Corso di Laurea Magistrale in Ingegneria Energetica e Nucleare

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Comparative study on the Sectoral implementation of European Green Deal in different types of Energy Models

By

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Declaration

I hereby declare that the contents and organisation of this thesis constitute my original work and do not compromise the rights of third parties, including those relating to the security of personal data.

Risvan Ubais

2022

I would like to dedicate this thesis to my loving father and mother, for their continuous love and support.

Abstract

The European Union's Power sector and the end-use sector are responsible for nearly 75% of the EU's Greenhouse Gas emissions. It is the need of the hour to decarbonise the EU's energy system to achieve climate neutrality by the mid-century. The European Green deal lays down very ambitious targets of 55% emission reduction in 2030 and 100% emission reduction in 2050 from 1990 levels. Increased penetration of renewable energy technologies in the Power sector and simultaneous electrification of the end-use sector to meet the increased supply of electricity from renewable energy will accelerate the decarbonisation process. Therefore, this thesis aims to analyse the impact of the European green deal targets in transforming the power sector into a carbon-neutral power sector.

This is done by conducting a comparative analysis of various energy system models which were modelled based on European Green Deal targets. Emphasis is placed on understanding the constraints and assumptions in running the energy system models. The results showed that achieving carbon neutrality by mid-century is possible while overachieving the Green Deal targets for 2030 and 2050. The use of carbon capture technologies in decarbonising the power sector is only in sequestrating residual emissions or when the carbon price is increasing exponentially. Increased carbon tax, Sector coupling and society's attitude toward reducing carbon emissions play a crucial role in achieving this ambitious goal.

Keywords: European Green Deal, Energy System Modelling, Paris Agreement, Climate Neutrality, Power sector

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List of Acronyms

AMB	Ambient Scenario
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Sequestration
CO_2	Carbon di Oxide
COP	Conference of the Parties
CSP	Concentrated Solar Power
EC	European Commission
EED	Energy Efficiency Directive
EFOM	Energy Flow Optimization Model
EGD	European Green Deal
EIB	European Investment Bank
ESR	Effort Sharing Regulation
ETS	Emission Trading System
EU	European Union
FEC	Final Energy Consumption
GAMS	General Algebraic Modeling System

GDP	Gross Domestic Product
GENeSYS	Global Energy System
GHG	Green House Gas
Gt	Gigaton
GW	Gigawatt
H2	Hydrogen
ISAaR	Integriertes Simulationsmodell zur Anlageneinsatz-und Ausbauplanung mit Regionalisierung/ Integrated Simulation Model for Plant Deployment and Expansion Planning with Regionalization
JIT	Just and Inclusive Transition
JTM	Just Transition Mechanism
LEAP	Long-range Energy Alternatives Planning
LIMES	Long Term Investment Model for the Electricity Sector
LP	Linear Programming
LRF	Linear Reduction Factor
MAC	Marginal Abatement Cost
MARKAL	Market and Allocation
Mt	Million ton
MW	Megawatt
NDC	Nationally Determined Contributions
NEWAGE	National European Worldwide Applied General Equilibrium
NTC	National Transmission Capacity
OPT	Optimal Scenario
POLES	Prospective Outlook on Long Term Energy Systems
PRIMES	Price Induced Market Equilibrium System
PSP	Pumped Storage Plant
PV	Photovoltaics
RED	Renewable Energy Directive
REF	Reference Scenario
RES	Reference Energy System
RET	Renewable Energy Technology
TIMES	The Integrated MARKAL EFOM System
TWh	Terawatt-hour
vRES	Variable Renewable Energy System
WEM	World Energy Model

Chapter 1

Introduction

1.1 Climate change and Paris Agreement

Climate change is one of the major issues humanities is facing today. Human activities have increased the average global temperature to unprecedented levels, leading to climate change. Global temperature rise is due to the increase in the emission of Green House Gases (GHGs), mainly due to the usage of fossil fuels in the power sector to generate electricity and the usage of fossil fuels in the end use sectors-industries, transport and buildings. The GHGs emitted will act like a blanket around the atmosphere, arresting the heat produced and leading to global warming. Natural sinks like oceans and forests could absorb nearly 56% of the GHG emission yearly. But with the increasing GHG levels, the ocean's surface is turning acidic as the absorption of the GHGs is going beyond its maximum capacity. The rising population, urbanisation, and the demand for energy from developing countries are the critical drivers for the increased use of fossil fuels, leading to an increase in GHG emissions. [1] [2] [3]

In Fig. 1(a), the projected average temperature over the past 20 centuries can be observed, along with the unprecedented increase in global temperature in the past few decades. In Fig.1(b), we can see the impact of human activities on the rise of global surface temperature and its comparison with the change in global surface temperature with no human activities.

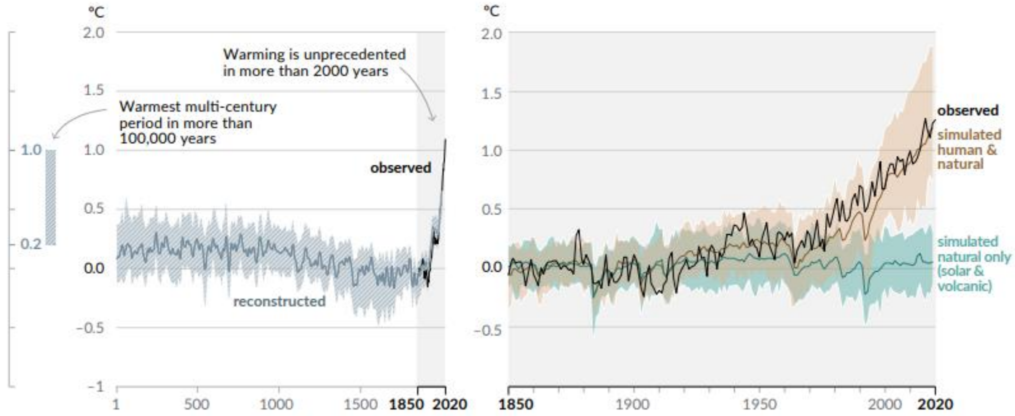

Figure 1 Variation in global surface temperature (a) The global surface temperature change from 1-2020 (to the left) (b) The global surface temperature over the period 1850-2020, with human and natural influences, and without any human influence (to the right) [1]

In December 2015, a legally binding treaty was signed by 196 parties at COP 21 in Paris to limit the increase in global temperature rise by 2°C, preferably 1.5°C compared to the preindustrial level. This treaty is called as Paris Agreement. The treaty's main agenda is limiting GHG emissions and achieving climate neutrality by 2050. According to Article 4 of the Paris Agreement, all parties are asked to present their national strategies to achieve the ambitious goals of the Paris Agreement through Nationally Determined Contributions (NDCs). This ambitious goal can only be achieved with each country supporting each other, especially the developed countries helping the developing countries. The help mentioned above could be in the following forms-Financial service, technological expertise and capacity building. Article 6 of the Paris agreement emphasizes the importance of public and private partnerships to mitigate GHG emissions and foster sustainable development for a green transition. Incentivizing the low carbon technologies is essential to promote their usage amongst the public. [4][5][6]

After the Paris agreement, the European Commission proposed a set of policies to achieve at least 50% and possibly 55% reduction in GHG emissions in 2030 and 100% in 2050. This set of policies is called as European Green Deal. It is an all-inclusive plan where no member states will be left behind. Stronger economies will support the weaker economies to achieve the climate neutrality goals. As part of the green deal, individual emission reduction targets are set for each sector to reduce its carbon emission. To achieve the green deal targets, it is essential to emphasize the EU ETS and ESR sectors. EU ETS system has two functions, a) it assigns a price/ton of carbon emitted and b) it reduces the emission cap every year to encourage decarbonisation. EU ETS has proven to be very effective since its implementation in 2005. Tightening these two functions can accelerate the transition to a carbon-neutral energy system. [7][8][9]

1.2 Aim of the thesis

The aim of the thesis is to conduct a comparative analysis on how the European Green Deal has been implemented in different Energy System Models. The power sector and the end-use sector combined are responsible for nearly 75% of the GHG emissions in Europe [10]. In this thesis, the decarbonization of the power sector by 2050 will be analysed by conducting a comparative literature study on various energy system modelling run based on European green deal targets and policies. Knowing the constraints and assumptions the modeler considers to achieve the European Green Deal targets through energy modeling is fundamental.

While several papers exist in simulating the pathway to achieving the climate neutrality targets of limiting the temperature rise to preferably 1.5°C through energy modelling, very few papers exist on achieving the European Green Deal targets through energy modeling. A thorough discussion is conducted on the types of energy models used to achieve climate neutrality through European Green Deal targets.

Finally, in the conclusion, the capacity addition achieved in renewable energy technologies and the influence of EU ETS (Emission Trading System) and CCS (Carbon Capture and Sequestration) technologies have had in this transition to a net zero power sector are discussed.

