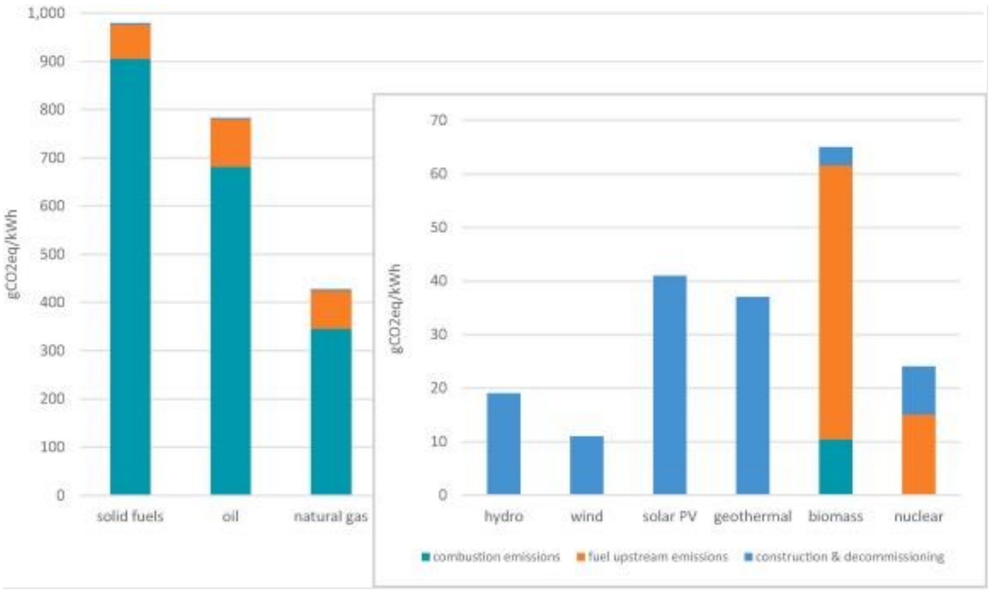

Figure 1: GHG emissions from the construction and decommissioning of electricity producing facilities (Scarlat et al., 2022).

As described in the previous section, emissions from energy use in the industrial, transportation, and building sectors account for 44% of total emissions. This percentage can be reduced by transitioning to electrification of consumption, i.e., replacing chemical energy from fossil sources with electrical (or chemical) energy from renewable sources; in the IEA report World Energy Outlook 2022, Birol (2023) states: “Clean electricity and electrification are absolutely central to the shift to a net zero emissions system.” The same report provides several forecast scenarios for the energy sector through 2050, the most optimistic of which is the net-zero emissions (NZE) scenario, which envisages a complete transition to renewables, the deployment of CCUS systems (BECCS = bioenergy equipped with CCUS; DACS = direct air capture and storage), a reduction in demand due to process efficiency, and, finally, the achievement of a high percentage of electrification of consumption. The chart in Figure 2 shows for each energy sector the effectiveness of these measures in reducing emissions, calculated in Gt of CO_2.

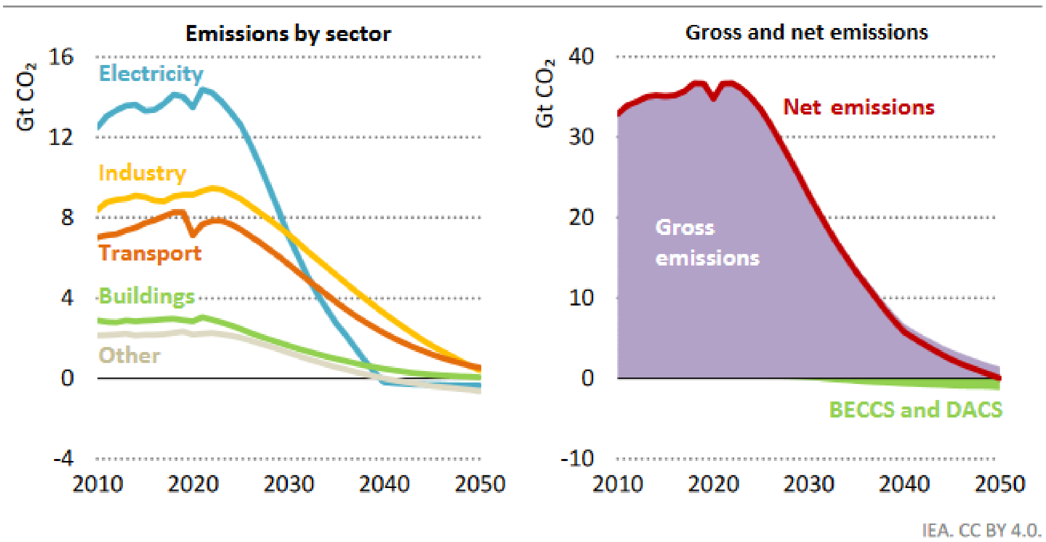

Figure 2: Energy-related CO2 emissions by sector and gross and net emissions in the NZE Scenario, 2010-2050 (Birol, 2023).

1.1.3. Dependence on foreign countries

In the Italian context, national fossil fuel production is not even remotely sufficient to meet energy needs; in fact, the share of net imports in gross energy availability, an indicator of the country's degree of dependence on foreign energy, was 73.4% in 2020 (MiTE, 2021), a figure influenced in part by the sharp drop in demand due to the Covid 19 emergency. This heavy dependence on imports makes Italy vulnerable to growing economic and geopolitical risks, exposing its internal economic-political situation and international relations to market instability, internal crises of producing countries, and interstate conflicts; a glaring example is Russia's unprovoked invasion of Ukraine in February 2022, which had a major impact on the global (and Italian) energy system by disrupting supply and demand patterns and fracturing solid international trade relations (Birol, 2023).

Energy security is therefore a key objective for the country, and to this end, a transition to renewable energy systems can significantly help reduce the risk of energy supply disruptions and the current dependence on imported fuels. Unlike fossil fuels, renewable energy sources are widely available in every country, and their use can achieve significant greenhouse gas reductions and various other positive co-benefits (Olz and IEA, 2007).

1.2. The challenges of the energy transition

The energy transition is a highly complex process that encompasses a wide range of sectors. Indeed, the transition to an emission-free energy system entails structural changes that not only concern technological aspects but also involve all areas of society. For this reason, the energy transition must be understood as a complex and dynamic system, the realisation of which is a goal that can be achieved by addressing numerous challenges at multiple levels. The following sections provide an overview of the main challenges of the energy transition with regard to the expansion of renewable energies in the three main thematic areas.

1.2.1. Technical challenges

Three major technical barriers to the deployment of renewable energy sources are described below:

- **Renewable energy intermittency**: the greatest difficulty for electricity grid operators is to meet energy demand with optimal use of available resources; electricity must be supplied in the same quantity as it is consumed, and in this delicate balance, a high share of renewables in the electricity mix is destructive because of their intermittent nature (Dalala et al., 2022). Indeed, with the introduction of renewables, periods of overproduction may occur, in which, in order not to exceed the grid's standard operating frequency limit, the operator is forced to recur to curtailment procedures, leading to an economically detrimental waste of energy. Alternatively, there may be periods of insufficient generation that not only fail to meet demand, but also cause the operating frequency of the grid to drop, requiring fossil fuel generation to be ramped up, resulting in a sudden and sharp increase in energy costs. Clearly, as the share of renewables in the power mix increases, it becomes increasingly difficult to schedule dispatch and achieve optimal allocation of resources.
  A promising solution to this problem is the use of energy storage systems, which not only avoid or reduce curtailments in the event of overproduction, but also allow the regulation and balancing of fluctuations in the frequency of grid operation caused by the unpredictability of renewables (Lakshminarayana et al., 2014; Ramos et al., 2023; Tiribuzi et al., 2023).

- **Grid congestion**: Network congestion is a situation of operation, even potential operation, of an electricity network characterised by deficiencies in the electricity transport service due to network constraints (ARERA, 1999). The unpredictability of renewables can lead to grid congestion at certain times, causing damaging infrastructure overloads, forcing the grid operator to implement curtailments. To avoid this, the grid infrastructure must be sufficiently sized to ensure that the transport capacity of the grid is adequate for the feed-in power of the connected generation plants. In Italy, the grid operator TERNA has included in its power grid planning the expansion of the grid infrastructure to accommodate the new renewable electricity needed to meet the national decarbonization targets (TERNA, 2023).
- **Skilled labor shortage**: Another challenge is the lack of skilled labour in the renewable energy sector. The low number of skilled workers combined with the high demand for equipment is slowing the pace of renewable energy equipment installation. To solve this problem, training programmes to increase the number of skilled workers must be implemented and made available to a greater number of people. (IEA, 2023).

1.2.2. Economical challenges

Renewable energy projects require very high capital investment and, by nature, typically have a high payback period, which makes the investment risky and less attractive to potential investors (Ansari et al., 2013). This problem is often exacerbated by overly stringent measures for accessing public funds. Renewable energy projects, particularly utility-scale projects, are often fraught with uncertainty, and obtaining investment is often tied to the provision of incentives that guarantee the financial viability of the project. According to IEA (2023), the uncertainty created by an absence of competitive auctions or limited visibility over future ones in some countries constrains the level of annual additions in renewable capacity. Therefore, it is critical that countries establish effective incentive programmes, both through the use of instruments such as feed-in tariffs that guarantee the project owner a favourable wholesale electricity price and by encouraging the spread of reciprocal power purchase agreements (PPAs) (Acharya, 2021).

1.2.3. Socio-political challenges

Like any change, the transition from conventional to renewable energy sources encounters opposition and resistance from the public; this is a social phenomenon due to the fact that the negative impacts caused by new renewable installations (modification of the landscape, land occupation, etc.) are much more evident than the benefits, which remain less visible and manifest themselves in the long term (Nasirov et al., 2015). This resistance often takes the form of the "Not In My Backyard" syndrome (NIMBY syndrome), according to which people are generally in favour of the concept of renewable energy, but not near where they live. Renewable energy projects very often face opposition from individual citizens and associations, and often even from environmentalists (Guo et al., 2014).

1.2.4. Regulatory challenges

One of the biggest problems slowing down the pace of expansion of renewables in several countries is the complexity and duration of the permitting process. Indeed, the permitting phase of a project is often hampered by long and complicated procedures, in some cases extending for more than a decade (Legambiente, 2022). Because of these long lead times, once approval is granted, there is a risk of ending up with technologically outdated projects that will inevitably require a variant of the authorised project, further extending the permitting period.

Looking at the case of Italy, a total of 303 GW of applications for connecting renewable energy projects to the national grid are counted for 2023. Of these 316 GW, about 264 GW are currently in the very early stages of the authorisation process, and only 5.3 GW (i.e., about 1.4%) have received a definitive connection solution from the grid operator (i.e., TERNA) (TERNA spa, 2023a). The slowness with which projects pass through the authorisation phase is evident; in 2019, about half of the projects submitted in Italy are still waiting for EIA approval; projects that, after this phase, must also pass through the subsequent approval procedure called "*Autorizzazione Unica*". The percentage of projects waiting for an EIA is increasing over the years, reaching 98 percent for solar and 100 percent for wind by 2022. (Legambiente, 2023).

In addition to (and often behind) permitting issues, there is a widespread lack of a clear regulatory framework, which in many cases, especially for large and innovative projects, leads to confusion and further lengthening of permitting duration (IEA, 2023).

1.3. Benefits of a conceptual logic model of the energy transition

From the previous section, it is clear that the energy transition is a complex, multidimensional process, divided into several thematic areas, each of which exerts its influence on the others and on the system as a whole. Understanding, initiating and managing an energy transition requires a solid understanding of the causal feedbacks between the elements involved, and the energy transition must be analysed in terms of the micro, meso and macro levels (Geels et al., 2017; Selvakkumaran and Ahlgren, 2020). For this purpose, the representation of the actual dynamics, involved processes and cause-effects relation-ship throught a system dynamic (SD) approach (Forrester, 1961) allows to highlight connections that are less evident with an analitic approach[1]. Indeed, these models include all three levels and allow to visualise a complex system in its dynamic structure, to map the interactions between the different factors and to highlight the properties of the system such as feedbacks, delays and leverage points. Several examples of the use of SD models to analyse specific systems can be found in the literature, some of which are presented below.

A first example is provided by Freeman (2021), who proposes a SD model for energy transition that relates political and social factors to energy, emissions, and climate change mitigation; the model has a 100-year time scale and is calibrated to historical UK data. Freeman's model is designed to provide a range of different possible scenarios with detailed pathways to decarbonization. This model, called TEMPEST (Technological EconoMic Political Energy System Transition), provides a conceptual overview of the socio-political challenges underlying the energy transition and uses simplified system modelling to emphasise the importance of controlling certain variables to reduce the uncertainty associated with the transition process. Due to the affinity with the present work, some considerations of Freeman's model are also included in the discussions of this thesis.

A second example of the use of SD in energy transition research is the work of Nair et al. (2021): Nair conducts an analysis of the impact of renewable energy penetration in Malaysia's energy mix on short- and long-term energy security using a SD modelling approach. The methodology used is causal loop diagrams (CLDs), which show the relationships between the numerous factors contributing to the country's energy security through the analysis of three main dimensions of energy security, namely: availability, affordability, and sustainability. For each of these dimensions, Nair creates a CLD and outlines two different scenarios to analyse the impact that renewable energy growth could have on energy security. Nair's model highlights the positive aspects of the transition to renewables while highlighting the critical aspects, such as the intermittency of renewables or the constraints due to high investment costs.

[1] The system dynamics is by nature a synthetic approach, which 'reduces' reality to make it representable and modelable

Finally, it is interesting to look at the work carried out by Savio et al. (2022), in which an SD model is used to investigate the dynamic interdependencies between coal, gas and renewables in the German energy market. Savio's model provides a comprehensive understanding of the system through simulations and helps prepare strategic policies to promote renewable energy. The methodology used by Savio involves modelling using "Stock & Flow" diagrams, which provide a logical-mathematical representation of the system and can be translated into differential equations (Forrester, 1961). Through this methodology, Savio's study can be a useful tool to describe and study the dynamics between different energy sources.

1.4. Purpose of the work

Given the timeliness of the energy transition issue and the complexity of the energy transition as a system, the study of the structure of this system is of utmost importance. Most of the studies on energy transition available in the literature so far, are sectoral studies that focus on single aspects of the problem and rarely provide a multi-dimensional overview of the sectors, levels and functional areas of the system.

The purpose of this thesis is to help fill this gap in literature and to create a logical-conceptual model that captures the structure of the energy transition system at all his functional levels. The model aims to map the variables involved, the relationships that connect them, and the properties that emerge from the feedbacks. The purpose of this qualitative exploration of the system and its logical interrelationships is to lay the groundwork for the creation of a quantitative mathematical model capable of faithfully reproducing the system and its dynamic behaviour through simulations, and to provide a tool for policy makers to promote the energy transition process with system awareness and knowledge, gained through the analysis of the scenarios generated by the simulations.

2. MATERIALS AND METHODS

2.1. The system thinking approach

In order to map the various processes involved in the energy transition, it was necessary to adopt a methodological approach that would allow factors of a very different nature and scope, such as political, technical, economic, and social factors, to be considered in a single analysis and highlight the causal relationships linking them. To meet this need, the methodological approach of systems thinking was chosen for this work.

In a complex system, a multitude of factors interact with each other and determine the behaviour of the entire system; System Thinking enables the representation, analysis, and classification of these dynamics by providing a spatial and temporal overview. System Thinking includes two other concepts, System Analysis and System Dynamics; System Analysis is the process of representing the mental model of the problem, and System Dynamics is the replication of the problem in mathematical terms, usually a step after the mental model is realised (Haraldsson, 2004).

For the realisation of this work, the Causal Loop Diagram (CLD) (Forrester, 1961) was chosen from the possible modelling techniques that belong to the group of System Thinking.

The CLD is a diagramming tool that allows a qualitative analysis of a system by mapping the main factors that compose it and the interactions that occur between them; in this way, one is able to capture the structure of a system and understand its behaviour and underlying motives; the CLD describes reality through the causalities between variables and how they form a circular dynamic influence (Haraldsson, 2004).

2.1.1. Structure and syntax of CLD

The Causal Loop Diagram is a diagram consisting of variables connected by arrows; these arrows represent the causal relationship connecting the two variables. Each arrow is associated with a polarity, which can be positive or negative marked by the signs (+) and (-), respectively. (Figure 3).

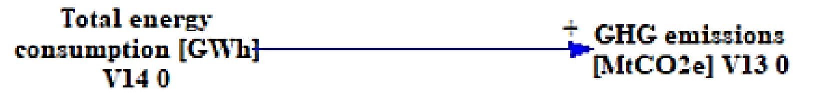

Figure 3: *Example of causal link extracted from the CLD elaborated in this thesis.*

According to Sterman (2000), a positive line means that if the cause (at the tail of the arrow) increases, the effect (at the point of the arrow) increases above what it would otherwise have been, and if the cause decreases, the effect decreases below what it would otherwise have been. A negative link means that if the causes increases, the effect decreases below what it would otherwise have been, and if the cause decreases the effect increases above what it would otherwise have been.

The links do not tell you what will happen, but rather what will happen if the cause changes value (Burns and Musa, 2001).