Chapter 2

Literature Review

2.1 European Green Deal

The European Green Deal (EGD) is the European Commission's ambitious plan to make Europe "the first Climate Neutral continent by 2050". The European Commission proposed the European Green deal in December 2019 to transform the European economy into a more sustainable one. This is to be achieved through a "Just and Inclusive transition", "Affordable and clean energy", "Sustainable and Smart mobility", "A Clean and circular economy", "A Fair and healthy food system", and "Protecting the biodiversity". To achieve the targets of the Green Deal, at least €1 trillion needs to be mobilised. Fig. 2 shows the main components of the European Green Deal. [7]

The European Commission intends to release at least €1 trillion in funding as part of the European Union Green Deal investment plan. Around €503 billion will be from the EU budget, and nearly €25 billion will be from the EU Emissions Trading System (EU ETS). The remaining funding will be from Private and public investors (primarily private), around €279 billion.

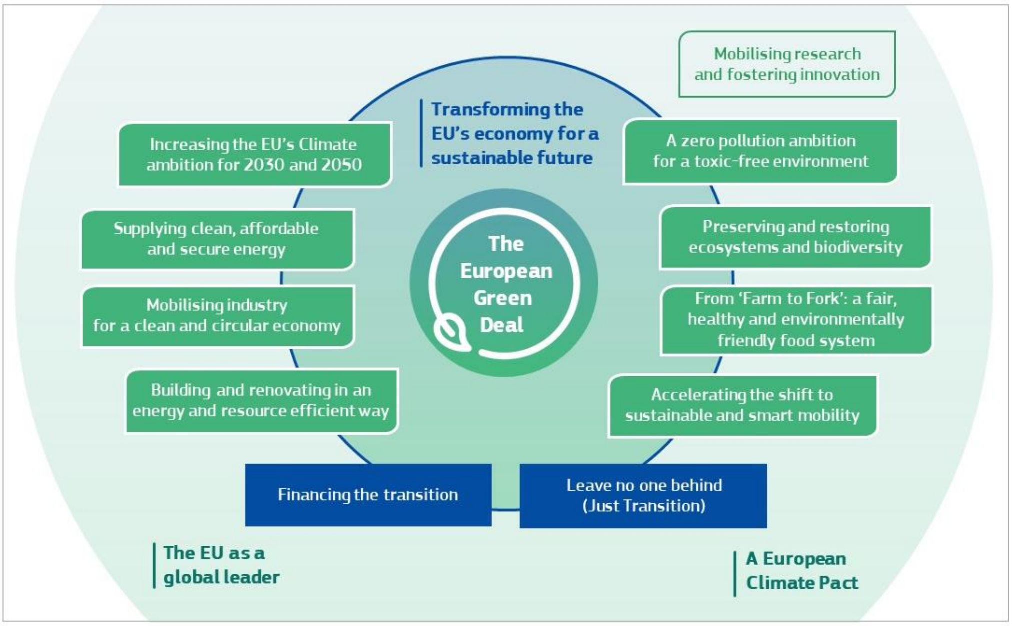

Figure 2 The European Green Deal [10]

€100 billion is dedicated to the 'Just Transition mechanism' [11] proposed in the European Green deal, which will be used as leverage for economically weaker members to achieve the Green Deal targets. This fund can also be used to fund the projects that would help the economically weaker members fight climate change. €45billion from the Invest EU funds will be used for the 'Just Transition mechanism'. The European Investment Bank (EIB) will provide low-interest loans to the public sector, which is backed up EU budget for investments that would involve a green transition. This loan from EIB would range from €25-€30 billion which are mainly focused on investment for projects like the renovation of buildings for energy efficient facilities, road and infrastructure for sustainable mobility, and improving the district heating networks. The funding mechanism followed by the European Commission to meet the European Green Deal targets can be see in the fig. 3.

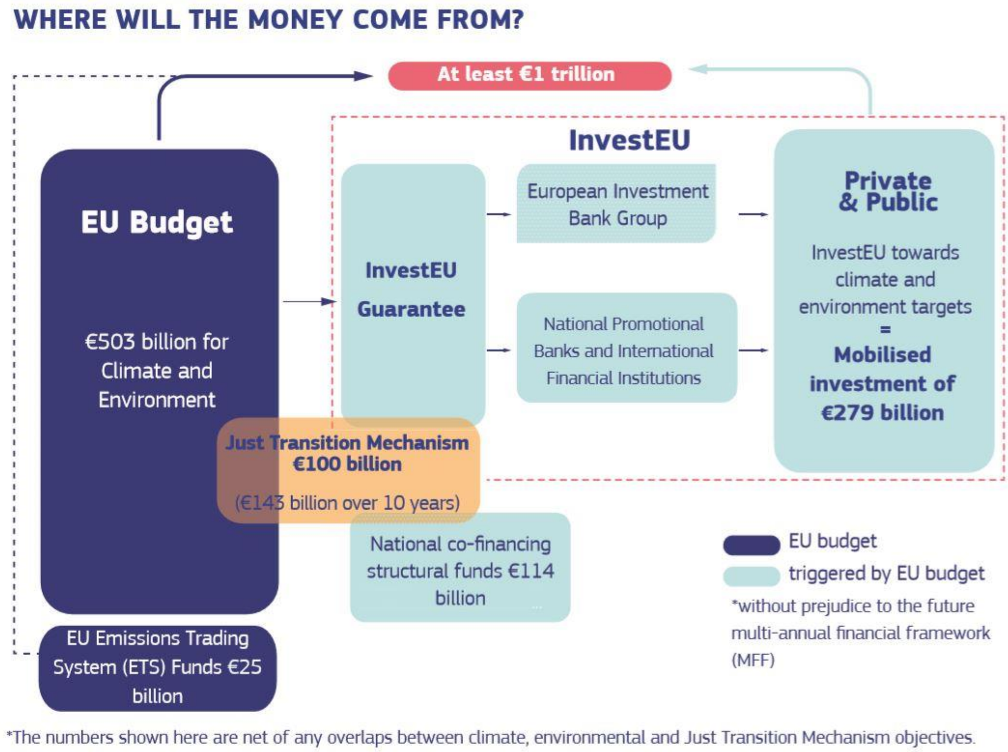

Figure 3 The funding strategy for the European Green Deal [12]

While the GHGs emission has come down by 23% from 1990-2018, the EU's economy has grown by 61%. To comply with the Paris Agreement targets, the EU needs to become more ambitious in its climate targets. The commission intends to set a trajectory to achieve climate neutrality by 2050 through European Climate Law. The main intention is to keep track of the advancement towards the goals in equal intervals.

The European Climate law needs all the European rules and regulations to align with the European Green Deal. 'Fit for 55' package was launched regarding EU's emission reduction target of at least 55% from 1990 levels in 2030. The 'Fit for 55' package is intended to align the EU legislation to the 2030 Climate goals. [13]

The EU's emission trading system (EU ETS) is the EU's tool to combat climate change by putting a price on carbon emission. EU ETS is the largest Carbon trading market in the world. The EU ETS uses the 'Cap and trade' mechanism, where a certain limit (or cap) is placed on the emissions allowed to each installation in the system. The low carbon emitters have the provision to either trade their excess allowance with high carbon emitters or carry forward the allowances to the following year. This limit is reduced over time to bring down the overall emissions eventually. The reduction is determined by Linear Reduction Factor (LRF), which is currently 4.2% and will be revised in equal intervals [14]

The sectors that are accounted for in EU ETS are the power sector, the energy-intensive industries and the aviation sector within Europe. The EU ETS was revised in 2021 to include maritime transport entirely by 2025 and the buildings and transport sector from 2026. The EU ETS previously contributed to nearly 40% of the EU's emissions. This share has increased with the inclusion of new sectors. The EU ETS's current reduction target is 61% by 2030 compared to 2005 emission levels. This is a very ambitious target; to achieve this, significant changes will be made to the Energy system. [14]

While the EU ETS covered 40% of the EU's emission, 60% of the emission was covered by the Effort Sharing Regulation (ESR) previously. After the inclusion of the Maritime, transport and Buildings sectors into ETS from 2025 and 2026, respectively, the contribution of emission from ESR sectors will reduce significantly. ETS and ESR are interconnected with the new amendments to the Green Deal. With the revision of the ambitions, the emission reduction from ESR has increased from 30% to 40% by 2030 compared to 2005 emission levels. Each member state is given nationally binding individual targets based on its GDP for the ESR sector emissions. This reduction could range from 10% to 50% from 2005 emission levels. [15]

In order to meet these emission targets, European Commission has proposed various legislations as part of the European Green Deal. On 14 July, 2021 these legislations were amended to meet the increased target of 55% reduction by 2030. One of the most important legislations of all is the Renewable Energy Directive (RED), which emphasizes on having 40% (old target -32%) of renewable energy share in the energy mix by 2030.[16]

The Renewable Energy directive (RED) has put down various targets for the expansion of potential renewable energy technology capacity until 2050. Offshore wind energy production is targeted to increase from 12 GW (in 2020) to 300 GW capacity by 2050, and Ocean energy capacity to increase from 12 MW in 2020 to 40 GW by 2050. For H2 to be able to support the transition, H2 should be produced in very large scale and its production process should be carbon neutral. EU Industry has an ambitious goal to achieve 2*40GW electrolysers by 2030. 40 GW of electrolysers in EU and 40 GW of electrolysers in the Europe's neighbouring countries, with import into the EU. [16]

EU's Solar photovoltaic installed capacity stands at 136 GW in the year 2020, with 18GW installed in the year 2020 itself. According to EU Solar Energy strategy [17], EU targets to achieve Solar Photovoltaic capacity of 320 GW by 2025 and ~600 GW towards the end of this decade. In order to achieve this ambitious goal, capacity addition of nearly 45 GW/per year is needed. This is part of the REPowerEU plan to reduce the dependency on the fossil fuel import from Russia. EU's high dependence on Solar Photovoltaic has brought down the Solar PV price by nearly 82% in the period 2010-2020 [18]. By 2030, EU renewable electricity production should be double from 2020 levels of 32% i.e., 65%+. [16]

In order to compensate for the increased electricity production, increased electrification of the end use sector is needed. Industry, Transport and Buildings constitute the major energy consumers of energy in the end use sector. Commissions Impact assessment shows 36-37% decrease in the final energy use and 39-41% decrease in the primary energy use. [19]

The industry sector which is responsible for 25% of the energy consumption, 50% of the heating and cooling demand is less than 200° C. This is considered as low temperature demand. This demand can be met by replacing fossil fuel technologies with Heat Pump which can deliver this demand. The 50% of the high temperature demand should be met using H2 as fuel. This target has to be met by increasing the renewable energy share in industry by 1.1% every year.[20] Similarly, increasing the share of renewables in heating and cooling by 1.1% every year.[21]

The emission reduction target for the transport sector is set at 90% by 2050. Reduction in 50% CO_2 emission/km for passenger cars (2021-2030) is the intermittent goal for transport sector, with passenger cars CO_2 reduction to be 55% and CO_2 reduction from vans to be 50% by 2030. In order to achieve this target, European Union is estimated to have 30 million electric vehicles on road by 2030 with 3.5 million charging and hydrogen refuelling station available throughout the major transport corridors within EU. This number is estimated to increase to 16.3 million by 2050.[16] [22]

The building sector is responsible for nearly 40% of the final energy consumption and 36% of the GHG emissions related to the energy usage. As part of the revised EED and RED, a minimum of 49% of the energy used in the building should be from renewable energy sources by 2030. The usage of renewable energy for heating and cooling needs should be incremented by 1.1% annually [16] [19]. Similarly, the use of district heating should increment by 2.1% annually in buildings [23][24][25]

To meet the above-mentioned climate neutrality targets of the Green Deal, we need to assess the changes these policies can bring to the energy system. This can be done using Energy system Models.

2.2 Energy System Models

Energy system Models became widely used in early 1970s after the oil crisis, when there was a need to analyse the energy system to forecast the energy supply and demand. The basis of energy system modelling was the interaction between energy and environment, energy and the economics. Eventually, the focus of the energy system modelling shifted to analyse the impact of the energy sector on the environment with the increasing concern towards climate change and Global warming, especially in terms of the GHG emitted from the energy system. [26]

In order to model the interaction of each element in the energy system, a network diagram is designed to clearly describe the Supply chain of the energy System. This network is called as 'Reference Energy System (RES)'. Energy models that analyse the electricity consumption use three main components while modelling: a) Objective function to minimize the cost of the energy system) Decision variables that is decided based on the scenario being modelled, and c) the constraints that restrict the decision variables range. [27]

It is important to understand the decision variable of each of the energy system models, and the constraints input by the modeler to achieve the Green deal targets through energy modeling. The energy models considered for this thesis are modelled according to the Green Deal climate targets.

2.2.1 Types of Energy System Models

The Energy system Models can be classified on the basis of the aim of the modelling. The aim of the energy system model could be assessing the energy and environment interaction, modelling the interaction of the energy sector with the economy, or to make the energy system more efficient, or on the basis of the spatial scale (local, National, international) or the temporal scale (short term or long term).

Based on the above criteria, the energy system models can be classified into the following 4 categories:

- Top-down/Macroeconomic simulation model
- Bottom-up/Optimization model
- Bottom-up/Accounting model
- Hybrid Models (Top down +Bottom up)

The top-down and the bottom-up energy models have the fundamental difference in how it affects the energy sector. While the top-down modelling approach analyses the effect of the price and other economic factors to the energy system, bottom-up energy system is based on having a detailed characterization of the energy technologies in the system. The hybrid models contain both the macroeconomic economic and the detailed technology characterization of the end use sector connected to each other. [27]

The table 1 gives detail description about each type of energy model discussed above and gives their differences on the basis of their Spatial coverage, Temporal coverage, Level of disaggregation, Skill requirement, Ability to incorporate different policies and technology addition.

Table 1 Energy System Models types and characteristics [27]

Criteria	Bottom-up, optimisation	Bottom-up accounting	Top-down, econometric	Hybrid
Geographical coverage	Local to global, but mostly national	National but can be regional	National	National or global
Activity coverage	Energy system, environment, trading	Energy system and environment	Energy system and environment	Energy system, environment and energy trading
Level of disaggregation	High	High	Varied	High
Technology coverage	Extensive	Extensive but usually pre-defined	Variable but normally limited	Extensive but usually pre-defined
Data need	Extensive	Extensive but can work with limited data	High	High to extensive
Skill requirement	Very high	High	Very high	Very high
Capability to analyse price-induced policies	High	Does not exist	High	Normally available
Capability to analyse non-price policies	Good	Very good	Very good	Very good
Rural energy	Possible but normally limited	Possible	Possible but normally limited	Possible but normally limited
New technology addition	Possible	Possible	Difficult	Possible but often limited
Informal sector	Difficult	Possible	Difficult	Possible
Time horizon	Medium to long term	Medium to long term	Short, medium or long term	Medium to long term
Computing requirement	High end requires commercial LP solvers	Not demanding	Econometric software required	Could required commercial software

The following table classifies the Energy System Models commonly used and their type based on the classification discussed above.

Table 2 Classification of commonly used energy system models [27][47]

CRITERIA	ENERGY MODEL
BOTTOM-UP OPTIMIZATION	EFOM, MARKAL, TIMES, LIMES, anyMOD
BOTTOM-UP ACCOUNTING	LEAP
TOP-DOWN SIMULATION	PRIMES, NEWAGE, ISaAR, GENeSYS
HYBRID	POLES, WEM

Among the above-mentioned models, the following models were used in different scenarios to achieve the European Green deal targets.

1. LIMES EU
2. ISAaR
3. GENeSYS and anyMOD
4. TIMES and NEWAGE

LIMES-EU

LIMES-EU stands for “the Long-term Investment Model for the Electricity sector of Europe” [28]. LIMES EU is a linear optimization energy system model, solved in GAMS. The main objective of the model is to minimize the cost of the system based on the exogenously determined electricity demand or policies like Carbon emission constraints, increased penetration of Renewable energy technology into the energy systems. One of the major policy focus of LIMES EU is EU ETS, where the emission mitigation is focussed on energy intensive industries.[28]

The Total system cost is determined by the Equation 1

Equation 1 Objective function of LIMES-EU [28]

$$C^{tot} = \sum_t \left(\Delta t \, e^{-\rho(t-t_0)}\left(C_t^I + C_t^F + C_t^{OM} + C_t^{CO_2}\right)\right) - e^{-\rho(t_{end}-t_0)}V$$

Where C^{tot} is the total system cost which is sum of the following in each time step *t*

C_t^I Capacity Investment Cost,

C_t^F Fuel cost,

C_t^{OM} Operation and Maintenance cost and

$C_t^{CO_2}$ Emission cost due to CO_2.

The factor Δt is the time period between two years that is being modelled. A salvage value V for the capacity remaining towards the end of the time horizon is subtracted. ρ stands for discount rate, which is usually considered as 5% in standard situation.