Another graphic element to note is the delay marker: the symbol “ // “ shown in

Figure 4 indicates that the causal relation on which it insists is not immediate but occurs later than the other causal relations in the other links, which instead occur simultaneously. This can have significant implications for the behaviour of a system; for example, it may cause a balancing feedback loop that slows a particular phenomenon to occur too late, or it may explain why one behaviour predominates over another. In any case, it should be made clear that the relationships represented by the links never occur instantaneously, and that no causal link, even without a delay marker, expresses an immediate action, with the exception of the links that connect a flow variable to its level variable (e.g., open faucet (flow) →+ water in the tank (stock).

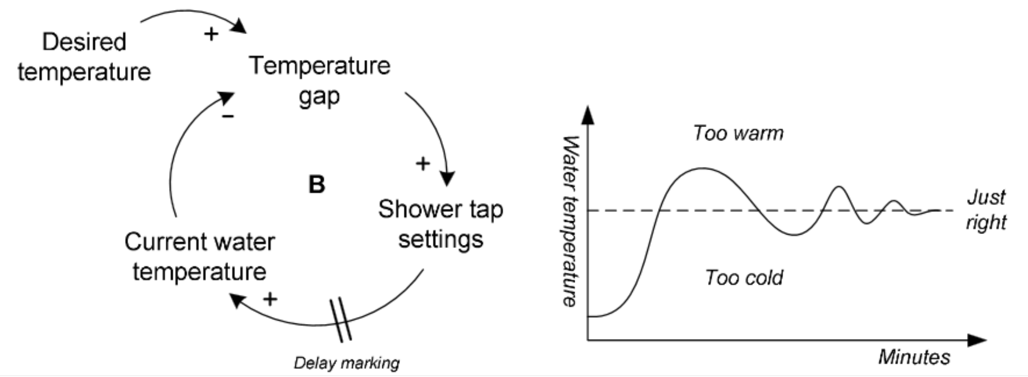

Figure 4: Example of feedback loop. A delay marker can be seen in the bottom of the balancing loop (adapted from Haraldsson, 2004).

In some situations, causal links between variables form a closed loop called a feedback loop (Figure 4). Feedback loops can be of two types, depending on the polarity of the causal links involved:

- **Balancing feedback loop:** characterised by an odd number of arrows with the sign (-), the balancing loop gives the system a slowing behaviour, the course of which has a logarithmic trajectory towards an equilibrium state.
- **Reinforcing feedback loop:** characterised by the absence or an even number of arrows with the sign (-), the reinforcing loop gives the system a self-amplifying behaviour, the course of which is exponential.

Sometimes the systems represented with CLDs present structures, i.e., configurations of dynamics between the variables that determine their behaviour; these configurations are sometimes recurrent and in this case are called "archetypes"; thus, the feedback loops described above are indeed archetypes.

Archetypes are a category of structures of a system that can recur and explain various behaviours. They apply to both physical and social systems and are elements of great importance within such a model, as they allow to capture dynamic cycles of influence between variables and reveal the behaviour of a given system, i.e., its evolution over time. Archetypes are a great advantage in exploring the system; a modeller, if he has a basic knowledge of the behaviour of the system, can focus the search on certain archetypes and easily identify certain key relationships, or, if the expected archetypes do not appear, he can focus his attention on the reason for their absence.

Figure 5 provides an explanation of the syntax and symbology used in the CLD.

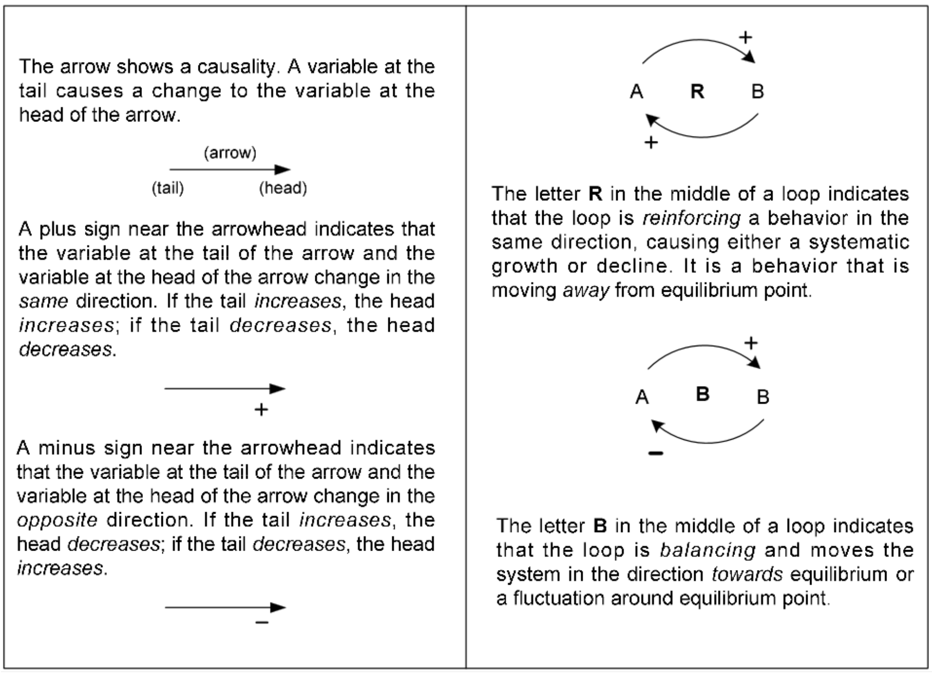

Figure 5: *The causal loop syntax explained (adopted from Roberts et al. 1983, p56).*

2.1.2. CLD construction process

The modelling of the energy transition system was carried out using the Vensim PLE software, a visual modeling tool that allows to conceptualize, document, simulate, analyze, and optimize models of dynamic systems. Vensim uses a workbench-toolbox design that combines visual models with powerful model simulation and analysis tools (Vensim Product Overview, 2023).

By connecting words with arrows, relationships among system variables are entered and recorded as causal connections. No mathematical implementations were carried out in the present model, which will be the subject of future work. For the time being, it was preferred to start with a logical-qualitative investigation of the structure of the system in order to obtain a model on which the subsequent quantitative study can be based. The causal loop diagram proposed in this thesis is the result of an iterative construction process divided into three phases, which are repeated several times until a sufficiently complete and representative model of the system under study is achieved. The individual steps of the process are described below.

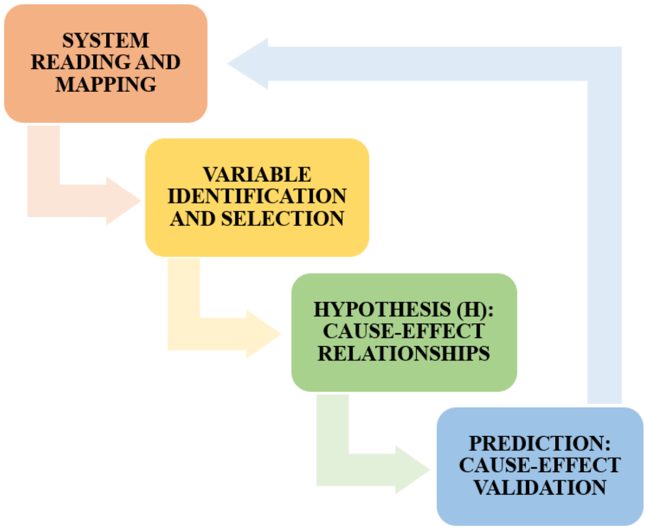

Figure 6: *Workflow diagram of the building process of the CLD.*

1. System reading and mapping (boundary mapping)

The first step was to determine the structure of the system and identify the main factors involved. This was done through an in-depth literature review, drawing on the most important sources on the subject (see next chapter) as well as numerous studies and publications on various aspects of the energy transition.

The system factors to be presented in the CLD were selected according to two basic criteria:

Representativity - Representativity refers to the significance of a factor/variable within the system, i.e., how effectively that factor represents a particular characteristic element of the system. It is important that the factors one chooses to represent in the CLD are representative in order to capture the dynamics of the system in a concise and understandable language and to avoid including factors that have little influence and unjustifiably increase the complexity of the model.

Measurability - The model realised in this thesis make use of a logical-qualitative syntax of the energy transition system; however, the language and the related software can be used to provide a structural basis on which numerical simulation models can be implemented. This will firstly make the model applicable in a real-world context and provide a potential tool to support strategy decisions, and secondly, the adopted language will allow to calibrate and validate its predictive power through numerical simulations. However, for this to happen, it is essential that all modelled factors be measurable, i.e., that each factor be assigned an indicator or unit of measurement. This concept, while trivial, has important implications that should be made explicit. The reader must be aware that to assign a unit of measurement to all

23 factors included in the CLD, a 'summarization" of information was required for each of them. Each variable presented in the model therefore has a broader implicit meaning of factors that are difficult to assign a unit of measurement to. This reflects the approach that must be taken when trying to represent reality using a conceptual model; this approach is called “reductionist” because it consists of reducing complexity for the sake of modelling convenience.
An example is given below to explain this concept:

Critical Raw Materials availability = Critical Raw Materials **Price [€],** V20

Variable V20, to be measurable, has been described as a price variable, but included in this cost are a few aspects related to the availability of these materials, the difficulty of finding and extracting them, the fact that these materials are under a monopoly of some countries, and so on. Apart from the fact that these aspects are difficult to measure, it would be impossible, or at least impractical, to include in the model all the elements that contribute to defining the availability of a given resource, therefore, adopting the reductionist approach mentioned above, all this information flows into a single measurable variable, which is the price.
It is imprtant to clarify that the system represented by the CLD has a maximum time span of 30 years (to 2050), beyond which its predictive ability is likely to become meaningless. Moreover, the model, although internationally valid, is focused on the Italian energy scenario, and in particular, only wind and photovoltaic have been considered among the renewable energy sources, since both the international literature (Birol, 2023; IEA, 2023; Tiribuzi et al., 2023) and the official data of the Italian grid operator TERNA confirm the poor prospects for an increase of hydropower, geothermal energy and biomass compared to photovoltaic and wind energy (Birol, 2023; IEA, 2023; Tiribuzi et al., 2023) (Figure 7). APPENDIX I provides an in-depth look at the state & trends of renewable energy in the Emilia-Romagna region, Italy, through the collection and processing of TERNA's official renewable consistency data.

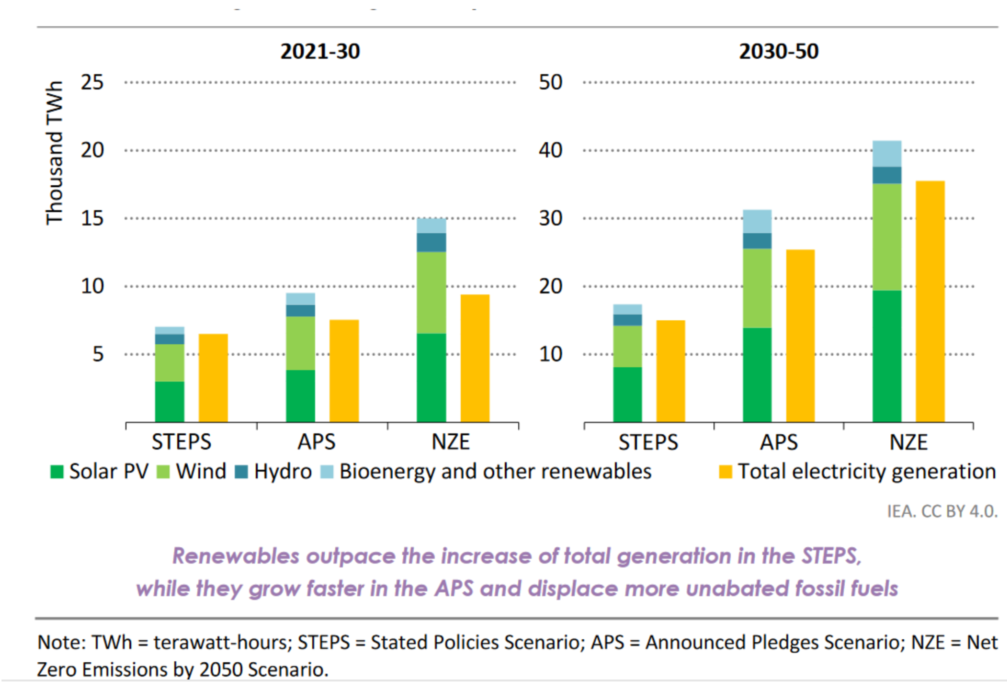

Figure 7: *Global growth in renewable electricity relative to total electricity generation growth by IEA scenario, 2021-2050 (Birol, 2023).*

2. *Hypothesis formulation*

After selecting the factors involved in the definition of the system to be analysed, the relationships linking them are defined by formulating hypotheses. These hypotheses are the positive or negative causal links between factors. These hypotheses are formulated by the modeller based on a reading of the system carried out with a comprehensive approach, embracing all the areas involved.

3. *Hypotesis validation or confutation*

After formulation of the hypotheses, i.e., after the causal relationships between the variables were established, they were tested by investigations to validate/refute each hypothesis. This was done, first, through a new, detailed literature review and, second, through direct discussion with academics, research groups, and experts in the field, to whom the model was presented and explained and who were then asked to comment on the hypotheses formulated by the modeller through directed questions and free-form discussion.

4. *Subsequent cycles of work*

After testing the hypotheses that had been established, the process of constructing the model just described was resumed, then the system was examined in light of the knowledge gained, some factors removed from the system or others added; new hypotheses were formulated, new causal relationships were added and others removed, and the newly established hypotheses were tested again.

As mentioned above, this is an iterative process in which each point has been repeated several times (and could continue to be repeated) until a satisfactory and acceptable CLD has been reached from the point of view of representativeness and clarity of the system.

2.2. Sources of information

As described above, the preparation of the CLD involved research of a strongly bibliographic nature, so it was essential to select national and international sources of the highest quality.

To collect the necessary data, articles and papers published in the main repositories of academic literature, such as Elsevier and Scopus, were consulted using several combinations of keywords and Boolean operators. In general, the use of academic articles was preferred to sitography, and the most recently published sources were always chosen whenever possible. Quantitative data on the Italian territory were retrieved from portals provided by the grid operator Terna and other national institutes. Most of the information on the European energy sector comes from international agencies such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA). Since the creation of the CLD is based on an iterative process of consulting sources, the literature search could continue for several more cycles, new articles and sources could be considered, and, in general, the information should be updated from year to year.

For the data on installed renewable energy capacity, production, energy demand and more general numerical data on the energy sector, the choice fell on the main official sources on the subject, listed in Table 1.

Table 1: *Official sources consulted.*

DATA CATEGORY	SOURCE OF INFORMATION
Renewables state & trends	IEA; IRENA;
Permitting (Italy)	Legambiente
Grid operations (Italy)	TERNA S.P.A.
Critical raw materials	IRENA

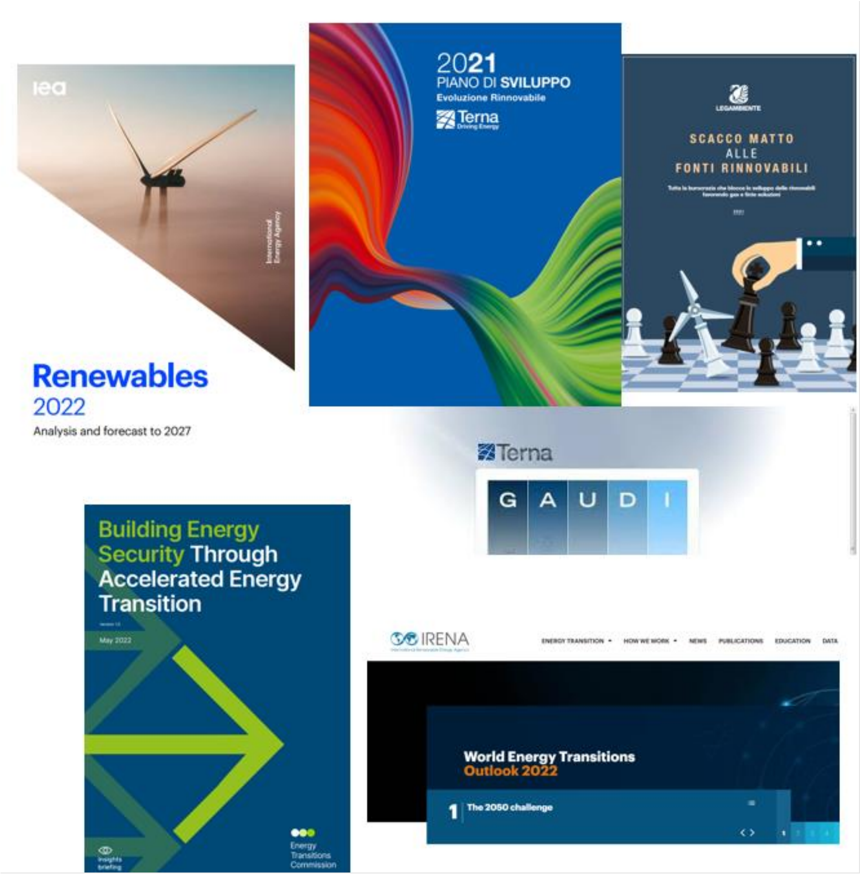

Figure 8: *Some of the main official sources of information used for the CLD construction.*

Below is a list of the main keywords used in the search.