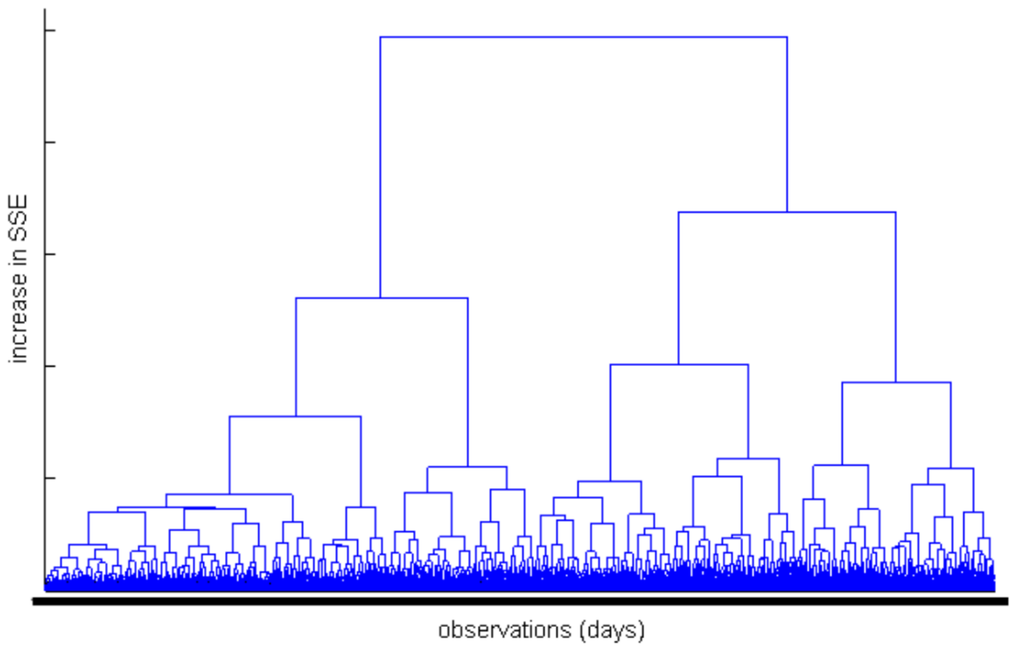

Figure 4 Schematic of the Clustering procedure followed by LIMES EU model, with Observations days in x-axis and Sum of Square Errors in y-axis [28]

The clustering algorithm as shown in the fig.4 is used in choosing the load demand of the vRES (Variable Renewable Energy System) and optimizing it, while accounting for the other load demand [28]

ISAaR

ISAaR is an acronym for "Integriertes Simulationsmodell zur Anlageneinsatz-und Ausbauplanung mit Regionalisierung" [29], which in English would be "Integrated Simulation Model for Plant Deployment and Expansion Planning with Regionalization". ISAaR is a linear optimization energy system model, which accounts for the energy production from the power sector, energy transmission from the power sector to the end use sector, and the energy consumption at the end use sector. Its spatial scope is 28 European countries.[29][30]

The energy consumption at the end use sector-Industry, household, tertiary and transport should be exogenously determined into the model. In the fig.5, ISAaR's system boundary, technological mix and energy carriers are clearly determined.

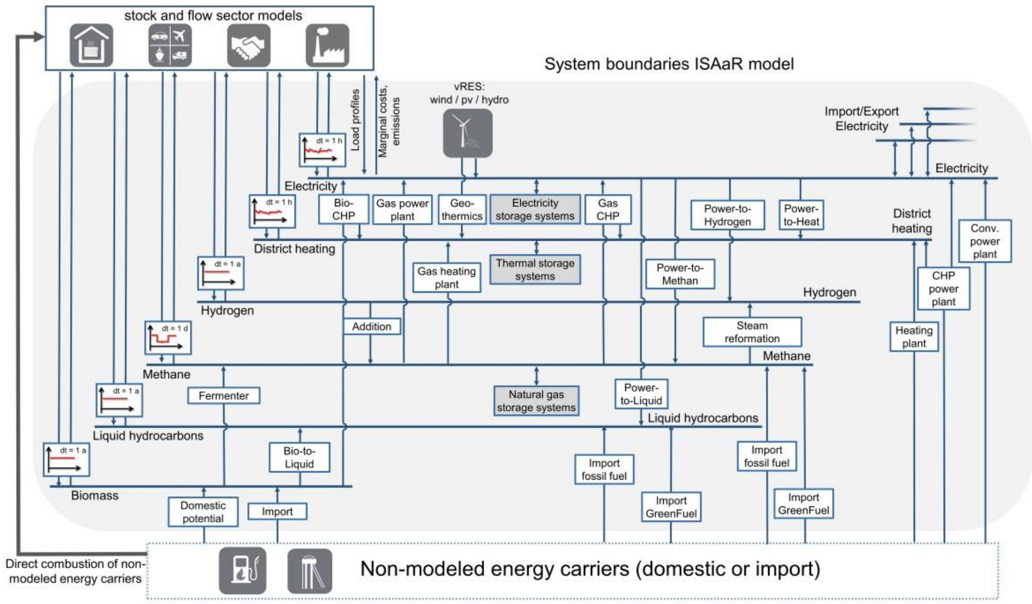

Figure 5 Schematic of the System Boundaries of an ISAaR model [29]

GENeSYS

GENeSYS-MOD is a linear programming energy system model, which works on the principal of achieving a minimal total system cost. In GENeSYS-MOD, the energy demands are exogenously determined, and the model endogenously determines the least cost pathway for the intermittent energy sources along with different storage technologies and investment to improve the transmission capacity. In this model, different emission targets can be set as constraints to achieve a decarbonised energy system in the required time frame. [31]

In the fig. 6 the structure of the GENeSYS model, where different technologies present in the model are shown, and the connection amongst them.

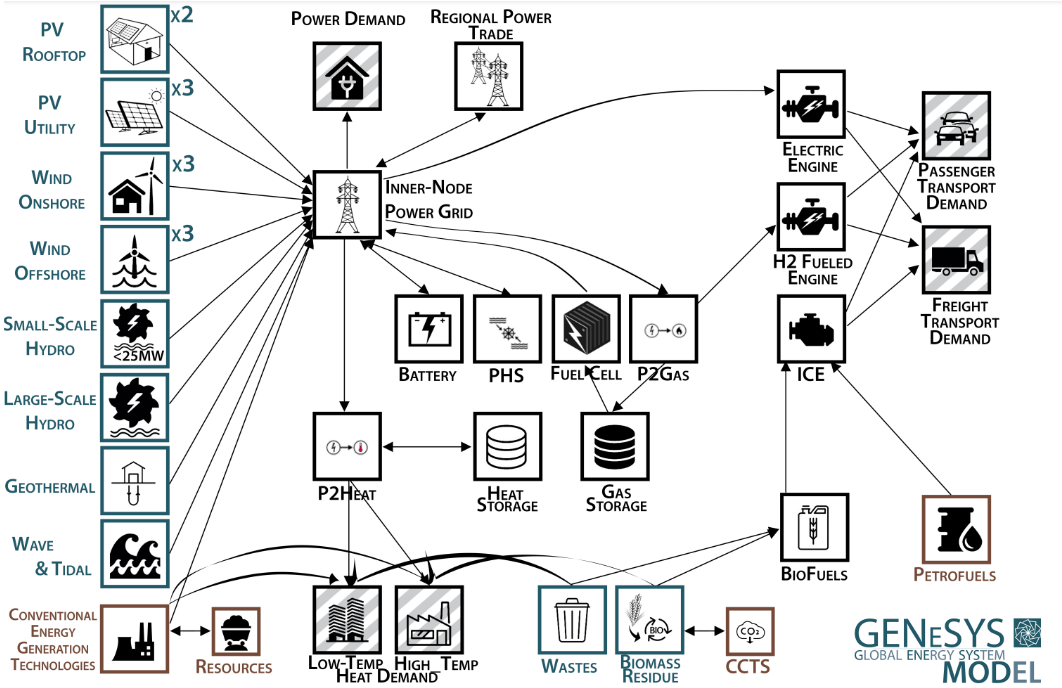

Figure 6 Structure of the GENeSYS energy system model [31]

AnyMOD

AnyMOD (officially known as anyMOD.jl) is a large scale energy system model that is created in a Julia framework. The modelling approach is a linear optimization methodology using JUMP.jl AnyMOD is an energy system model where the temporal and spatial resolution can be varied depending on the energy carrier. This in turn reduces the model size, without the compromising the level of detail with regards to the vRES. The substitution of the energy carriers can be carried out with ease due to its tree like structure where every entity is connected in a seamless manner. It uses a graph-based approach to connect all the elements within the energy system which makes it convenient to introduce intermittent energy sources like wind energy and solar energy. The novel graph-based approach (fig. 7) also allows the modelling of sectoral integration of the system. High levels of intermittent energy sources and sectoral integration are key players in achieving the climate neutrality goals of European Green Deal.[32][33][34]