Table 2: *Main keywords used for the literature research.*

Keywords	Energy Transition; Energy Storage; Renewable energy; Power grid transmission + Renewable energy; Renewables incentivation policies; Critical Raw Materials for Renewable energy; Causal loop diagram + Energy transition; System Dynamics; Technology readiness + Renewables; Energy market; Energy price; Electrification; GhG mitigation;

2.2.1. Interviews

When dealing with complex systems, it often happens that much of the information about the variables involved and the causal relationships between them cannot be obtained from conventional data sources but is stored in the mental models of experts (Ford and Sterman, 1998). In the case of this dissertation, "experts" are intended as those who are directly or indirectly involved in the system or in some of its processes, in operational or managerial roles (Ford and Sterman, 1998). Much of the information about the structure of the system in fact resides in the mental models of the participants in the process, and remains tacit

(Forrester, 1992). For this reason, system dynamics models of complex systems must include expert knowledge that guides and constrains their processes (Barlas, 1996).

Once the CLD was developed, a number of experts were identified to whom the work would be submitted to discuss the hypotheses and gather comments and considerations. For this reason, a pool of seven experts was selected, all of whom have been involved in research or publications on the energy transition or is working in the field. Each one of them has expertise in specific areas, from economics to permitting to more technical issues.

Ford and Sterman (1998) identify five main factors that should guide the methods of elicitation of this tacit knowledge:

- the purpose of the modelling effort;
- the phase of the model-building process and type of task being performed (e.g., elicitation, exploration, or evaluation);
- the number of people involved in the elicitation process;
- the time available;
- the cost of the elicitation methods.

Based on these factors, a one-hour videoconference was organised with seven experts to introduce and describe the CLD. A debate was then opened to discuss individual hypoteses and to gather a series of observations on the completeness, clarity, and meaning of the CLD through focused questions and free-form discussion.

The interviews were carried out according to the following schedule:

i. **Context establishment**: the presenter briefly described the purpose of the model and gave the experts the basis for reading the model by explaining the CLD syntax. The presenter then described the model, its major subsystems, their interactions, and the factors, structures, and relationships identified.

ii. **Focus on relationship:** After and during the description of the model, the experts directed their attention to some interesting causal relationships on which they thought further elaboration or comment was appropriate. Here, the presenter was able to collect comments on the individual links, regarding their correctness, completeness, and relevance.

iii. **Free discussion:** Finally, the experts were asked to comment on the model in general and to point out any shortcomings, weaknesses, and opportunities for improvement.

3. RESULTS

3.1. Causal Loop Diagram

To accurately reconstruct the mechanisms driving the energy transition, a CLD of the system was created using Vensim PLE software, based on data gathered from several literature reviews. The construction of the energy transition diagram CLD resulted into a model made of 22 main variables and 1 constant The selected vVariables and related causal relationships are described in Table 3 and Table 4, respectively. Feedback mechanisms emerge from the diagram, some of which are arranged in recurring structural patterns called “archetypes” in the language of system dynamics (view section 2.1.1).

The CLD can be divided into two main functional domains:

- the functional domain of energy production, whose causal links are highlighted in orange, is concentrated in the left part of the diagram;
- the functional domain of final energy consumption, whose causal links are highlighted in green, is concentrated in the right part of the diagram.

Highlighted in blue are all links connecting an exogenous variable to the system, i.e., a variable that is not a function of other variables specified in the CLD, at least in the context of the present analysis.

Starting on the left, the diagram shows how the production domain self-balances, with loop R1 causing an exponential increase in installed renewable capacity (defined by V2) but suffering from the braking effects identified in loops B1, B2, and B3; those behaviours are described in detail in Chapter 3.4.

Moving on to the domain of consumption, we can see how the increasing competitiveness of electricity, fuelled by lower renewable energy costs, policies, and rising fossil fuel costs, is driving the electrification of end use, i.e., the shift from fossil fuel-based processes to processes that use electricity. In this case, a negative feedback mechanism also emerges with a balancing effect on electrification; reinforcing feedback (exponentially increasing electrification) is assumed through an R2 loop, which is not made explicit in this CLD and gives the consumption domain similar behaviour to the production domain (see Chapter 3.4).

Finally, the trends identified in the two functional domains are reflected in the greenhouse gas emissions responsible for global warming.

In addition, there are six exogenous variables that play a key role in slowing or incentivizing the energy transition and to which it might be important to focus policy attention; some particularly relevant exogenous variables are listed below:

- Variable 22 - Permitting process length: V22 slows the expansion of RES (often severely), and in many cases, obtaining a permit is a lengthy process with many obstacles.
- Variable 20 - Critical Raw Materials price: the price of CRMs is rising and is a key factor in the competitiveness of many technologies, such as batteries needed for storage or e-mobility.
- Variables 17 & 18 - Carbon price and fossil fuels price: the rising cost of fossil fuels and the tightening of carbon tax measures are having a significant impact on the cost of non-renewable energy while encouraging electrification of consumption.

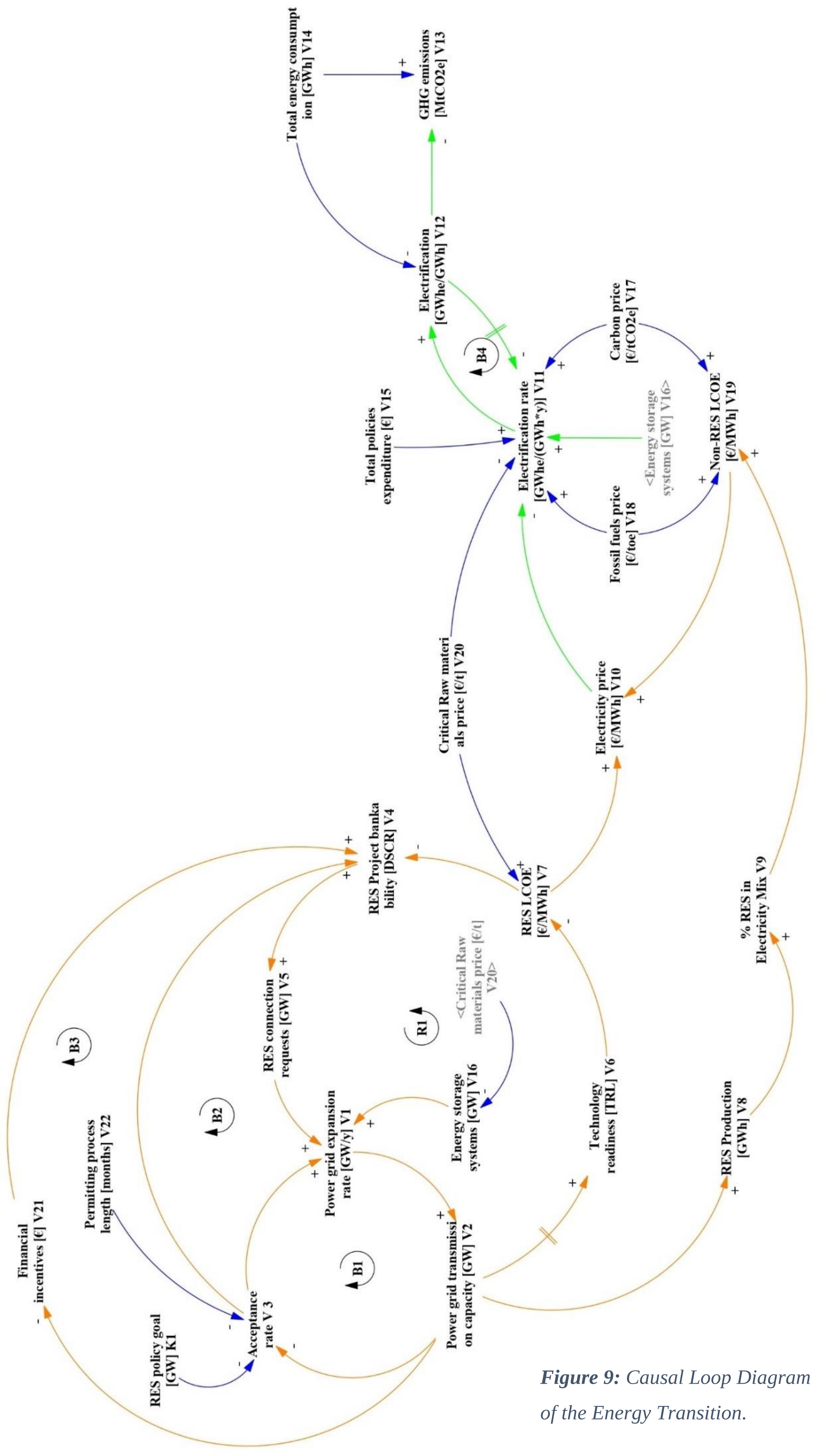

Figure 9: *Causal Loop Diagram of the Energy Transition.*

3.2. Model variables

The table below provides a brief description of the variables which emerged from the process of construction (see workflow in section 2.1.2) and that meet representativity and measurability criteria.

The table contains 23 variables; the middle column contains a description that helps the reader understand the implicit and explicit meaning of each variable, which is crucial for a correct interpretation of the CLD. The left column contains the identification number of the variables.

Table 3: *Description of the variables chosen for the CLD.*

VARIABLE	DESCRIPTION	N°
Power grid expansion rate	This is a flow variable indicating the expansion of the electricity grid at each time step, i.e., the annual increase in renewable energy that can be (and thus is) transmitted through the national electricity grid in Italy operated by Terna. Since applications for grid connection of renewable energy installations always exceed the grid capacity, this variable implicitly indicates the annual rate of increase of renewable energy. This variable is expressed in GW/year and is a function of the connection requests (GW) and the acceptance rate.	V1
Power grid transmission capacity	This is a stock variable, function of Power grid expansion rate (V1) and indicates the cumulative capacity of the grid to transmit renewable energy. Variable V2 is also a measure of total installed renewable capacity (GW). Since the acceptance of the connection request by the grid operator (Terna) is a prerequisite for the construction of renewable energy installations (at least for the ones intended for transmission to the national grid), and since this acceptance depends on the capacity of the grid to transmit non-programmable renewable energy flows, V2 can be understood de facto as the operational amount of renewable energy.	V2
Acceptance rate	Acceptance rate, in a broader sense, is the success rate of projects from the initial stage of acceptance of the connection request, to the building permit.	V3

	The acceptance rate (V3) is a function of three elements: ▪ the transmission capacity of the power grid (V2); ▪ the length of the permitting process (V22); ▪ the capacity limit set by policy objectives (K1). According to the CLD presented in the thesis, the acceptance rate is defined by the following formula: V3= [(V23-V2t)/V23]*V22	
RES project bankability	The bankability of a project represents the security of investment in a renewable energy project; in the case of this study, given its comprehensive nature, it is more appropriate to understand it as an indicator of market security in the renewable energy sector. The economical index selected to measure bankability is the average Debt-Service Coverage Ratio (DSCR).	V4
RES connection requests	This variable indicates the number of GW applied for connection to the national grid, or in other words, the new renewable energy projects that go through the permitting process each year (time step).	V5
Technology readiness	The term "technology readiness" refers to the level of development (i.e., efficiency in terms of yield, cost, material use, etc.) of renewable energy technologies, as well as the level of expertise in their construction, operation, and maintenance. V6 should be understood not only as the state of advancement in renewable energy technology, but includes the entire set of improvements resulting from the increasingly frequent and widespread application of certain technologies, i.e., including know-how in project development, supply chains, regulatory framework, etc. To measure the technology readiness of a particular technology, the Technology Readiness Level (TRL) indicator is commonly used, which has a scale of 1 to 9.	V6
RES LCOE	LCOE stands for Levelized Cost of Energy, it is the product of all the lifetime costs associated with the construction and operation of the energy farms, divided by the electricity	V7

	produced during this lifetime; LCOE also allows to compare various generation technologies as each technology might involve different cost elements (Acharya, 2021). In the case of the present study, an average value of LCOE of Italian Renewable projects could be considered for V7.	
RES production	RES production is measured in MWh and is a function of installed renewable capacity (GW) and plant operating hours. In this CLD, V8 has a similar meaning to V2, being a direct function of the total installed renewable capacity, which corrisponds to the transmission capacity of the power grid.	V8
% RES in energy mix	National energy mix refers to the heterogeneous origin of the energy circulating in the national transmission grid: each kWh taken from the grid comes from different sources in certain proportions. In the case of this study, the variable of interest is the percentage of renewable energy in the energy mix.	V9
Electricity price	The price of electricity is the amount of money a consumer must pay to purchase a unit of energy (€/MWh). This price is determined by complex energy market mechanisms, which, in a very simplified way, depend on the LCOE of the energy sources on the market.	V10
Electrification rate	Electrification rate is a flow variable that indicates the increase in electrification percentage at each time step, i.e., the annual change in the ratio of electric consumption to total energy consumed. The electrification rate is a function of many factors and is generally a cost-driven process.	V11
Electrification	According to Bompard et al. (2020), electrification refers to the replacement of other energy commodities by electricity, such as using electric vehicles rather than internal combustion engine cars. In this study, is intended as the percentage of electricity over the total energy consumption. V12 is the stock	V12

	of the flow variable V11 and is therefore expressed by the following percentage: V12= GWhe/GWhtot consumed.	
GhG emissions	Greenhouse gas (GHG) emissions are emissions that result from human activities burning fossil fuels such as oil, gas, and coal. They are the direct causes of global warming, with carbon dioxide being the most prevalent GHG, although not the strongest in terms of GWP. Greenhouse gas emissions are measured in metric tonnes of CO2 equivalent (tCO2e).	V13
Total energy consumption	This is the total amount of energy consumed; it includes both electricity and energy from fossil fuel combustion; since in this CLD V14 is the denominator of V11 and V12, it is measured in MWh, the unit of measure for electricity.	V14
Total policies expenditure	Similar to variable V21, variable V15 indicates the country's economic efforts in favor of electrification; in the present CLD, they are calculated as the amount of money (€) allocated by the government for incentive measures for electrification, such as incentives for the purchase of electric vehicles.	V15
Energy storage systems	Electrical storage is the conversion of electrical energy into another, storable form of energy that can be converted back into electricity when needed. This is possible through three main types of technologies: ▪ battery Energy Storage Systems (BESS); ▪ storage through energy carriers such as hydrogen; ▪ storage by pumped hydroelectricity.	V16
Carbon price	Carbon pricing refers to the economic cost of GHG emissions: Certain carbon-intensive human activities (e.g., thermal power plants, cement plants, steel mills, etc.) are subject to monetary instruments to regulate emissions that convert greenhouse gas emissions into an economic item. One example is the Emissions Trading Scheme (ETS), a market for "units"	V17

	of authorization to emit GHG (The World Bank., 2022).	
Fossil fuels price	Refers to the price of fossil sources such as oil, gas, and coal. the price of these resources is largely determined by supply & demand market mechanisms.	V18
Non-RES LCOE	V19 refers to the LCOE of non-renewable energy sources. For the definition of LCOE, see the description of V7.	V19
Critical Raw Materials price	Critical raw materials are a category of limited and not easily replaceable resources, typically metals, minerals, and rare earths elements, that are needed to manufacture a variety of modern devices, from smartphones and batteries to photovoltaic cells and wind turbine generator components and are therefore key materials for the energy transition (Schrijvers et al., 2020).	V20
Financial incentives	Financial incentives are all financial measures taken by the government to support the energy transition; similar to V15, they are calculated in this CLD as the amount of money (€) provided by the government in RES incentive measures.	V21
Permitting process length	The length of the permitting process is defined as the average duration of the process between the request to initiate the approval process for a RES project, and the issuance of a building permit. Although V22 was given a temporal dimension, this variable contains a wide range of meanings: Behind the duration of the approval process is implicitly understood the complexity of the procedures, public resistance, NIMBY and NIMTO syndromes, political aspects affecting the procedures, etc. The choice of months as an indicator was due to the fact that it was not possible to find an effective unit of measurement for these socio-political aspects.	V22
RES policy goal	K1 is a constant value that represents the upper limit (defined in this case by policy objectives but could be intended also as a technical limit) of the installed renewable capacity (GW) on Italian territory until 2030.	K1

	The closer the installed capacity (variable V2) is to the value of K1, the lower the acceptance rate of connection requests (V3).

3.3. Causal links

The table below provides a brief description of the causal relationships between the variables presented in the CLD; each of the links was examined and evaluated through literature review.

Table 4: Description of the causal relationships between variables.