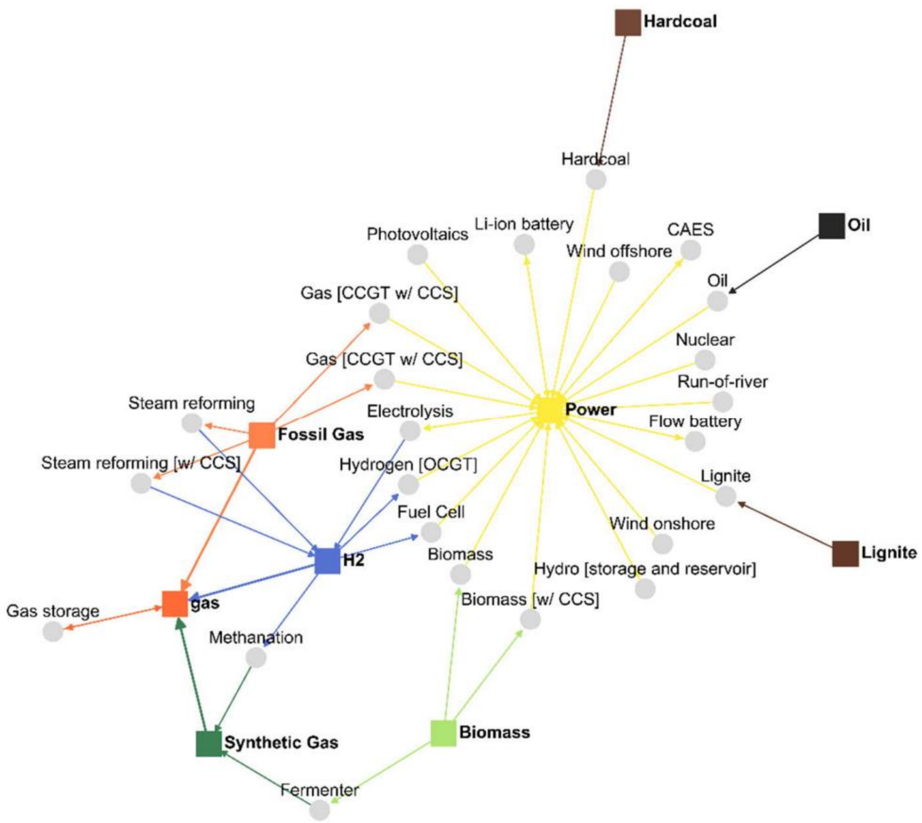

Figure 7 Structure of the energy carriers and technologies in an anyMOD framework [35]

TIMES

TIMES stands for The Integrated MARKAL-EFOM System, is a bottom-up energy system model. It is a technology rich energy system model, which used linear programming to deliver a least cost energy system model. The TIMES model can be used to analyse the end use sectors of all many countries or an individual sector of a particular country as well. The demand is exogenously calculated and input into the TIMES model. [36]

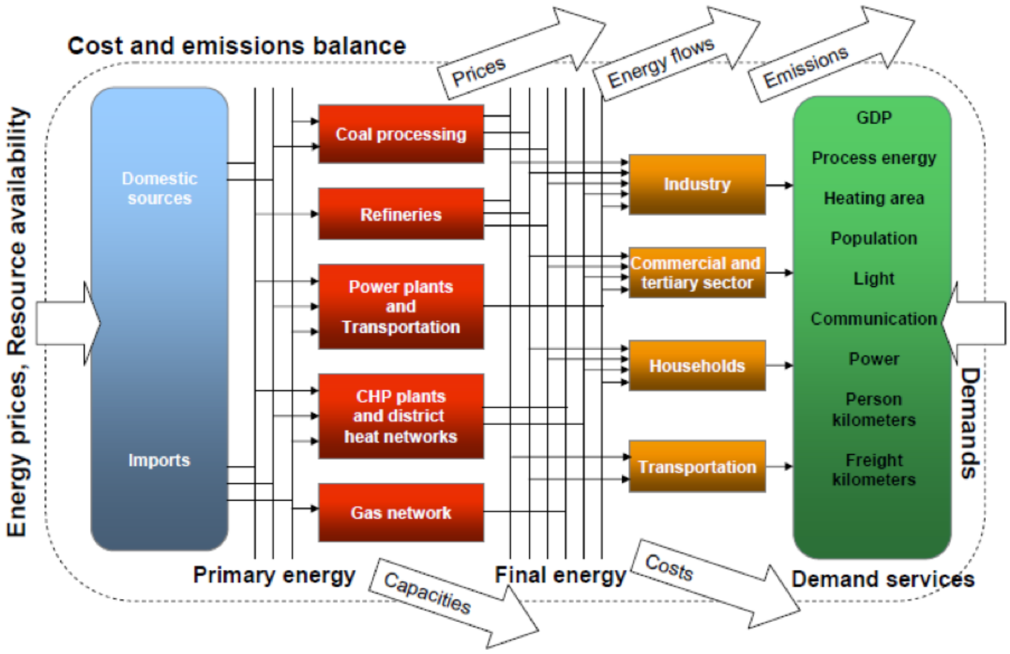

Figure 8 Schematic of TIMES inputs and outputs [37]

NEWAGE

The NEWAGE, "National European Worldwide Applied General Equilibrium" is a general Equilibrium model. The model works on the basis of macroeconomic parameters quantified from the energy and climate policies. The model focusses on implementing these parameters into the Power sector, especially in the electricity production. The model can analyse redistribution of the technologies in the energy system on the basis of the CO_2 pricing exogenously determined.[38] In fig. 9 the structure of the NEWAGE energy system model is shown.

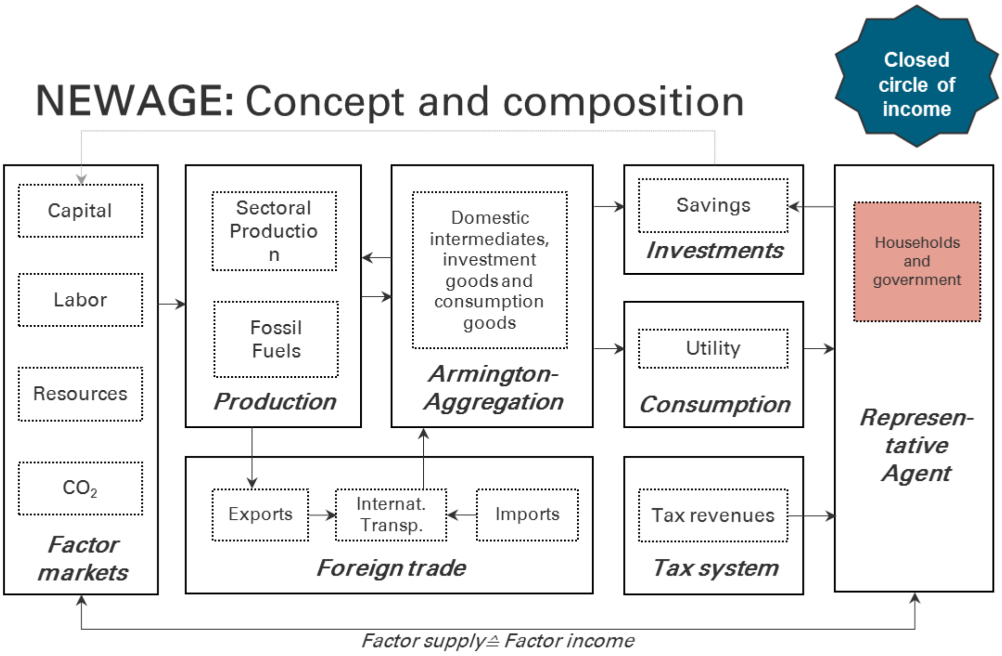

Figure 9 NEWAGE Energy System Model structure [39]

Chapter 3

Analysis

After the launch of European Green Deal in December 2019, many papers published discussing various aspects of the Green Deal. Most of them included policy recommendations to accelerate the transition to Net zero emissions by 2050. Research activities around modelling the European green deal were very few. I have found 4 research activities which involved achieving the 'Fit for 55' targets and the 'European Green Deal' targets using Energy system modelling. In the table 3, Titles of the research activities in which the Energy System Modelling is performed to achieve Green Deal targets. Emphasis is placed on decarbonisation of the Power sector.

Table 3 Overview of the studies carried out on the EGD.

Study	Title	Institution	Year published
Study 1	"Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector" [40]	Potsdam Institute for Climate Impact Research, Potsdam, Germany	2021
Study 2	"Greenhouse Gas Abatement in EUROPE—A Scenario-Based, Bottom-Up Analysis Showing the Effect of Deep Emission Mitigation on the European Energy System" [41]	Ffe Munich	2022

Study 3	"Make the European Green Deal Real – Combining Climate Neutrality and Economic Recovery" [44]	TU Berlin, Coal Exit Research Group, DIW Berlin	2020
Study 4	"How to Reach the New Green Deal Targets: Analysing the Necessary Burden Sharing within the EU Using a Multi-Model Approach" [46]	Institute of Energy Economics and Rational Energy Use (IER), Stuttgart	2021

3.1 "Tightening EU ETS targets in line with European Green Deal" [40]

This paper analyses the impact on the EU power sector with tighter EU ETS targets, and the techno-economic changes that follows.

The study uses the long-term Investment Model for the electricity sector **(LIMES-EU)** discussed in the section 2.2.1. This model was updated so as to include the dynamics of the EU ETS, the emissions involved and also the Marginal Abatement Costs (MAC) for all the sectors accounted in the EU ETS. The model generates the optimized energy generation and transmission capacity based on the emission constraints provided.[28]

The 4 key variations considered in this study are: a) with the increased electrification in the end use sector and the sector coupling, the significant increase in the electricity demand. b) Investment in the expansion of the transmission grid capacity, c) The availability of carbon sequestration or nuclear technologies in the energy system, and d) the emission reduction target to be achieved to achieve the climate neutrality. Based on the calculations by the author, the emission cap was set at 637 Mt CO_2 eq. for energy intensive industries in 2015. Similarly, The EU ETS covers the emissions released due from the sectors providing Heat to the end use sector (district heating). Its emission is fixed at 212 Mt CO_2 eq. in 2015 and increase linearly to 120% in 2050.[40]

The model is characterized by various elements sourced from different studies: Negative emission technologies, technology parameters, cost of fuel, availability factor of the intermittent renewable energy system and the energy storage costs.

The generation and transmission capacities are fixed and carbon price is fixed at 8 €/ton CO_2 in 2015. The ETS price is fixed at 25 €/ton CO_2 in 2020. Emission value in 2019 is roughly estimated to be 750 Mt CO_2 eq. The investment in CCS is very restricted, as the introduction of CCS into the energy system will only slow down the decommissioning of power plants using fossil fuels (for ex. Natural gas).[40]

For the Reference Scenario (REF) the LRF is set at 2.2% and for the Ambitious scenario (AMB) in the current energy model the LRF is calculated to be at 4.26%, in order to achieve the -55% emission target for 2030. The LRF set at 2.2% underachieves the emission target. In order to achieve the -55% target, the EU ETS needs to reduce additional 859 Mt CO_2 eq. by 2030 from previous 2030 emission target. This would increase the LRF from 2.2% to 4.26% from 2021 onwards. [40]

With the tightening of the emission targets in the EU ETS sector, we can notice deep decarbonization achievable in the AMB scenario. In the fig.10 we can notice that with net emissions being negative in 2050 (AMB scenario) the carbon price has more than tripled to €350 /ton CO_2 as compared to 100 €/ton CO_2 in REF scenario. This reduction was achieved mainly due to three factors: a) phasing out of coal usage from 2020 to 2040, b) Reduced Natural gas usage from 2025 and c) Usage of BECCS for negative emission from 2030. As the Carbon price went above €100/ton CO_2 in 2030, the model invested into BECCS to be able to contribute in terms of negative emissions. BECCS was responsible for providing up to 40 Mt CO_2 eq. negative emission in 2050. [40]

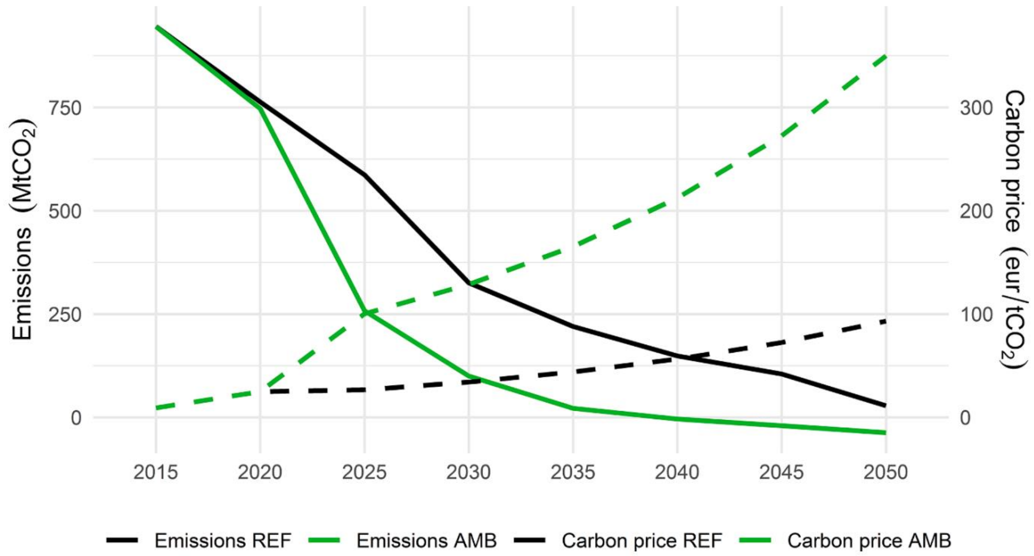

Figure 10 Emissions due to electricity generation [40]

Tightening of the EU ETS targets has fostered rapid phase out of fossil fuels in the power sector. From the fig. 11 we can notice the phase out of coal is very drastic. The phasing out of coal was achieved in 2030 in AMB scenario, while the coal was phased out in 2045 in REF. Natural gas acts as a transitional fuel. As the penetration of vRES increases in the Power sector, Natural gas power plants are used to balance the intermittency in energy production caused due to vRES. Although gas-based generation is considered as transitional fuel, with increase in Carbon price early phase out of Natural gas is noticed in AMB scenario. Natural gas-based generation is <74 TWh in AMB in 2035, while the generation remains above 74 TWh in REF in2045. In 2030, the RES share is 74% in AMB (~10% higher than REF).

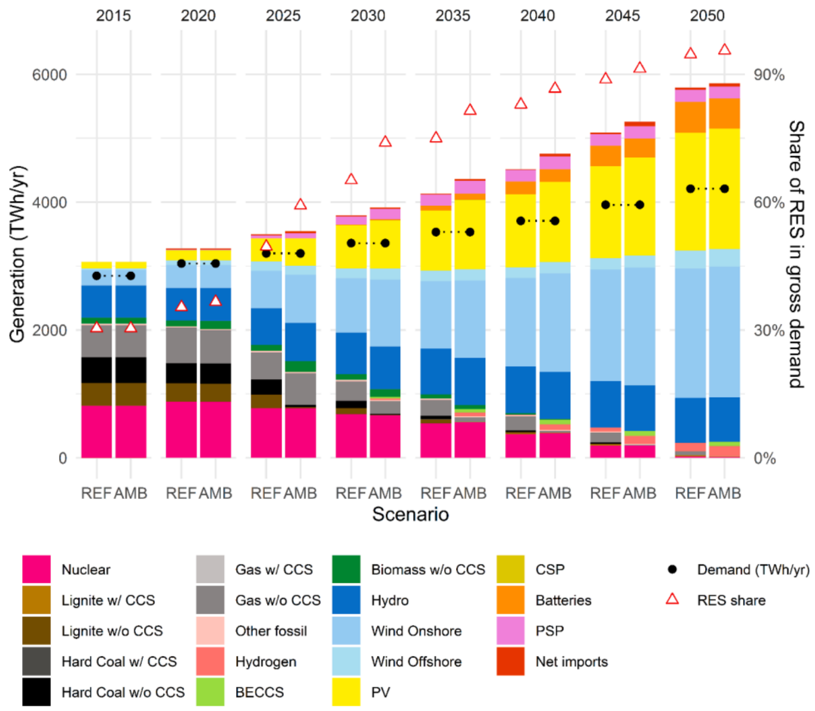

Figure 11 Energy Generation mix in the EU ETS sector [40]

The effect of the new EU ETS target is evident in fig. 12 where the deployment rate of photovoltaics and Wind turbines increased by 2 year and 7 years, respectively. The new deployment rate is 30 GW/year for wind and 50 GW/year for Photovoltaics. Drastic reduction in the energy generation from the Nuclear Power plants can be noticed. The energy generation from Nuclear Power Plants reduced from 880 TWh (2020) to 20 TWh (2050), a 98% reduction over a span of 3 decades. Due to its high cost, the model doesn't prefer to invest in building new Nuclear Power plants.

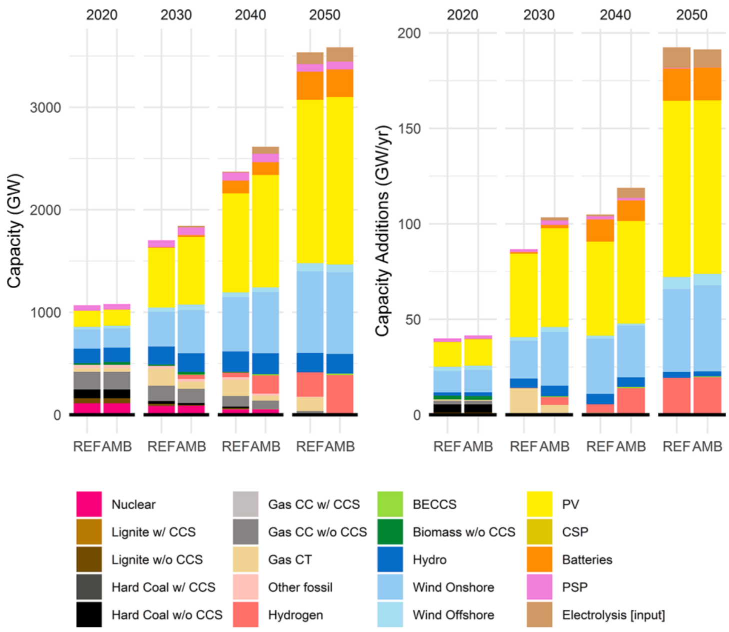

Figure 12 Total capacity (left) and capacity addition (right) from 2020 to 2050 in EU ETS sector [40]

3.2 "Green House Gas abatement in Europe" [41]

The study is focused on exploring the possible pathways to mitigate the Greenhouse gas emission in the European energy sector using the solidEU scenario. [41][42]