VARIABLES	LINK TYPE	EXPLANATION
V1 – V2 **Power grid expansion rate → Power grid transmission capacity**	L+	This link expresses the flow-stock relationship between V1 and V2: If the rate of expansion of the power grid, i.e., the annual installed renewable capacity (flow), increases, the transmission capacity of the power grid, i.e., the installed renewable capacity (stock), also increases more than it would without V1; V2 is the accumulated sum over time of V1* timestep.
V2 – V3 **Power grid transmission capacity → Acceptance rate**	L-	As the installed capacity of RES increases (V2), it approaches the threshold set by the policy goal of RES (K1). This leads to a decrease in the acceptance rate of connection requests. The more we approach the upper limit, the more difficult it becomes to further expand the trasmission grid, and the more difficult it becomes for new RES connection requests to be accepted. This feedback will not be activated until the total renewable capacity begins to approach the upper limit (K1), so for the first few years will remain in a silent state.
V3 – V1 **Acceptance rate → Power grid expansion rate**	L+	The acceptance rate of connection requests determines the amount of new renewable GW connected to the grid in each time step (V1), consequently the rate of grid expansion (V1) increases with increasing acceptance rate (V3).
V3 – V4 **Acceptance rate → RES project bancability**	L+	A higher success rate of renewable energy projects, i.e., a high average of projects that receive construction permits from the concept

		stage, leads to greater stability in the renewable energy sector. More specifically, if a single project survives the permitting phase, which is one of the riskiest phases, it leads to a significant increase in value and greater attractiveness to potential investors. If we extend this consideration to the entire renewable energy sector, a high rate of projects making it through the permitting phase gives the market more certainty and, consequently, a greater willingness on the part of investors to take financial action in the sector (IEA, 2023).
V4 – V5 **RES project bancability → RES connection requests**	L+	The more attractive the market is, the more players will participate in it. This means that the more the renewable energy sector becomes a reasonably safe and profitable business, the more projects will be proposed, increasing the number of GWs applied for connection to the national grid.
V5 – V1 **RES connection requests → Power grid expansion rate**	L+	Power grid operators will tend to invest in the development of new infrastructure as connection requests increases (TERNA, 2023). Moreover, the grid expansion rate is also understood as the rate at which new renewable capacity is added to the grid and is defined in this CLD by the following equation: *V1=V5*V3* Where: ▪ V1 is the power grid expansion rate ▪ V5 are the RES connection requests ▪ V3 is the acceptance rate of the requests. Therefore, according to the implicit meaning of V1, requests for grid connection of renewable energy projects are converted into newly installed renewable capacity depending on the success rate.
V2 – V6 **Power grid transmission capacity → Technology Readiness**	L+	Over time, an increase in installed capacity brings with it an increase in know-how and a maturation of the technology: this principle generally applies to all the sectors related to those technologies: the more a technology is used, the more it develops and improves. An expansion of solar or wind power plants brings an improvement of both technologies over time, both in terms of technical and economic

		efficiency, as well as in the use of raw materials and know-how in their design and implementation, even up to the related regulatory and market frameworks.
V6 – V7 **Technology readiness → RES LCOE**	L-	Technological progress in the field of renewable energies brings with it a number of advantages that translate into better cost efficiency and thus lower LCOE. In the case of photovoltaics and wind power, the following trends in technological evolution are recorded (IRENA, 2022a): ▪ The need for less raw materials or the use of alternative, lower-cost raw materials, resulting in savings in machine costs; ▪ Improved process efficiency, leading to lower system losses and thus higher profits; ▪ Improved performance, leading to higher productivity, or the ability to produce in conditions where the availability of renewable resources was previously insufficient, thus expanding the market.
V7 – V4 **RES LCOE → RES project bancability**	L-	The lower the LCOE of a project, the more bankable it is and the more attractive it is to an investor. according to Acharya (2021), one of the most effective ways to improve bankability is through power purchase agreements (PPA), and from a developer's perspective, the LCOE must be as low as possible to obtain an advantageous PPA contract. Extending this concept to the sector level, making projects more cost-effective helps make the market more attractive in that industry.
V2 – V8 **Power grid transmission capacity → RES production**	L+	As, in this analysis, the transmission capacity of the grid is assumed to be equal to the total connected renewable capacity, an increase in V2 (GW) is followed by an increase in renewable generation (GWh).
V8 – V9 **RES production → %RES in electric mix**	L+	As renewable energy production increases so does the share of RES in the electricity mix. This is achieved straightforwardly thanks to the obligation to give priority to energy from renewable sources in the feed-in, imposed by the Italian authorities responsible for regulating the energy market (*DECRETO LEGISLATIVO 16 marzo 1999, n. 79 - Normattiva*, 1999).

V7 – V10 **RES LCOE → Electricity price**	L+ Conditional	This causal link connects the cost efficiency of renewable energy projects to the price of electricity in the energy market: as the cost efficiency of renewables increases, the price of energy decreases in proportion to the share of renewables in the electricity mix.
V19 – V10 **Non-RES LCOE → Electricity price**	L+	Under the current electricity market mechanisms, the wholesale price of electricity is determined on the basis of an equilibrium price, i.e., the average marginal price of the different producers in the market (Berardi et al., 2022). An increase in the average LCOE of energy not sourced from RES leads to an increase in this average marginal price and consequently to an increase in the wholesale price of electricity.
V10 – V11 **Electricity price → Electrification rate**	L-	End-use electrification is a cost-driven process. The competitiveness of electricity versus oil is an essential prerequisite for making electrification possible. This applies to all sectors that can be electrified, from industrial processes to transportation (electric vehicles) to building heating. The lower (and more competitive) the cost of electricity, the higher the electrification rate will be.
V11 – V12 **Electrification rate → Electrification**	L+	This link expresses the direct flow-stock relationship between V11 and V12: the electrification rate, i.e., the annual ratio of electric and non-electric GWh consumed (flow), increases the total electrification (stock) at each time step.
V12 – V11 **Electrification → Electrification rate**	L- delayed	Similar to the transmission capacity of the power grid, electrification can be assumed to be self-balancing, determined by a maximum electrification limit; the closer this limit gets, the more complicated any further increase in the electrification percentage becomes. The link has a delay marker to indicate that the feedback of the compensation is not instantaneous, but that there are intermediate steps that are not made explicit in the CLD. Further information can be found in Table 5.
V12 – V13	L-	As previously discussed, a large portion of energy-related greenhouse gas emissions are caused by end-use energy consumption,

Electrification →GHG emissions		particularly in transportation, industry, and building heating. Replacing fossil fuels with electricity, especially when it comes from an electricity mix with a high percentage of renewable energy, results in significant reductions in GHG emissions.
V14 – V13 **Total energy consumption → GHG emissions**	L+	Energy-related GHG emissions come from the combustion of fossil fuels, historically used as a source of energy. this link indicates that at a constant level of electrification, the higher the total energy consumption, the higher the GhG emissions will be.
V14 – V12 **Total energy consumption → Electrification**	L-	This link clarifies the mathematical relationship adopted for the definition of electrification between variables V14 and V12: In fact, V12 represents the percentage of electricity consumption in total energy consumption, according to the following equation: V12= GWe/V14 The link therefore has a negative polarity because V14 is in the denominator.
V15 – V11 **Total policies expenditure → Electrification rate**	L+	An increase in public economic resources provided as incentives for end-use electrification promotes its development by increasing the annual electrification rate. An example of this is electric vehicle (EV) incentives, which according to Hardman et al. (2017), are an effective policy measure to increase EV sales and thus increase electrification rates, as envisioned in this CLD.
V16 – V11 **Energy storage systems → Electrification rate**	L+	Energy storage systems can promote electrification in two main ways: ▪ Energy storage coupled with distributed off-grid renewables: through this model, end-use electrification can be encouraged in areas not easily reached by the transmission grid; due to the variable nature of RESs, the Battery Energy Storage (BES) acts as a critical element in an islanded microgrid and regulates the voltage and frequency. It also maintains the generation and balances in loads, thus improves the reliability of the system (Shubhra Chauhan and Bhim Singh, 2020).

		▪ Energy storage aimed at increasing the stability (and flexibility) of electricity supply in industrial processes: for example, in the chemical industry, if olefin production would be electrified or a catalytic alternative would be used, the process needs to run 8000 h per year. This means also during periods when green electricity is very expensive or not available. Battery energy storage systems have been investigated as storage solutions due to their responsiveness, efficiency, and scalability (Van Geem and Weckhuysen, 2021).
V17 – V11 **Carbon price → Electrification rate**	L+	Historically, systems that use energy (Transportation, industrial processes, heat production etc.) were based on the principle that fuel energy carriers were much cheaper than electricity; this price difference is likely to flatten out and even reverse in the long run, in part due to carbon taxation policies (Luderer et al., 2021). These measures in fact increase the cost of using fossil fuels, making them progressively less competitive compared to electricity.
V18 – V11 **Fossil fuels price → Electrification rate**	L+	As mentioned earlier, end-use electrification is a cost-driven process. Particularly in conjunction with falling electricity prices, rising fossil fuel costs are a major driver of electrification, making it more economically advantageous to replace traditional fossil fuel-based processes with alternative processes powered by electricity.
V20 – V11 **Critical Raw Materials price → Electrification rate**	L-	Similar to energy storage systems, the electrification of some sectors also involves the use of critical raw materials: one example is electric mobility, in which vehicles replace the internal combustion engine with a battery-powered electric motor. REEs are used to produce permanent magnets for EV motors, the average hybrid EV uses about 3-5 kg of rare earth permanent magnets (depending on the design), accounting for about half the cost of the motor (IRENA, 2022b).
V17 – V19	L+	Since EU ETS applies to carbon dioxide (CO2) emissions from electricity and heat generation, an increase in the carbon price consequently

Carbon price → Non-RES LCOE		leads to an increase in the LCOE of fossil fuel-based electricity generation plants.
V18 – V19 **Fossil fuels price → Non-RES LCOE**	L+	An increase in fossil fuel prices will lead to an increase in the LCOE of energy derived from fossil fuels.
V9 – V19 **% RES in electricity mix → non-RES LCOE**	L+	Given the structure of the energy market, which today is based on a "pay as clear" auction mechanism, high penetration of renewables will lead to a drastic reduction in the wholesale price of energy (based on marginal production costs, which are close to zero for renewables), but will also reduce the market space of fossil fuels, which will only be used to meet residual demand, i.e., energy demand not covered by renewables. According to Berardi et al. (2022), when renewable generation is high for many consecutive hours, the price will be equal to zero until, even suddenly, the lack of natural resources (solar radiation and wind) causes gas-fired power plants to be selected as marginal power plants, which will bid at extremely high prices because they have no certainty about how often they can be called upon again to produce. Under this mechanism, in a high decarbonization scenario, 80% of the hours of the year will be characterized by prices equal to zero and 1% will be characterized by prices above $1,000/MWh.
V20 – V7 **Critical Raw Materials price → RES LCOE**	L+	In the manufacture of various components of a renewable power plant, such as photovoltaic and wind power, many raw materials defined as critical are used, which are often scarcely replaceable; therefore, the price development of these critical raw materials has a strong impact on the cost of these technologies and affects the entire renewable energy sector. Two examples of the importance of CRM in the manufacture of RES according to IRENA (2022), are highlited below: ▪ Concerning PV costs, it is the demand for silver and copper that currently accounts for 10% of the manufacturing cost of solar PV modules, not accounting REEs such as germanium and tellurium;

		▪ For wind power, the critical raw materials used depend on the technology: there are two main technologies, gearbox and direct-drive. Gearboxes power the generator through the rotational torque force of the turbine, while direct-drive uses magnetic poles to power the generator. Direct-drive technology requires the use of rare earth elements, while gearbox does not.
V20 – V16 **Critical Raw Materials price → Energy storage systems**	L-	Among the different types of energy storage systems described above, one of the most popular is via batteries (BESS). Materials such as cobalt, lithium, graphite and nickel are usually used in the manufacture of BESS (European Commission, 2020). Rising prices of such materials may cause a slowdown in the development of these strategic energy storage systems.
V16 – V1 **Energy storage systems → Power grid expansion rate**	L+	The implementation of energy storage systems in the power grid allows overcoming a number of technical limitations related to the inherent characteristics of the energy generated by RES, which usually has a lower propensity to maintain the basic parameters for the safe functioning of the power grid than conventional energy sources (Divya and Østergaard, 2009). Indeed, storage systems are an important tool to manage the energy transition, both from an efficiency and grid security point of view, as they can provide fundamental services in the new context dominated by RES.
V21 – V4 **Financial incentives → RES project bankability**	L+	Incentivation policies are demonstrated to be key factors for RES to reach positive margins and market parity (Morea and Poggi, 2017), which are key determinants of project bankability.
V2 – V21 **Power grid transmission capacity → Financial incentives**	L-	This link shows the phenomenon of 'shrinkage' of incentive instruments as installed renewable capacity increases. Renewables are expected to become cheaper and more competitive as installed capacity increases, allowing projects to increasingly develop under market conditions without the need for financial incentives that, once exhausted, are no longer renewed.

V22 – V3 **Permitting process length → Acceptance rate**	L-	One of the major bottlenecks determining the success of renewable energy projects in Italy is the complexity (and thus length) of the permitting process, especially for utility-scale projects. The current structure of responsibilities for permitting renewable energy installations typically involves an excessive number of competent authorities, from the state down to individual municipalities (e.g., in national EIAs, there may be as many as 68 competent authorities (Legambiente, 2022)). This diversity in permitting responsibilities, especially for environmental impact assessment, along with the heterogeneity of decisions at the regional level in renewable energy legislation are elements of bureaucratic complexity that, while in some cases aimed at improving environmental protection, often arbitrarily block or at least significantly slow down the permitting process for new renewables.
K1 – V3 **RES policy goal → Acceptance rate**	L-	According to the proposed model, the acceptance rate of new connection requests decreases as the renewable capacity upper limit, i.e., K1, is approached. The proposed mechanism is described by the following equation: $$V3 = \left(\frac{K1 - V2}{K1}\right) * V22$$ Where: V3 is Acceptance Rate K1 is the limit set by RES policy goal V2 is the Power grid transmission capacity V22 is the Permitting process length

3.4. Causal loops

Feedback loops are circular configurations of the causal relationship patterns between variables, where any change in one variable trigger a cascade of changes in subsequent variables, that eventually feed back to the initial variable; the end result can be either an amplification of the initial change (amplifying loop, R) or, conversely, a reduction of it (balancing loop, B).

Within the CLD, five causal loops have emerged, one of which is reinforcing (R1) and four of which are balancing (B1-B4).

Specifically, in the functional domain of production, loops B1 and R1 form a causal pattern that can be attributed to the "*Limits to Growth*" (Meadows et al., 1972) system archetype. This archetype represents a system in which a development process drives itself to generate growth or expansion, until this growth comes to a halt or even changes direction and an accelerated collapse sets in. The growth phase is caused by a reinforcing feedback process (R1) and the deceleration is caused by a balancing process (B1) that is brought into play when an upper limit (represented in this case by K1) is approached.

Table 5: *Feedback loops emerged within the CLD.*

	LOOP N°	VARIABLES	V_N°	EXPLANATION
Balancing causal loops	B1	Power grid expansion rate Power grid transmission capacity Acceptance rate	V1 V2 V3	Together with loop R1, loop B1 forms the "limits to growth" archetype detected in the renewable energy production domain. Loop B1 illustrates the balancing behavior of the growth of RES, which approaches the upper bound (K1) as the stock value (V2) increases, affecting the rate of absorption of new demand (V3), on which the grid expansion rate (V1) depends.
	B2	Power grid expansion rate Power grid transmission capacity Acceptance rate RES project bankability RES connection requests	V1 V2 V3 V4 V5	This balancing loop shows the same effect as loop B1 and is contiguous with it: The acceptance rate (V3)-which is subject to the balancing effect of loop B1-is a key factor in project bankability (V4), on which the number of connection requests (V5) depends; the number of connection requests, in turn, determines the rate of network expansion (V1) as a function of the acceptance rate.
	B3	Power grid expansion rate Power grid transmission capacity Financial incentives RES project bankability	V1 V2 V21 V4	The third balancing loop has the same effect as loop B2: the increase in the transmission capacity of the grid (V1) leads to a gradual decrease in incentives (V21); the incentives have the effect of increasing the bankability of the projects (V4), which decreases

		RES connection requests	V5	accordingly, leading to the same dynamics as in loop B2.
	B4	Electrification rate Electrification	V11 V12	Loop B4 exhibits balancing behavior similar to that of loop B1. In fact, it is assumed that a "limits to growth" archetype exists between variables V11 and V12, with the presence of a balancing loop and a reinforcing loop, which is not made explicit in the CLD. When the electrification rate (V11) and consequently its stock function V12 increases, it is assumed that positive feedback mechanisms occur, favored by a price reduction trend due to improved technology (caused by the increase in V12) and other possible factors. At the same time, as with renewable capacity (i.e. Power grid transmission capacity, V2), it is expected that there is an upper limit to electrification, the approach of which (represented by the increase in V12) slows the rate of electrification (V11).
Reinforcing causal loops	R1	Power grid expansion rate Power grid transmission capacity Technology readiness RES LCOE RES Project bankability RES connecion requests	V1 V2 V6 V7 V4 V5	Loop R1 is the reinforcing element of the "Limits to Growth" archetype generated by loops B1 and R1. R1 exhibits the reinforcing behavior triggered by an increase in the expansion rate of the power grid. When the expansion rate of the power grid (V1) increases, and so does V2, the level of technology readiness (V6) gradually increases, leading to lower LCOE (V7). Lower LCOE increases the bankability of projects (V4), which has a positive effect on connection requests, on which the grid expansion rate (V1) depends.