The modelling approach is a hybrid type, where four Final Energy Consumption (FEC) models are used to generate the demand from end use sectors and then the demand is input into a multi energy system model. The FEC models for Industry sector, transport sector, Household sector and tertiary sector are used. The FEC demand provided contains high level of spatial resolution and temporal detail. This demand data is fed into the multi-energy system Model 'ISAaR'. As we discussed in section 2.2.1, ISAaR is a linear optimization model which provides us with a least cost energy system. The scenario descriptors are used as constraints, and the description is converted on the basis of a 7-point scale ranging from -3 to 3, where -3 is for strongly restricting and 3 for strongly promoting. [29]

The constraints considered for this modelling approach are based on the 'SolidEU' scenario descriptors shown in fig.13 [42]. Key Constraints and assumptions considered on the basis of the descriptors are:

1. Emission reduction of 95% in 2050 from 1990 levels. Using historical data from EU GHG inventory [43]. This emission cap is set at 288 Mt CO_2 eq for 2050.
2. Emission reduction of 55% in 2030 (compared to 1990 emission levels). The emission cap between 2030 and 2050 is linearly interpolated.
3. Increase in the Net Transmission Capacity (NTC) of the transmission lines by 70% of their thermal capacity from 2030. This assumption is based on EC's proposal to increase the NTC by 75%. The Capacity will increase from 129 GW (2020) to 637 GW (2050)
4. No Nuclear plant expansion is allowed from 2025, and the decommissioning trends for the nuclear plants are extrapolated from the year 2040 to 2050.
5. Import of synthetic fuels into the Europe is encouraged, while the Hydrogen required for the consumption in Europe is produced within Europe itself.
6. Investment in innovative technologies that do not consume fossil fuels and are highly efficient. This is mainly focussed on technologies in the end use sector-transport and building.
7. In the building sector, large scale replacement of the heating and cooling systems with heat pump, increased renovation rate and all of this accompanied with reduced rate of final energy consumption.
8. Change in EU ETS prices as the SolidEU storyline address the new policies in line with the emission reduction targets. This is because the storyline influences the increase in the exchange of heating systems running on fossil fuels and the IC engine vehicles with Heat pumps and zero emission vehicles.

Emission

In the solidEU scenario, the emission target for 2030 in -55% [13], while the emission target for 2050 is set at -95%. From the fig. 13 we can observe that the energy sector's emission is significantly reduced, which amounts to around 620 Mt CO_2 eq. (2020-2030). The main cause for this emission reduction is electricity produced majorly with RES. In transport sector, the emission reduction achieved between 2020 and 2030 in 398 Mt CO_2 eq. This is due to the increased electrification of the transport sector. [42]

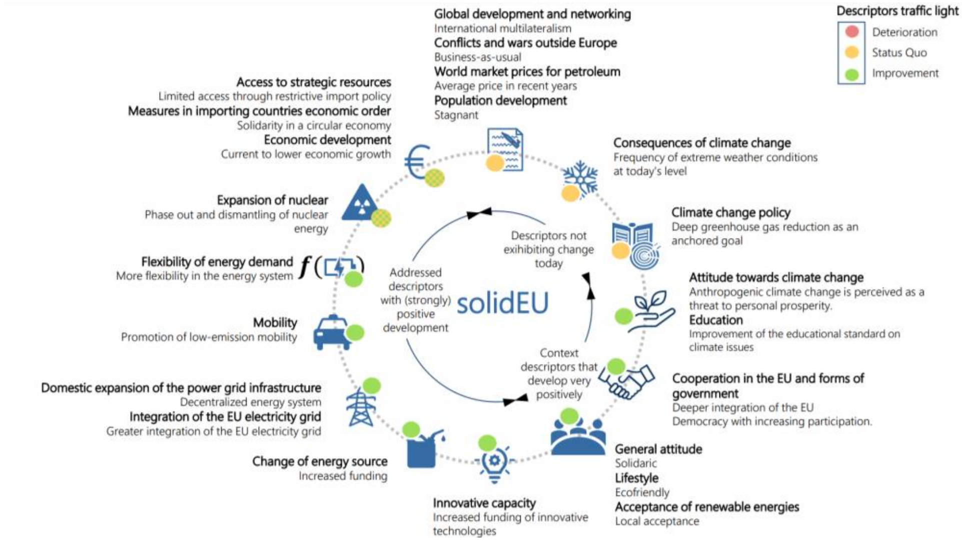

Figure 13 SolidEU scenario descriptors and trends [42]

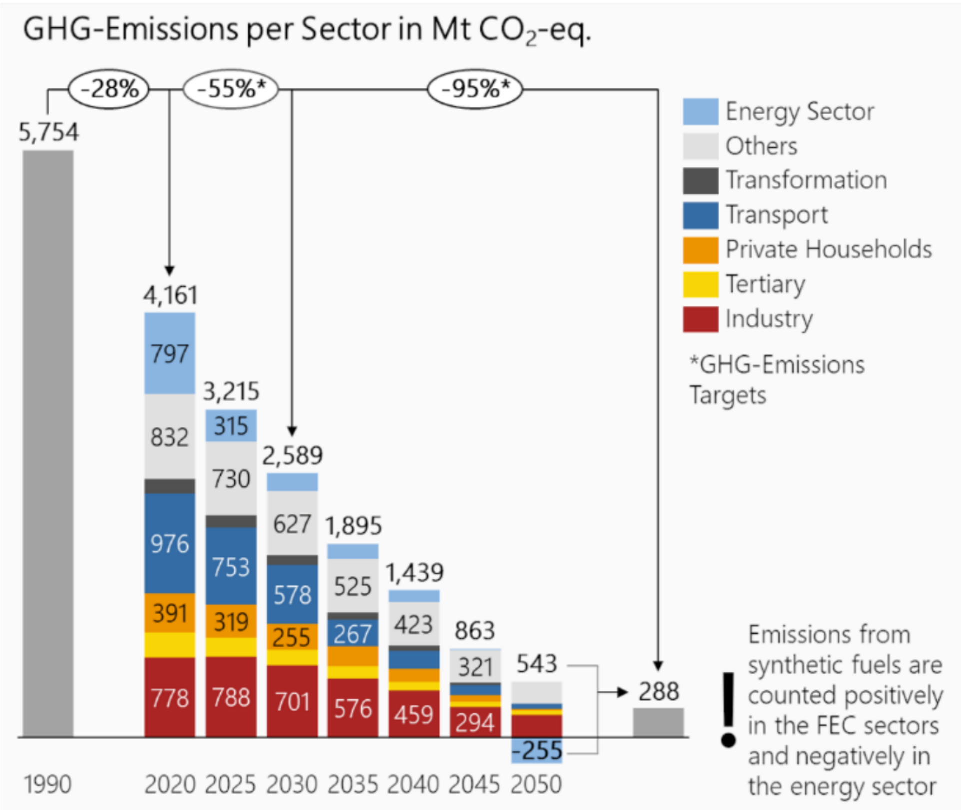

Figure 14 GHG emissions per sector based on the SolidEU descriptors [42]

Energy

The installed RES capacity increases from 417 GW in 2020 to 3154 GW in 2050 (fig.15). With the largest capacity increase in offsite solar system, 49 GW (2020) to 1633 GW (2050) 33 times increase in the installed capacity. The second highest capacity addition was of onshore wind, where the installed capacity increased from 176 GW (2020) to 856 GW (2050). On an average, the annual capacity addition of the vRES technologies until 2050 is 53 GW, 23 GW and 13 GW for PV, onshore wind, and offshore wind respectively.

In the fig. 16, The Final Energy Consumption (FEC) comes down from 13, 200 TWh (2020) to 7800 TWh (2050), a 40% reduction in the energy consumption over the span of three decades. Increased efficiency and rapid electrification of the end use sector technologies are the key drives for this transformation. The electricity consumption in 2050 is ~5000 TWh, an increase of 70% from the 2020 levels.