4. DISCUSSIONS

4.1. Advantages and disadvantages of using SD to model the energy transition

According to Köhler et al. (2018), system dynamics is a modelling tool suitable for the study of energy transformations as it involves the explicit study of causal feedbacks between interconnected factors; moreover, transitions must be analyzed in terms of micro, meso, and macro levels. The modeling methodology of SD can be applied at all three levels and thus serves as an important tool for the design and assessment of energy transitions (Papachristos, 2019). Selvakkumaran and Ahlgren (2020) in their paper, conduct a review of the suitability of the System Dynamics approach for representing energy transitions. As a result of a thorough and comprehensive literature review, they identify the following four main categories of reasons used to justify the use of System Dynamics to model energy transitions:

i. System Dynamics ability to model dynamics, feedbacks and delays, and the aptitude to deal with complexity;
ii. the mapping process and the holistic and systematic view offered by System Dynamics makes it suitable for the study of transition;
iii. the suitability of System Dynamics to facilitate multidisciplinary and interdisciplinary domains and topics in a modeling framework;
iv. the suitability of System Dynamics for considering actor interactions and behaviors in its modeling framework.

Although the method is recognized as valid in the literature, there are some considerations about the way it has been applied in this thesis. Indeed, this is a purely qualitative work, based on a CLD created using information from the literature to explore each factor and its causal relationships, hence, it lacks the quantitative aspect of the system, i.e., a Stock and Flow Diagram (SFD) that can support simulations that allow the construction of an empirical model.

SFDs, in fact, convert the system structure into a simulation model consisting of levels (stocks), rates (flows), and auxiliary variables that aid in the quantitative generation and analysis of dynamic behavior. Among others, Prusty et al. (2017) argue the authenticity of explaining the dynamic behavior of a system from a mere CLD. Only a single causal loop diagram cannot be sufficient in adding value to the modeler in reasoning and analyzing the complex system and its behavior. Moreover, Ford (1999) argues that an explanation of behavior based only on causal loops could be biased, incomplete, and lead to different interpretations because of the bias of the modeler's expectation; however, Coyle (2000) notes that a qualitative description of the system is useful to better understand the problem at hand. In summary, while quantitative modeling by SFD appears to be superior, mapping the system by CLD can be a starting point for developing a quantitative model, which is indeed a future purpose of this work.

4.2. Other examples of the use of SD for energy transition assessment

In order to get a complete picture of the system, it is useful to seek a comparison with other studies in the bibliography that have addressed the issue of energy transition using similar methods. In this case, two recently published studies were examined and the comparison with them is given in the following paragraphs; the focus was mainly on:

- Differences/similarities with the present thesis in terms of results;
- Differences/similarities with the present thesis in terms of methodology.

Furthermore, for the sake of completeness, a comparison was made with the MEDEAS framework for energy transition in Europe.

4.2.1. Modelling energy transition in Germany: an analysis through ordinary differential equations and system dynamics

This study by Savio et al. (2022) focuses on the interdependence between energy production from renewables, gas, and coal and the competitiveness of each energy source relative to the others, taking Germany as a case study. Differently from the present thesis, the method used by Savio et al. involves an initial analysis using the ordinary differential equations approach, which allows to statistically test the significance and nature of the interactions between the three energy sources. Subsequently, the obtained results are used to model the system by means of CLD. The latter, of the Stock and Flow Network type, allows to identify reinforcing or balancing loops and provides the basis for simulation studies that have not yet been implemented in this thesis.

The following considerations arise from the comparison of the results:

- As common result there is the central role of social forces and demand dynamics in renewable energies adoption: both increasing renewable energy incentives and restricting coal and natural gas use would have accelerated the decarbonization in Germany and the energy transition towards renewable sources.

- Differently from the present thesis, Savio et al. highlight a significantly negative effect played by gas and coal on renewables, limiting their expansion, while there appeared to be a kind of "collaboration" between coal and gas; this negative effect was not found in the present study, which instead considers non-renewables irrelevant, if not weakened by the expansion of renewables.

4.2.2. Modelling the socio-political feasibility of energy transition with system dynamics

This paper by Freeman (2021) focuses on the challenge of understanding the whole-system, real-world processes involved in transforming a national energy system to emit net zero greenhouse gas emissions by 2050, taking UK as the geographical area of interest. Freeman creates a conceptual model of the energy transition based on a CLD that shows the complex interactions among social, political, and economic factors related to the energy transition. A sensitivity analysis of this conceptual model is then conducted by running numerous simulations (1000).

Freeman's study and this thesis thus share common ground, however there are also some key differences: Freeman analyses the system from a political and social perspective, focusing on variables such as "*Political capital*", "*policy ambition*", "*policy soup*", "*Public willingness to participate*" and "*policy-society feedback*" (Freeman, 2021). This is reasonable but does not present the system from all angles. Secondly, as mentioned earlier, Freeman's model is fed with historical data from 1980 to 2019, and simulations have been run from 2020 to 2080; this is work that has not yet been implemented in this paper but is being sought.

As for the results, some similarities with the present thesis emerge, as follows:

- The concept of Policy Capital ("*PolCap*" in the paper), i.e., the stock of money to be invested in energy transition measures, has a similar effect as the variables 'total policy expenditure' and 'financial incentives' in this CLD.
- The concept of 'learning by doing' (LBD) emerges, with the same meaning as our variable (V6) "Technology readiness", which explains the phenomenon of a self-sustaining/accelerating technology: the more it spreads, the more the know-how about it grows. Just like in the CLD of this thesis, this variable gives rise to a reinforcing feedback loop with the same result as loop R1. The main difference is that the LBD concept refers to the improvement of the ability to implement the energy transition policies and in this work it refers instead to the know-how in the sector and the state of technology readiness.

- Two balancing feedback loops similar to B1, B2 and B3 are identified: in particular, Freeman shows how, as the target approaches, it becomes increasingly difficult to apply measures to reach it. Of these balancing feedback loops, one has similar behaviour to B3, i.e., it shows how approaching the target erodes the 'PolCap', i.e., V22 in this thesis; another exerts its braking effect through technological difficulty and impact on the population; in this case, it is loops B1 and B2 that exhibit similar behaviour.

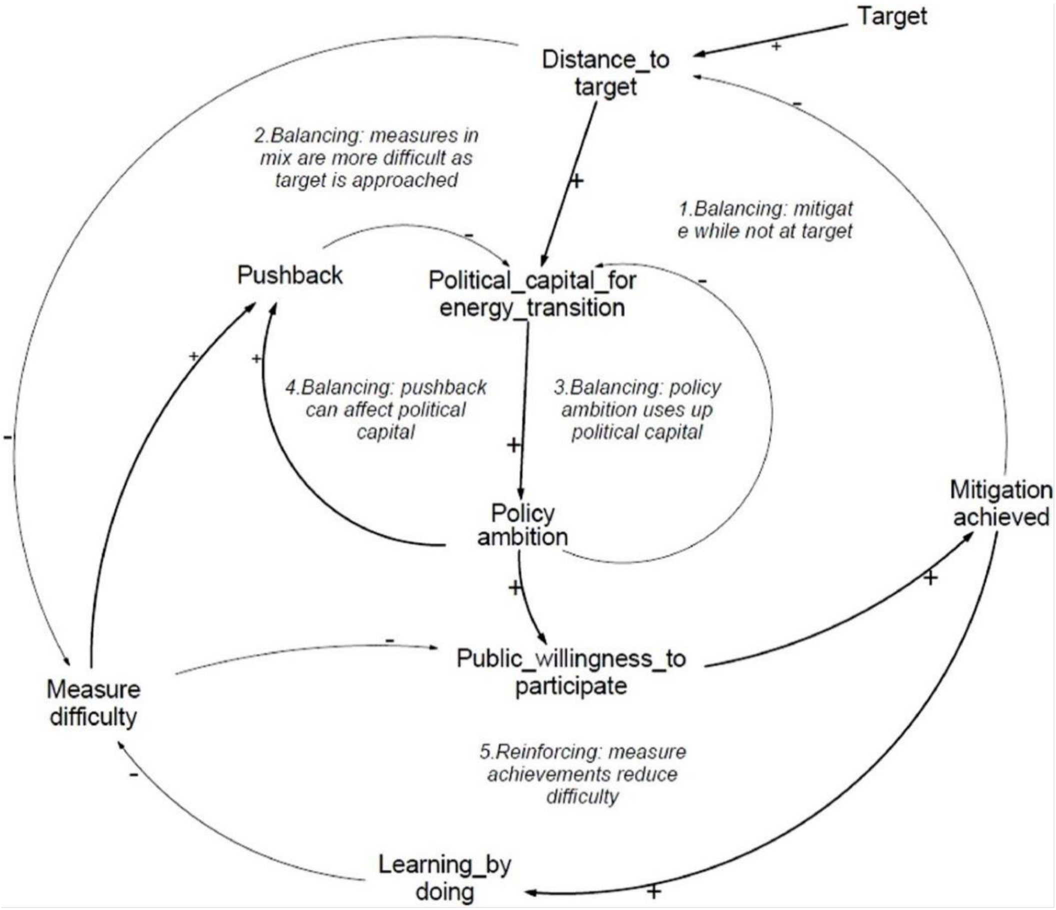

Figure 10: *Simple representation of Freeman's model as a causal loop diagram (Freeman, 2021).*

Overall, Freeman's SD modeling, even though it mainly considered political, economic, and social variables, produced similar results to those in this thesis, but strengthened by simulations and sensitivity analysis. It should be noted, however, that there are variables in Freeman's work that are difficult to measure, such as "*public willingness to participate*", which were avoided in this work, where instead, each variable was selected to be accurately and rigorously measured, to allow further improvement through numerical modeling.

4.2.3. MEDEAS – A new open-source energy model to guide the transition to a low carbon European socio-economy

MEDEAS stands for "Modelling the Energy Development under Environmental And Socioeconomic constraints"; and is the most importat and updated computational model developed to define the future of the energy system in Europe, taking into account physical as well as social constraints ("Overview | Medeas," 2023). In fact, the introductory section of the MEDEAS project hints at an ambition similar to that of this thesis, namely to address the lack of integration of different thematic areas in the energy transition analysis tools available to the community by developing an integrated and multidimensional framework.

Methodologically, MEDEAS is based on the integration of several existing global SD models on environmental, energy, social and economic issues and includes input-output analysis. The methodology is divided into sequential steps of data collection and scenario elaboration according to case studies, on the basis of which simulations are carried out to identify future development paths. The results of the simulations are collected and compared, and similarities and differences are evaluated. The model was initially developed using the software VENSIM DSS, another version of the same software used for this thesis.

The MEDEAS framework, of course, differs from the present work in many ways, beginning with the nature of the work itself; nevertheless, some interesting elements of comparison emerge, as follows.

First, it was created using system dynamics, recognised as an approach capable of integrating knowledge from different perspectives and showing the relationships between different subsystems. This similarity in methodology further argues in favour of using SD for the analysis of the energy transition.

Second, the MEDEAS model identifies seven subsystems that define the energy transition system; the subsystems are listed below, and a comparison is made to see whether the same subsystems are identified in the model developed in this thesis:

1. **Economy:** the subsystem was modelled; the CLD contains numerous variables of an economic nature, including bankability, incentives, and energy costs.
2. **Energy:** The subsystem was modelled; energy is one of the main themes of the CLD and runs throughout the model, from the production domain to the end-use domain.
3. **Infrastructures:** The subsystem was modelled; the topic of infrastructures is covered extensively in the CLD and plays a central role: "power grid expansion rate (V1) and

"power grid transmission capacity (V2)" are the "engines" of the model, on which the entire production domain depends.

4. **Materials:** the subsystem was modelled: Critical Raw Materials were included in the CLD as an exogenous variable that exerts a large influence on many important variables such as RES LCOE, energy storage systems, and most importantly, electrification.
5. **Land use:** this subsystem was not modelled. MEDEAS refers to this subsystem as land demand for renewable energy. This topic was not addressed in the discussion of this paper, but the same website refers to it as "*the less developed module of MEDEAS*" ("Overview | Medeas," 2023).
6. **Climate change:** the subsystem has been partially modelled: The issue of climate crisis is not directly addressed in the CLD but is indirectly and implicitly linked to the variable "GhG emissions (V13)", which is practically the last output of the system.
7. **Social & Environmental impacts indicators:** The subsystem was only partially modelled: There is no pure environmental or social variable in the CLD. This was a conscious decision, the reasons for which lie in the criteria of "measurability" and "representativeness" of the variables selected for the model. However, social aspects are implicitly included in the variable "Permitting process length (V22)", and environmental aspects are reduced to the variable (V13), i.e. GhG emissions.

4.3. Considerations on the feedback loops detected in the CLD

4.3.1. Loop B1, B2 and B3

As discussed in Table 5, feedback loops B1, B2, and B3 are interconnected and represent the same self-balancing phenomenon as V1. It is therefore possible to consider them as a single loop, whose balancing effect is exerted by different variables: In particular, in loops B1 and B2, it is the acceptance rate (V3) - which in turn is a function of the grid capacity V2 and the renewables upper limit K1 - that exerts the braking effect on V1; this behaviour is confirmed by the work of Freeman (2021): Looking at loop B2 in Figure 10, we can see the phenomenon of slowdown due to the increase in 'difficulty' as the target - represented in our case by K1 - is approached. On the other hand, in loop B3, the braking effect is exerted by the phenomenon of erosion of incentives due to the increase in renewable capacity (implicitly represented by V2); this again is also confirmed in Freeman's study, which shows the same dynamics of erosion of *political capital* when what he calls *political ambition* - which in our case can be interpreted as V2 - increases.

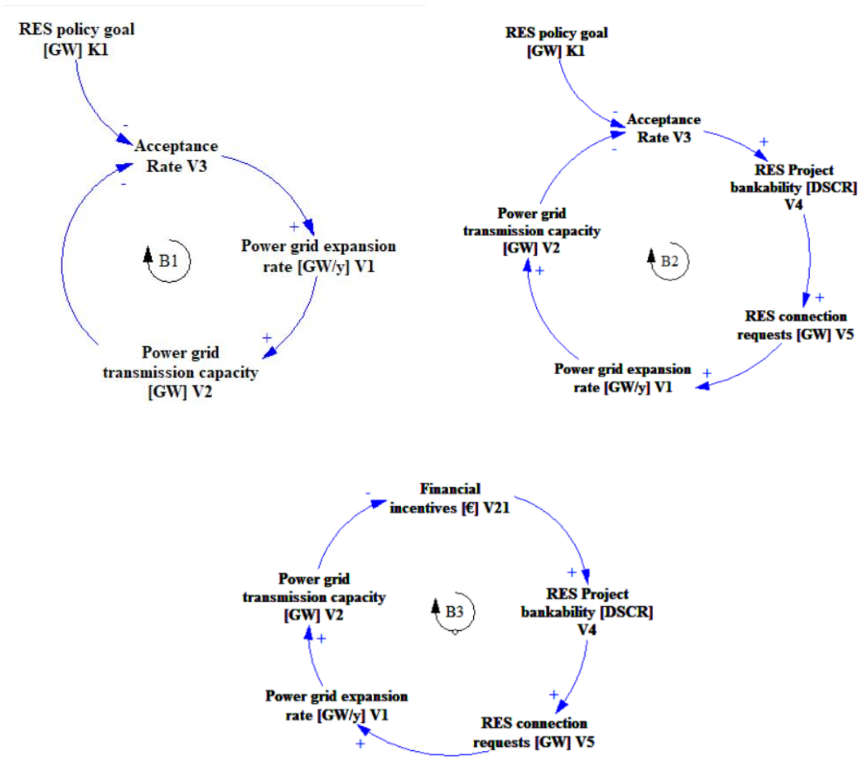

Figure 11: Feedback loops B1, B2 and B3. The loops in this figure have been reworked from CLD in Figure 9. Note that some causal links have been omitted to simplify reading.

4.3.2. Loop R1

Loop R1 represents the reinforcing component of the functional domain of production. The reinforcing effect is exerted by the increase in technology readiness (V6) due to the increase in total installed capacity (implied by V2). V6 should be understood not only as the state of advancement in renewable energy technology, but includes the entire set of improvements resulting from the increasingly frequent and widespread application of certain technologies, i.e., including know-how in project development, construction and maintenance, development of supply chains in the sector, etc. This concept is once again reflected in Freeman's work, which shows how "*learning by doing* (LBD)" - which in our case is represented by V6 - leads to a reduction in the difficulty of implementing mitigation measures. In Figure 10, loop 5 shows this dynamic, and although Freeman's work refers to a political and socio-economic sphere, the analogy with loop R1 of the present CLD can be seen (Figure 12).

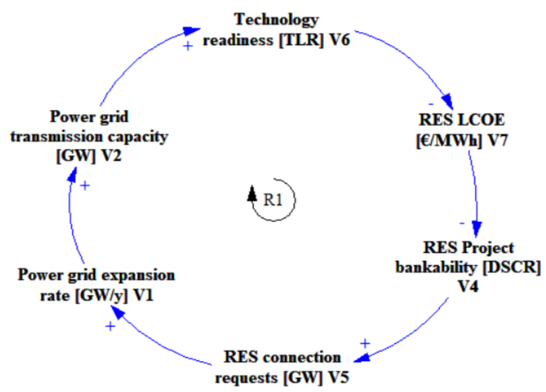

Figure 12: *Reinforcing feedback loop R1. The loop has been reworked from CLD in Figure 9. Note that some causal links have been omitted to simplify reading.*

Another aspect of the R1 loop on which some consideration should be made is variable V4: in this CLD, bankability is represented as a function of costs and incentives (V7 and V21, respectively) and the acceptance rate (V3). However, according to Hampl et al. (2011), bankability comprises legal, technical and economical dimensions, and addressing only one dimension will be not sufficient. Therefore, other variables should be taken into account, such as the expertise of the developers, the stage of development of the technology, and the regulatory framework. For simplicity, this has not been included in the CLD at this time, but it would not be incorrect to establish a direct link between V6 and V4. In addition, it should be noted that the unit of measure assigned to bankability is strictly economic (DSCR). This is reductive, as explained by Hampl et al, but allows for greater practicality in future simulations.

4.3.3. Loop B4

Loop B4 (Figure 13) implicitly represents the same phenomenon as loops B1, B2, B3, and R1, but was not made explicit in the CLD. Just as for the functional domain of production described in the four loops discussed above, the presence of a "*limits to growth*" type archetype governing the dynamics between V11 and V12 is plausible for the functional domain of end use.

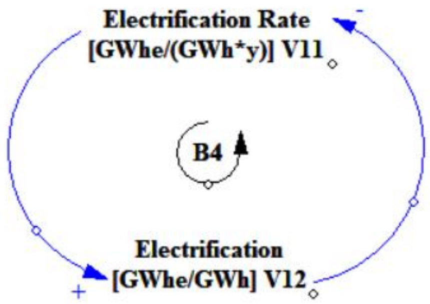

Figure 13: *Balancing feedback loop B4. The loop has been reworked from CLD in Figure 9. Note that some causal links have been omitted to simplify reading.*

There will be a reinforcing behaviour triggered by a "*learning by doing*" (Freeman, 2021), phenomenon, similar to that of R1, which will be mitigated and eventually balanced by an upper limit of electrification. All of this was implicitly captured in a simple balancing loop.

4.4. Interviews

As already discussed in chapter 2.2.1, much of the information about the structure of the system resides in the mental models of those involved in the process and is tacitly retained there. Compared to explicit knowledge, tacit knowledge is subjective, personal, and context-specific, and therefore not easy to test and use. (Ford and Sterman, 1998). However, in this tacit knowledge often lies a significant part of the information about the system being modelled, and it is therefore an important activity for the modeller to collect and articulate this knowledge. To this end, interview sessions were conducted with seven system experts, whose sector of competence is listed in Table 6.

The following are the most controversial aspects of the CLD that emerged from the discussion with the experts:

- **Bankability**: the role played by this variable is commonly understood and confirmed, but the use of DSCR as its indicator is discussed. This issue was addressed by different experts in two different interview sessions.
- **Power grid expansion rate**: the importance of this variable has been recognised by all, but some argue that it depends on measures to control the grid operator, others that the influence of social acceptance factors is much stronger.
- **Permitting process length**: this variable is viewed as a key factor, and some consideration about its unit of measure and its exogenous nature are made. The existence of a less evident reinforcing loop involving this variable was hypothesized.

- **Total energy consumption**: the fact that energy demand was treated as exogenous was discussed by two different experts in two different sessions; one suggested that the energy consumption is influenced by energy price, as the demans is always “elastic” in the long term, according to the economy theory. Another suggested that energy consumption is under the influence of energy production, because of the non-predictable nature of renewable energy.

The topics above, along with other considerations thet emerged from de group interviews are discussed in the following sections.

NOTE: confrontations with the experts were not directly used to verify the robustness of the CLD, and their contributions are not to be understood as validation of the model, but as free observations that the modeller used to mark possible new aspects to be investigated. Expert opinions are personal and independent and do not necessarily reflect the position of the group/company to which they belong.

Table 6: *Field of competence of the interviewed experts.*

INTERVIEW	N° OF EXPERTS	WORKING SECTOR	COMPETENCE
1	3	Financial consulting; research	Energy market; Market design; Energy sector regulation
2	2	▪ Renewable energy industry ▪ NGO	▪ Economy & Finance; RES project development; National power grid ▪ Permitting; RES regulation framework; Sustainability
3	1	Foundation	Green-economy; Sustainability; Models; Energy

4.4.1. Interview session #1

In this session the work was presented to three experts from a research and advisory group on economic and financial issues. The group worked on a number of publications related to energy market mechanisms and explored possible market design scenarios in light of increased market penetration of renewable energy. The main contributions of the interview are summarised below.

About Power grid expansion rate (V1)

With regard to the power grid expansion rate (V1), experts suggest the existence of a possible exogenous variable that exerts a negative influence on V1, limiting it according to a mechanism similar to K1.

This is because in Italy the grids are managed as a monopoly by the grid operator Terna, whose market value is measured by the RAV, i.e. the value of the assets it develops. For this reason, Terna, benefiting from a guaranteed remuneration, could tend to maximise investments in assets in order to maximise revenues; however, these investments would be charged to consumers through grid cost components of electricity bills. To prevent Terna from investing endlessly in the grid to the detriment of consumers, the competent authority, i.e., ARERA, intervenes to limit investments by determining which investments are feasible and which are not. Thus, grid expansion would be determined by a balancing factor between the need for grid expansion and the increase in costs borne by consumers. Thus, in addition to the limiting factor K1, which acts through a different channel, i.e., tends to affect the approval of new infrastructure (V3), it is proposed to introduce an exogenous variable "regulatory constraint" that acts directly on V1.

About Bankability (V4)

The experts point out a phenomenon according to which an increase in renewable energy is accompanied by an increase in market volatility, which destabilises investors' returns and leads to a decrease in bankability. It is therefore proposed to investigate a possible negative feedback loop between renewable energy expansion and bankability, which is passed on through other market variables not explicitly displayed in the CLD.

Regarding the bankability indicator, instead of DSCR, it is proposed to calculate a ratio indicating how much banks are willing to finance, i.e., with what percentage of financing investors are willing to step in (e.g., 70% to 30% may be considered too risky, while 30% to 70% is considered acceptable). One suggested indicator may be the project's D/E (debt to equity) ratio. Also because DSCR is a more appropriate index for project financing, which can only occur if incentives are present; the positive influence of incentives on bankability exists, but as also reflected by the negative V2-V21 link, they will be exhausted, and already many renewables are being developed without incentives, in market parity.

Another aspect that speaks against the use of the DSCR is the fact that it is generally very difficult to find information on an average market DSCR.

Another contribution of the experts concerns the phenomenon of price cannibalization: as new renewable energy installations continue to be developed, a point will be reached where there will be a very large number of renewable energy installations, but not yet enough to meet all electricity demand; these installations will probably have very low LCOE, but in the way the energy market is currently structured, an excess number of renewable energy installations (consequently an 'oversupply') will set the wholesale price of energy to zero. This phenomenon leads to a 'missing money problem' where, paradoxically, despite the extremely low LCOE, investments stall and connection requests (V5) shrinks. It is assumed that this effect occurs before the slowing effect exerted by K1.

About Total Energy Consumption (V14)

The experts point out that a negative influence between the price of fossil fuels and total consumption should be made explicit: Namely, in this thesis, energy demand is postulated to be completely inelastic, i.e., it constantly increases regardless of the price. This is questionable and is disputed by experts who, to prove the contrary, cite the impact of the recent fossil fuel price shocks due to the war in Ukraine on energy demand in Italy, which has fallen sharply. In general, however, economic theory holds that there is no such thing as perfectly inelastic long-term demand.

4.4.2. Interview session #2

Two experts were interviewed in this session: one, Gian Luca Vaglio, is chief operating officer of an Italian offshore renewable energy project development company called Agnes; the other is Tommaso Polci, expert on renewable energy development in Italy, responsible for and editor of two authoritative reports on the permitting situation in Italy. The main contributions of the interview are summarised below.

About Power grid transmission capacity (V1 & V2)

The use of grid transmission capacity to indicate total renewable capacity is discussed. According to Vaglio, the grid is in fact expanded according to connection requests, not the other way around. In any case, the connection V6 - V1 is considered correct and confirmed.

About Energy Storage systems (V16)

A positive feedback loop between V1 and V16 is suggested by Polci, as the increase in renewable energy installations promotes the increase in new storage systems. This feedback is plausible but is partly outside the scope of the reading of the system as given by the

objective of the thesis. The function of the V16 - V1 link is to determine the positive impact of storage on grid development, and adding another causal feedback relationship would not describe the basic system behaviour and would run counter to the reductionist approach that the modeller must take to maintain the controllability of the diagram.
In addition, Polci argues that storage could have a negative impact on the cost of electricity from non- RES (V19) because storage in the capacity market provides a similar grid-stabilising service as non-renewables, depriving them of additional market space, resulting in an increase in LCOE.

About Permitting Process Length (V22)

In general, the use of time units to indicate the complexity of the process is considered a valid solution, and the connection between V22 and V3 is also considered correct. Vaglio suggest that for a future where the model moves to a quantitative analysis and simulations are performed, a consistent starting point for this unit of time should be found: The determination of the duration of the permitting process must be defined by a common starting point, which may be the connection request, the start of the EIA, or some other specific step of the authorization process.

About Bankability (V4)

Again, the use of DSCR as an indicator of bankability in terms of market attractiveness raises some concerns. First, the DSCR may also be low for reasons unrelated to the quality and feasibility of the project, and it is also dependent and subjective from company to company. Vaglio suggested that an average of the IRR of the different projects should be used instead, as this is the most important economic indicator in project financing. The D/E ratio can also be a valid indicator, but all these indicators are interrelated, and the IRR remains in some sense the basic indicator on which all other indicators depend. It is essentially an indicator of the economic performance of the project and is used by banks and all investors to assess attractiveness. Alternatively, the use of a percentage point difference from alternative technologies such as fossil fuels can be assessed.

About Financial Incentives (V21)

The relationship between financial incentives and bankability is positively evaluated and confirmed as a fundamental relationship to be indicated in the representation of the system.

4.4.3. Interview session #3

In this interview session, the work was presented to the head of the climate and energy division of a large Italian sustainable development foundation. The interviewee is a coordinator of research projects in different areas of the green economy and an expert in sustainability analysis, models, performance evaluation systems, indicators and reporting. The following are the main contributions from the interview.

About Permitting process length (V22)

The expert points out the possibility that the model did not take into account an important feedback loop, according to which V22 is in some way under the influence of loop R1, i.e., that the amplifying phenomenon due to the increase in renewable energy capacity (considered in the CLD only in its technical dimension with the variable (V6) Technology readiness) also influences the regulatory system underlying the permitting processes, making them more efficient and less time-consuming. In parallel, the same reinforcing phenomenon affects the social sphere by reducing the resistance of the public, which gradually overcomes the rejection phase caused by the NIMBY syndrome and becomes "accustomed" to the change and more inclined to accept new renewable energy installations.

About the link between % RES in electricity mix (V9) and Non-RES LOCE (V19)

The impact of an increase in the marginal cost of fossil-generated energy caused by an increase in the share of renewables in the electricity mix is understood and acknowledged, but the expert suggests that this impact will not occur gradually, as CLD suggests, but only when a certain threshold of RES in the electricity mix is exceeded.

About acceptance rate (V3)

According to the expert, one of the most important factors negatively affecting the approval rate of projects is social and political resistance. This resistance, in his opinion, is the real bottleneck and has a much stronger impact than other factors (such as the f regulation and limitation of Terna's investments by ARERA, mentioned by the experts in interview session # 1). Therefore, the introduction of another variable, hypothetically defined as "NIMBY index", which exerts a negative influence either directly on V3 or indirectly in conjunction with V22 (Permitting process length) is proposed.

About energy demand and its regulation

Another aspect suggested by the expert that is not modelled in the CLD is a phenomenon that does not come into play in the early years but will become noticeable when renewables reach a high penetration rate in the electricity mix: When generation is primarily renewables, energy production is likely to affect energy demand. Since the electricity mix will no longer be programmable, it is conceivable that demand-side regulation systems will be established based on generation: the demand will eventually be manipulated (or even enforced) to shift consumption to times of higher generation and to interrupt certain energy-intensive processes during times of scarce generation. Storage systems will likely be instrumental in mitigating this phenomenon. Another aspect that has not been modelled is the interconnection of grids between countries: It is likely that the energy transition, precisely to limit the phenomena described above, will require increasing integration of grids at the international level.

About the Causal Loop Diagram

The model is generally considered exhaustive, but according to the interviewee, it is too reductionist with respect to certain aspects, especially those of a social nature (social acceptance, NIMBY syndrome, etc.). However, the reductionist approach adopted is clear and understandable from the perspective of the development perspectives of the model, which is intended to move from a qualitative to a quantitative level, for which it is impractical to use variables that are difficult to measure, such as those related to social aspects.

4.5. Representativeness of the Causal Loop Diagram

Like all conceptual models, the CLD resulting from the modelling performed in this thesis is not free from methodological biases, which should be mentioned.

A typical problem in modelling complex systems is the fact that there are many different possible model structures and many sets of parameters in a given structure that can effectively represent the behaviour of the system; this principle has been called equifinality (Beven and Freer, 2001). The concept of equifinality should not be surprising; in theoretical physics, for example, it is often the case that in a given system there are so many interactions among its constituents that several representations are considered equivalent unless the properties of those constituents can be specified in detail (Beven and Freer, 2001).

A complex system such as the one studied in this thesis is no exception; indeed, the energy transition system has a large number of possible combinations of factors that lead to the same results, and unless the model is supported by numerical simulations, there is no scientific rigorous way to determine whether one representation is more effective than another.

According to Ryan et al. (2021), a best practice for solving this “convergence” phenomenon is to perform multiple data collection activities resulting in multiple CLDs that must somehow be aggregated to provide a coherent view of the phenomenon of interest in a "complete" model[2].

4.6. Numerical simulation tests

To complete the work, the model was mathematically verified using test simulations. The parameters and equations underlying these mathematical simulations were chosen arbitrarily, always in accordance with the logic of the hypotheses established in the model (causal relationships), and the numerical data used were chosen with the intention of reflecting real data, but they are not validated, therefore the simulations performed do not have the function of validating the model, but rather of verifying the shape of the trends of some variables (the complete test code used for the simulation can be found in APPENDIX II). The arbitrary nature of the choices made in assigning numerical values as starting points for the test simulations speaks to the need to begin the exploration of causal relationships with a qualitative conceptual scheme that can be used as a basis for subsequent investigations to obtain real numerical values.

The usefulness of these simulations was to make an initial assessment of the robustness of the model and to identify critical issues that did not arise from a simple consideration of the qualitative model.

Below are some diagrams resulting from the simulations. As mentioned earlier, the trends shown in the diagrams are the result of test simulations performed on fictitious data sets. This is to check the robustness of the model structure.

<u>NOTE:</u> The time steps used for numerical simulation in the diagrams are in months rather than years; this is a calculated error due to technical limitations of the test simulation. In fact, the model is designed for a 30-year period, and the time steps should be in years. In any case, the curves would be identical, so the error is not relevant.

[2] Although a model can never be a complete representation of a system, according to Groesser and Schwaninger (2012) a model can be considered complete if it is able to adequately represent the system under investigation in relation to the extent of content required for the analysis.

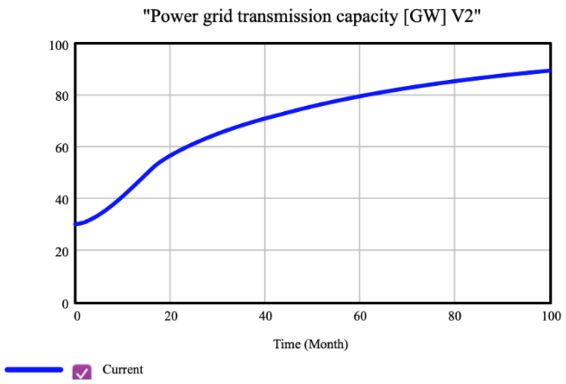

Figure 14: *Power grid transmission capacity over time (simulation test).*

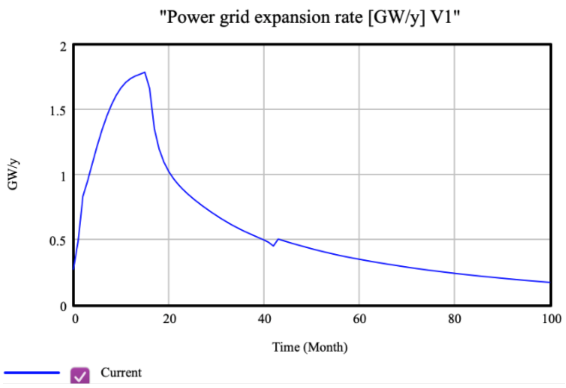

Figure 15: *Power grid expansion rate over time (Simulation test).*

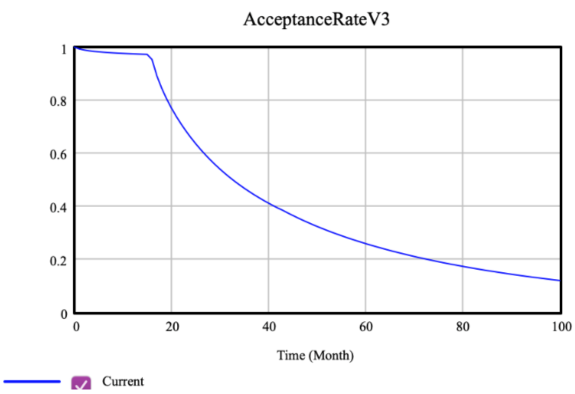

Figure 16: *Acceptance rate over time (simulation test).*

The three graphs in the figure show the trend over time of the total grid transmission capacity (i.e., the total installed renewable energy capacity), the grid expansion rate (i.e., the rate of renewable energy installation), and the acceptance of new renewable energy installations.

In Figure 14, the graph reflects the typical constant trend of the Power grid transmission capacity: namely, it has been defined as a stock variable, and therefore its value is the cumulative value of its flow over time and cannot but increase at each time step, at a rate that depends on its flow variable (i.e., V1, Power grid expansion rate).

The graph in Figure 15 reflects very well the exponential growth effect of renewable capacity triggered by loop R1, which drives the exponential growth of variable V1 in the first cycles until loop B1 comes into play, which causes a drastic slowdown.

The chart in in Figure 16 shows the onset of the slowdown effect of loop B1, according to which a limit (K1) is reached with the increasing of installed capacity (V2), and when this limit is reached, the acceptance of new projects (V3) decreases sharply. This is also reflected in the trend of V1, which is shown in Figure 15.

Another interesting result of the test simulation was that the importance of choosing an effective unit of measurement for the different variables became clear. This was particularly evident with the Technology readiness variable V6, which was assigned the TRL as its unit of measurement. However, TRL is an indicator that ranges from 1 to 9 and is impractical for implementing a mathematical model. In addition, the TRL index is inadequate to represent the broader meaning of the V6 variable, which not only indicates the level of technological readiness, but also represents the broader concept of learning by doing, i.e., improving not only efficiency, costs, and know-how in general, but also other aspects, such as better ability to manage permitting processes. This is a very important aspect to be studied and improved in the following phases of the work.

5. CONCLUSIONS

In this thesis, the structure of the energy transition was explored using a system dynamics approach by creating a CLD that was able to capture the multidimensional nature of the system. The model identifies two main functional domains through which the energy transition takes place: the energy production domain and the consumption domain. Along these two domains 23 main factors involved in the energy transition were identified and the relationships linking them were explored. The CLD showed that the two subsystems that make up the energy transition (i.e., the energy production and the end-use functional domains) appear to be driven by relevant feedback phenomena that are arranged according to recurring patterns; in particular, the "*limits to growth*" archetype was identified, according to which an increase in renewable capacity triggers a self-reinforcing feedback loop due to increasing progress in the field, which lowers costs and stimulates the development of new projects RES projects; this exponential growth behaviour is slowed by a balancing feedback loop triggered when total renewable energy capacity approaches an upper limit, near which further increases in capacity become slower and more difficult. This archetype is also conceivable for the functional domain of end-uses, but is not explicitly modelled. In addition, numerous variables that exert significant influence on the system were highlighted; Among these, a particularly important role in the production domain is played by the electricity grid infrastructure (V1,V2), which is assumed to be the main technical factor behind the diffusion of renewable energy. Together with the power grid, bankability (V4) is a key variable for the generation domain, governing the market attractiveness of the sector. A number of important exogenous factors exert strong effects on this functional area, which can be addressed as 'leverage points' of interest where intervention can be made to accelerate the system and facilitate the transition. Such as the constant K1, which puts a cap on grid (and RES) expansion, or V22, which lowers the authorisation rate for projects, or, moreover, energy storage systems (V16), which support grid expansion. Regarding the functional domain of consumption, it is evident that electrification (V11, V12), the protagonist of this domain, is a strongly cost-driven process. Exogenous and endogenous cost variables such as carbon price (V17), critical raw materials price (V20), fossil fuel price (V18), as well as electricity price (V10) drive the electrification of end-uses. Other important interrelationships among variables were identified, some of which are not always obvious to an audience unfamiliar with energy issues, such as the link between V9 and V19 (% RES in the electricity mix and non-RES

LCOE, respectively), which indicates the increasing costs of non-renewable generation, in some cases uncontrolled and painful, due to the cut-off effect caused by a high share of renewables in the electricity mix.

When compared with other studies that have used a similar approach to study the energy transition, many similarities with the results of this work emerged, despite significant differences in method or objectives. Further confirmation of the robustness of the CLD was provided by conducting a series of numerical simulation test runs, the results of which, although based on arbitrarily selected data, were consistent with what could be expected based on the diagram structure. As for the method used, the application of system dynamics in modelling multidimensional systems (i.e., social, technical, political, economic) and their transitions is well founded (Freeman, 2021; Köhler et al., 2018; Papachristos, 2019; Savio et al., 2022), and it is shown how a first qualitative determination of the variables and causal links underlying the system structure by using CLD is a key step for modelling with a system dynamics approach (Abdelbari and Shafi, 2017). Another aspect that became evident during the interview phase was the importance of the tacit knowledge that resides in the mental models of the stakeholders, i.e., the actors who are directly or indirectly involved in the system. Capturing this tacit knowledge through the interviews made it possible to obtain important suggestions for variables and relationships to be further investigated, new hypotheses to be tested, and improvements to be implemented in the subsequent phases of the work.

In fact, this thesis is intended to be the starting point for a further phase of exploration of the system, this time conducted not only qualitatively but also quantitatively. The CLD itself is not a complete model, but its function is to provide a smoother transition to the final stock and flow diagram (SFD) of the energy transition, which will be used to perform numerical simulations of the underlying dynamics of the system. The CLD created in this thesis has provided the structure of the system, qualitatively determined the function of the causal links, identified the exogenous variables for which numerical data will be collected, and furthermore, has already assigned its unit of measurement to each variable in the system to enable a quantitative approach to research.

Declaration of competing interest

The author declares that he has not known competing financial interests or personal relationships that could have appeared to influence the work reported in this thesis.

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APPENDIX I

State And Trends Of Renewable Energy Sources In Emilia-Romagna Region, Italy

This section contains a collection of data on photovoltaic, wind, hydro, bioenergy and thermoelectric plants in Emilia-Romagna region, Italy.

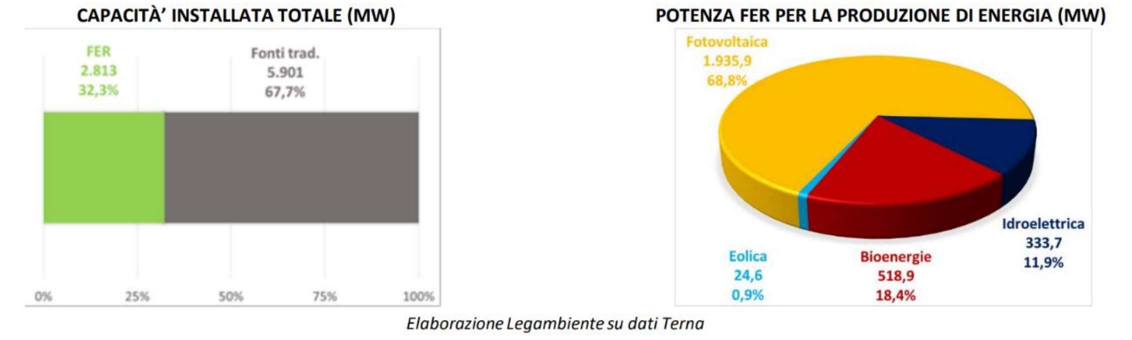

Figure 17: *Right - total installed capacity in E-R in 2016 with RES share in green; left - breakdown of RES share into photovoltaic, hydro, bioenergy and wind components (Legambiente, 2018).*

At the end of 2016, 75,419 renewable energy plants were installed in Emilia-Romagna, numerically distributed among a large number of photovoltaic plants with 99.28% of the total, followed by bioenergy with 0.41%, hydroelectric plants with 0.23% and wind power plants with the remaining 0.08%. The net efficient capacity of the installed renewable energy plants is 2,813 MW, which is about 32.3% of the net capacity available in the region. Again, photovoltaic is the technology with the largest installed capacity with 1,936 MW (68.8% from RES), followed by bioenergy plants with 519 MW (18.4%), hydroelectric plants with 334 MW (11.9%), while the remaining 0.9% is accounted for by wind power plants with about 25% MW.

From 2010 to 2016, renewable energies in Emilia Romagna registered a continuous growth both in terms of installed electric capacity (+178%, from 1 GW to 2.8 GW) and in terms of energy production (+98.1%). Only hydropower recorded a decrease of 21.3% during this period, but all other RES increased their electricity production. The most impressive figure is that of photovoltaic (+1,268%), which increased from about 153 GWh (364 MW) in 2010 to 2,094 GWh (1,936 MW) in 2016, followed by bioenergy (+73%) and wind power (+40%)

(Legambiente, 2018). The following graph confirms the continuous growth of all RES from 2010 to 2016.

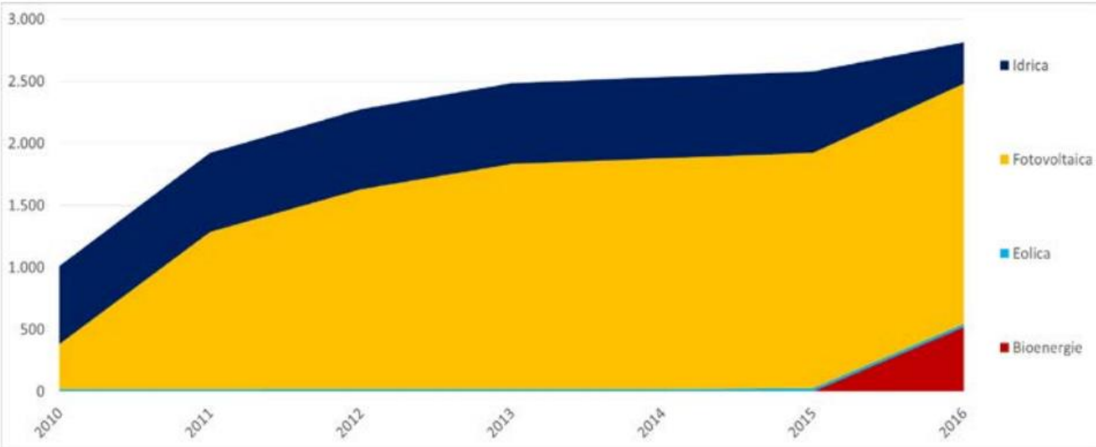

Figure 18: *Installed power*: RES trends in Emilia Romagna in the period 2010 - 2016. (Legambiente, 2018)*
** Bioenergy power data are only available since 2016.*

Regarding the installed power, understood as the maximum electrical power that can be supplied when the plant is operating for more than 4 hours and producing only active power under optimal conditions, and measured at the connections of the plants' electricity generators, in 2016 the gross active power of the electricity generating plants in Emilia Romagna was 9.254 MW and in 2017 it was 9151 MW, of which 3298 MW were plants powered by renewable energy sources, representing 36% of the installed capacity in 2017 (Cancila and Scapinelli, 2020).

Compared to 2016, total installed capacity decreased slightly in 2017 due to the decrease in fossil fuel thermoelectric plants, which was only partially offset by the increase in renewables. The capacity of the plants varies greatly depending on the sources from which they are fed: photovoltaic plants generally have a low capacity (average capacity of about 34 kW), thermoelectric plants generally have a high capacity (average capacity of over 20 MW), while biomass-fueled plants are in the middle range (average capacity of about 2 MW).

The renewable energy sources with the strongest growth in 2017 are photovoltaics and biomass, while the trend figures of hydro and wind power plants are almost unchanged.

Piacenza and Ravenna are the provinces with the highest installed power in the region, as important thermoelectric plants are located on their territory. As far as renewable energy plants are concerned, Ravenna and Bologna are the provinces with the highest installed power in absolute terms.

Table 7: Gross efficient power of electricity production plants in Emilia-Romagna in MW; elaboration by ARPAE on GSE and TERNA data (Cancila and Scapinelli, 2020).

Anno	Idroelettrico	Eolico	Fotovoltaico	Termoelettrico a biomassa	Termoelettrico a fonti fossili	Totale Termoelettrico	TOTALE
2000	608	4	0	95	3783	3878	4490
2001	608	4	0	89	3763	3852	4464
2002	610	4	0	135	4406	4542	5156
2003	617	4	0	165	4466	4631	5251
2004	617	4	0	190	5177	5367	5987
2005	620	4	0	193	5121	5314	5938
2006	620	4	0	202	5594	5795	6419
2007	620	4	7	204	5613	5817	6448
2008	625	4	40	299	6460	6759	7427
2009	627	16	95	371	6312	6683	7421
2010	629	18	364	423	6298	6721	7732
2011	638	18	1267	478	6342	6820	8742
2012	645	19	1610	571	6352	6923	9196
2013	651	19	1814	608	6189	6797	9281
2014	655	19	1859	613	6205	6817	9351
2015	665	25	1898	596	6076	6672	9259
2016	669	25	1936	628	5997	6624	9254
2017	**675**	**25**	**1983**	**615**	**5853**	**6468**	**9151**
Variaz % 2017/2016	0,9	0,8	2,4	-2,1	-2,4	-2,4	-1,1

TERNA'S GAUDI' SYSTEM - CONSISTENCY OF RENEWABLES IN EMILIA ROMAGNA

The following sections are the result of a data collection carried out in the period 2018 - 2022 on the consistency of renewables in Emilia-Romagna, provided by Terna's GAUDI database (TERNA spa, 2023b).

The "*Gestione delle Anagrafiche Uniche Degli Impianti di produzione*" (GAUDÌ) system is a platform (established by ARERA with resolution no° ARG/elt 124/10) developed and managed by Terna for the purpose of:

- collecting the master data of all power generation facilities;
- monitoring their life cycle, from application for connection to the grid to commissioning;
- streamlining the flow of information on master data between the various electricity operators (Terna, GSE, distributors, generators, etc.);
- provisioning of information on the management of the national electricity network in the planning, programming and operational phases;

- recording the technical characteristics of the installations, which are also useful for assessing the resilience of the electricity system.

This portal, therefore, has collected, recorded, categorised, and sorted by date the inventories of renewable energy facilities across the country and provides a database with monthly updated data on the inventories of four facilities RES:

- Wind
- Hydro
- Photovoltaic
- Bioenergy & thermoelectric

Data gathering and processing

This research was conducted using data provided by Terna's GAUDI system; the data considered and their use are briefly described below. As already discussed, the national stocks RES are divided into four categories; from the portal one can use Doc. Excel, for each month of the year from 17/06/2018 to 30/09/2022 for each category.

The four types of RES are categorised by power range, and the number of plants (and the total power of these) falling within the following ranges are indicated:

- P<12kW;
- 12kW<P<20kW
- 20KW<P<200kW
- 200kW<P<1MW
- 1MW<P<10MW
- P>10MW

	P < 12kW		12kW <= P < 20kW		20kW <= P < 200kW		200kW <= P < 1MW		1MW <= P < 10MW		P >= 10MW		Totale	
Regione	Numero	Potenza [MW]	Numero	Potenza [MW]	Numero	Potenza [MW]	Numero	Potenza [MW]	Numero	Potenza [MW]	Numero	Potenza [MW]	Numero	Potenza [MW]
PIEMONTE			1	0.0	94	10	218	145	25	81	4	115	342	352
VALLE D'AOSTA	1	0.00			4	0	3	2					8	3
LOMBARDIA			4	0.1	149	16	554	365	71	181	8	205	786	767
TRENTINO ALTO ADIGI	3	0.0	2	0	80	9	97	55	11	22	1	15	194	101
VENETO			2	0.0	99	11	276	181	30	84	3	50	410	326
FRIULI VENEZIA GIULIA					23	2	110	75	4	7	2	53	139	137
LIGURIA					1	0	6	4	4	17			11	21
EMILIA ROMAGNA	1	0.01	6	0.1	73	7	232	178	30	74	14	342	356	602
TOSCANA	1	0.01			43	4	99	68	15	52	34	980	192	1'104
UMBRIA					37	3	32	23	11	16	1	14	81	55
MARCHE			1	0.02	23	2	44	28	3	5			71	35
LAZIO					31	3	64	45	22	49	3	83	120	180
ABRUZZO					9	1	24	18	3	13			36	31
MOLISE					1	0.0	7	5	2	2	2	27	12	34
CAMPANIA	1	0.00			41	5	48	28	9	35	2	195	101	262
PUGLIA			1	0	20	1.9	42	28	8	20	7	312	78	362
BASILICATA	1	0			21	1.9	11	8	2	19	1	65	36	93
CALABRIA					12	1.4	26	17	6	16	5	186	49	220
SICILIA					20	2.3	22	17	15	53	2	32	59	104
SARDEGNA					13	2	22	18	2	5	4	100	41	125
Totale	8	0	17	0	794	81	1'937	1'308	273	751	93	2'773	3'122	4'914

Figure 19: *An example of a table that can be downloaded from the GAUDI portal; the table refers specifically to the consistency of bioenergy and thermoelectric power as at 31/10/2022 (TERNA spa, 2023b).*

Subsequently, all reports for all months of the 2018-2022 period were downloaded and integrated, and the data for the other Italian regions were cleaned. The process was performed for each year, then the consistencies of each RES type for each year were compiled until a table was obtained per RES with the consistency data of all months from 17/06/2018 to 30/09/2022, divided by power range.

Subsequently, the data of each range of each RES type were presented graphically, resulting in a plot of the trend in the number of plants and the total power of each category from 2018 to 2022. At the same time, graphs were created for the number of installations and total power of each RES, as well as for the number of installations and total power of all RES; these last graphs made it possible to show the trend of each RES over the five-year period, and of the total renewables in general. In order to assume a trend for the coming years, the trend line was calculated, showing the possible trend (under the heavy assumption that the trend can be estimated linearly) from the starting point (2018) to 2030.

The trends calculated for total RES show a steady and continuous upward trend, but the result so far is to be considered unreliable, due to the poor applicability of the linear model to the type of trend under consideration.

Below are some of the graphs produced during the analysis.

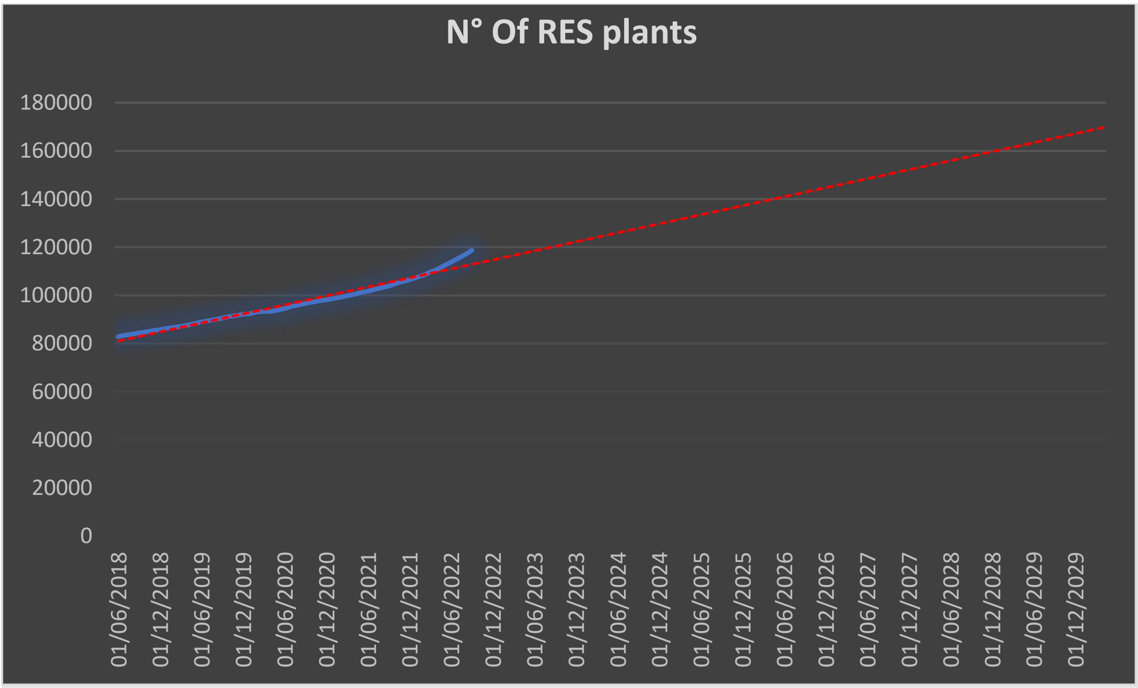

Figure 20: *In blue, the number of total RES plants in Emilia Romagna from 2018 to 2022; in red, trend line of the number of plants up to 2030.*

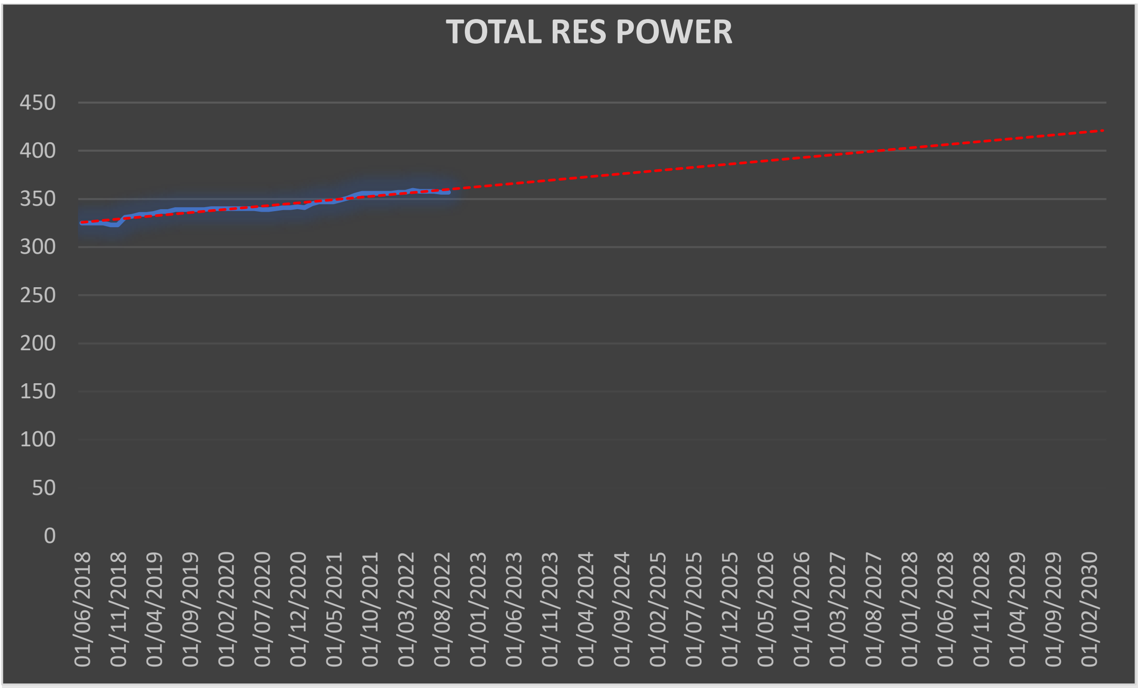

Figure 21: *In blue: total renewable capacity [MW] in Emilia Romagna from 2018 to 2022; in red: trend line of total renewable capacity until 2030.*

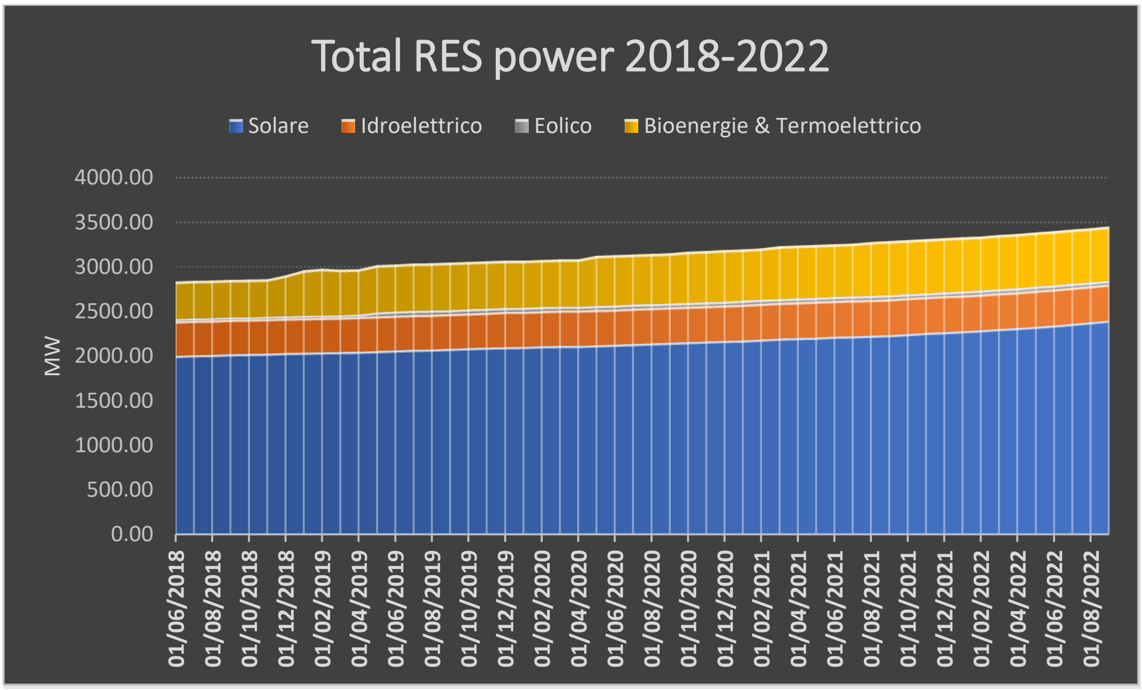

Figure 22: *Total power [MW] by RES type in the five-year period 2018-2022.*

The graph in Figure 22 shows the impressive superiority of photovoltaics in terms of capacity, followed by biomass and hydropower to a much lesser extent. In contrast, the total capacity share of wind energy is extremely modest, and it is hardly represented in this area. In general, however, a positive trend can be seen for all RES, although not particularly 'steep' (this is also due to the shortness of the period considered, 5 years, in facts, is a short time frame for the construction of RES plants.

APPENDIX II

NUMERICAL SIMULATION CODE - VENSIM PLE

This section provides the code used for the simulation tests shown in section Numerical simulation tests4.6. this code is provisional and arbitrary, based on fictitious values selected to test the model. Moreover, the simulation does not cover the entire CLD, rather, it has been run only including some variables belonging to the production domain.

*****

```
AcceptanceRateV3=
      IF THEN ELSE("Power grid transmission capacity [GW] V2">=50,("RES policy goal
[GW] K1"
   -"Power grid transmission capacity [GW] V2")/("Power grid transmission capacity [GW]
V2"
   )/("Permitting process length [months] V22"/100), 1-0.01*LN(Time+1))
   Units: **undefined**
   ATTENZIONE la misura della durata del processo è fissata a 100
         quindi adesso il valore di questo fattore è 1

BnkbtyAcceptance=
   IF THEN ELSE(AcceptanceRateV3<=1,0.3*(1-AcceptanceRateV3), 0)
Units: **undefined**
ALTRO CAMBIAMENTO: FORMULA SOSTITUITA PER EVITARE CHE I VALORI
      NEGATIVI BLOCCASSERO IL PROGRAMMA CON QUESTA NUOVA
ESPONENZIALE
      I NEGATIVI DIMINUISCONO DSCR IF THEN
      ELSE(AcceptanceRateV3<=1,(0.5^(1-AcceptanceRateV3*0.04))-1, 0)
      Per acceptance rate ((1-Acceptance rate)-0.05) è la base
      dell'equazione. Se Acceptance rate è 0.8, il complemento è 0.2
      a questo viene sottratta la soglia di sensibilità pari a 0.05;
      la y è l'esponenziale ^1.3; in corrispondenza di acceptance
      rate pari a 0.8 l'incremento di DSCR è incrementato di 0.015.

BnkbtyIncentives=
   IF THEN ELSE("FinancialIncentives[MEUR]V21">0,-
0.01*LN("FinancialIncentives[MEUR]V21"
),0)
Units: **undefined**
FATTORE DI SCALA CAMBIATO DA 0.1 A 0.01 Gli incentivi sono circa
      1M a livello iniziale cui corrisponde un ΔDSCR pari a 0.
      L'ipotesi è che se gli incentivi finanziari sono annullati il
      ΔDSCR deve crescere di 0.5. Quando gli incentivi sono 1M€
      l'incremento di DSCR è 0. Con Incentivi a 0.5 ΔDSCR è circa
      0.7, in prossimità dello 0 ΔDSCR è vicino a 0.5
```

BnkbtyLCOE=
IF THEN ELSE("RESLCOE[€/MWh]V7">="LCOE(0)",("RESLCOE[€/MWh]V7"-"LCOE(0)"
)/100,0)
Units: **undefined**

Critical Raw materials price V20=
100-sin(Time/3)-Time/10
Units: **undefined**
Time/10 è il fattore di evoluzione tecnologico che spiegherebbe la diminuzione

"DSCR(0)"=
1.05
Units: **undefined**

"Energy storage systems [GW] V16"= INTEG (
0.5*LN(100-Critical Raw materials price V20+1),
1)
Units: **undefined**
quanto è l'attuale capacità di immagazinamento dell'energia? suppongo che a base di partenza sia 1 GW. La diminuzione di prezzo genera un aumento logaritmico. Esempio la differenza di prezzo di 10 euro provoca l'aumento di capacità d'immagazinamento di 1.2 GW

EROSIONRATE=
0.001
Units: **undefined**
Questo è il tasso di diminuzione delle risorse che servono a finanziare lo sviluppo delle rinnovabili

"FinancialIncentives[MEUR]V21"= INTEG (
IF THEN ELSE("FinancialIncentives[MEUR]V21">=0, -EROSIONRATE*("Power grid transmission capacity [GW] V2"
-"PGT(0)") , 0),
1)
Units: MilionEUR
In ciascuna delle procedure di Registro o Asta, vengono assegnati differenti contingenti di potenza. Qui si ipotizza che i contigenti di potenza remunerati con tariffa incentivata sia nei registri che nelle aste (quindi il totale degli incentivi messi a disposizione) dimunisca a ogni time step del 1% della differenza tra la potenza di trasmissione di partenza delle rinnovabili "PGT(0)" (nel 2017 era 30 GW). Nota il valore del 1% è del tutto arbitrario e provvisorio. Approfondimenti:
https://www.gse.it/servizi-per-te/fonti-rinnovabili/fer-elettrich
e/incentivi-dm-04-07-2019, RER22_web.pdf

"LCOE(0)"=
40
Units: **undefined**

"Permitting process length [months] V22"=
100
Units: months [90,110,1]

"PGT(0)"=
30
Units: GW
Questo è il valore della potenza delle rinnovabili nel 2017.
PGT(0) sta per power grid trasmmission al tempo iniziale della simulazione (2017

"Power grid expansion rate [GW/y] V1"=
IF THEN ELSE("RES connection requests [GW] V5">=0,AcceptanceRateV3*"RES connection requests [GW] V5"
*(0.5*LN("Energy storage systems [GW] V16"+1)), 0)
Units: GW/y
Acceptance rate*richieste connessione=quante richieste sono accettate e vengo trasmesse in rete; il fattore energy storage è un moltiplicatore che vale 1 se energy storage è 0 e aumenta prograssivamente meno all'aumentare dello storage. Quando energy storage è 1 GW il fattore moltipicativo è 1.34 (34% in più di richieste). A 4 GW il fattore moltiplicativo è 1.8. Forse questa modellazione è esagerata: da rivedere.

"Power grid transmission capacity [GW] V2"= INTEG (
"Power grid expansion rate [GW/y] V1",
"PGT(0)")
Units: **undefined**

"RES connection requests [GW] V5"=
-0.5*LN("RES Project bankability [DSCR] V4"-"DSCR(0)"+0.01)
Units: GW
con questa equazione se la differenza tra DSCR attuale e DSCR(0) è 0 le richieste sono prossime a 1.7 GW

"RES policy goal [GW] K1"=
100
Units: GW
provvisoriamente fissato a 100 GW L'obiettivo è statico (non soggetto a variazioni)

"RES Project bankability [DSCR] V4"=
"DSCR(0)"+BnkbtyLCOE +BnkbtyAcceptance+BnkbtyIncentives
Units: **undefined**
ATTENZIONE FORMULA PROVVISORIA DA RIVEDERE DSCR (Debt Service Cover Ratio) è un indice di rischio. In Italia nel 2019 vale

1.05 al minimo e 1.10 al massimo. Più alto è il tasso di accettazione, gli incentivi finanziari e minori i costi (LOCE) minore il rischio. Qui si immagina una composizione di indici. Per acceptance rate ((1-Acceptance rate)-0.1) è la base dell'equazione. Se Acceptance rate è 0.8, il complemento è 0.2 a questo viene sottratta la soglia di sensibilità pari a 0.05; la y è l'esponenziale ^1.3; in corrispondenza di acceptance rate pari a 0.2 l'incremento di DSCR è incrementato di 0.015. Gli incentivi sono circa 1M a livello iniziale cui corrisponde un ΔDSCR pari a 0. L'ipotesi è che se gli incentivi finanziari sono annullati il ΔDSCR deve crescere di 0.5. Per modellare questo la soglia di tolleranza è 0.1M€. Quindi (vedi commento BnkbtyIncentives)

"RESLCOE[€/MWh]V7"=
("LCOE(0)"*0.5)+"LCOE(0)"^((9-"Technology readiness [TRL] V6")-0.3*(100-Critical Raw materials price V20
))
Units: **undefined**
!fattore 0.3 da parametrizzare! Da questo documento
https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf
ho ottenuto un LCOE delle rinnovabili attorno ai 50 €/MWh (una sorta di media pesata) spannometrica

"Technology readiness [TRL] V6"= WITH LOOKUP (
"Power grid transmission capacity [GW] V2",
([(30,7)-(200,9)],(30,8),(40,8.1),(50,8.5),(90,8.9),(200,9)))
Units: **undefined**
!delay non modellato!