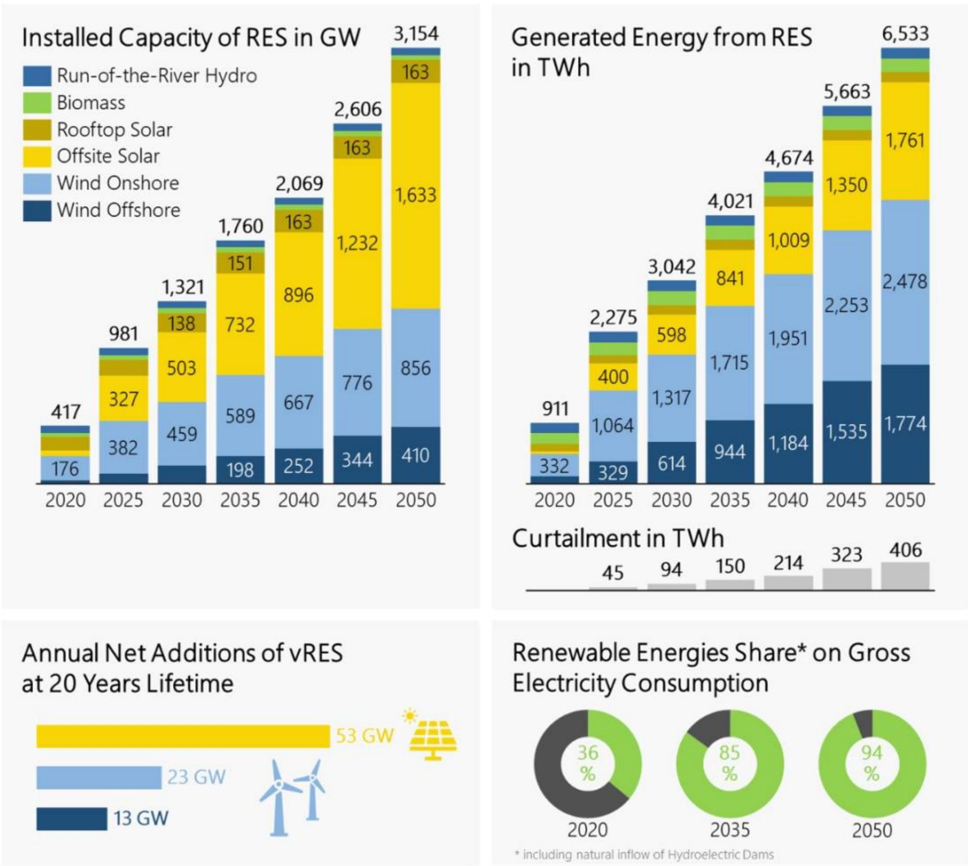

Figure 15 Renewable Energy System overview in solidEU scenario [42]

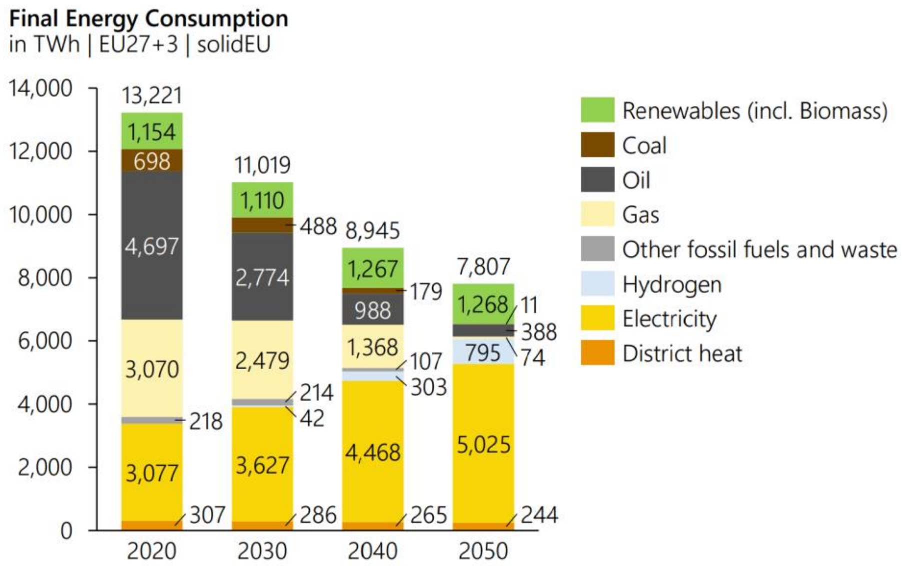

Figure 16 Final Energy Consumption in the end use sector [42]

In fig. 17, we can observe the rise in electricity consumption in the end use sector from 3507 TWh (2020) to 7404 TWh (2050). Rapid electrification of the end use sector is responsible for this increase in electricity consumption. H2 production through electrolysis is also responsible for the increase in electricity consumption. With the PEM electrolysis price falling down to 50% from 2020 to 2050. [42]

H2 production is completely shifted from Steam reforming to electrolysis. H2 production requires high amount of electricity. In 2050, the energy consumed to produce H2 through electrolysis is 1,539 TWh to produce 1,079 TWh of H2. The installed capacity of electrolysers is nearly 45GW and 340 GW in 2030 and 2050, respectively. The shift in H2 production technology from Steam reforming to electrolysis is evident from the fig. 18. In 2050, 73% of the H2 produced is used in the industries, mainly for high temperature heat requirements. The rest of the H2 is consumed in the transport sector in Fuel Cell vehicles.

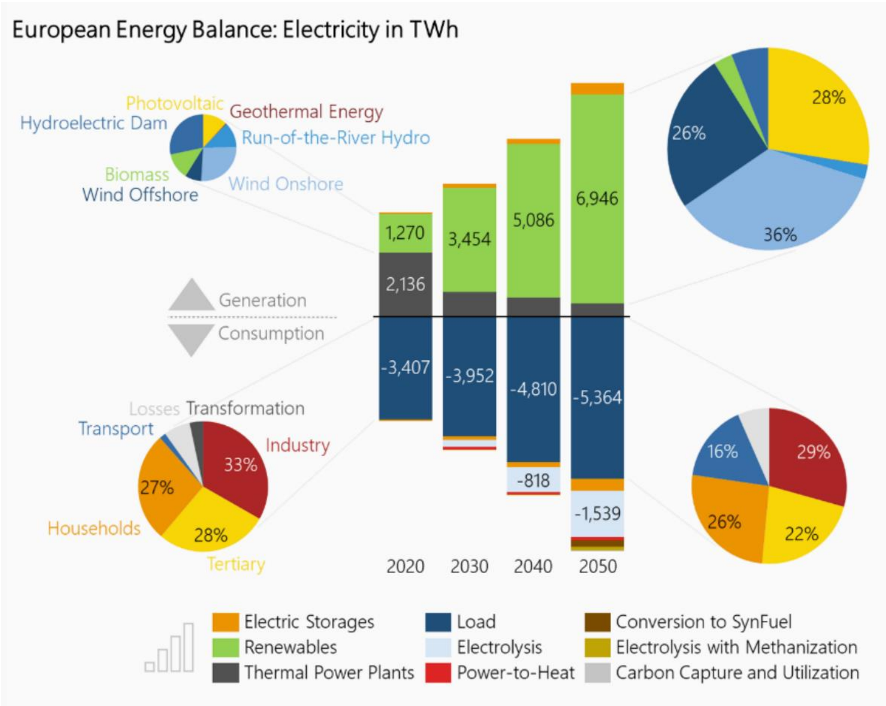

Figure 17 Electricity Production and Consumption between 2020 and 2050 [42]

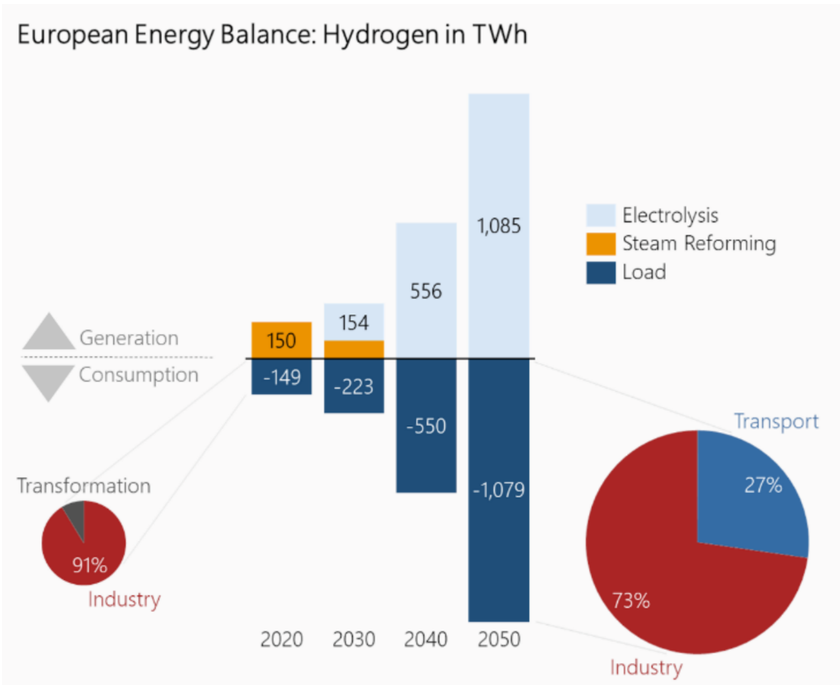

Figure 18 Hydrogen production and consumption between 2020 and 2050 [42]

3.3 "Make the European Green Deal Real" [44]

This study focusses on analysing the pathways to achieving the goals of European Green Deal, especially the agenda to achieve climate neutrality.

The modelling approach (fig. 19) is done by using two types of models, by feeding the output results from one model into another. The models used are **GENESYS** (a top down energy system model) and **anyMOD** (a bottom up energy system model). The GENESYS model generates the cost-effective trajectory after conducting the simulation based on constraints. This trajectory is given for power sector and all the end use sectors-Industry, transport and buildings. Later these results are input into anyMOD model to generate the demand profile for each type of technology in the years determined.

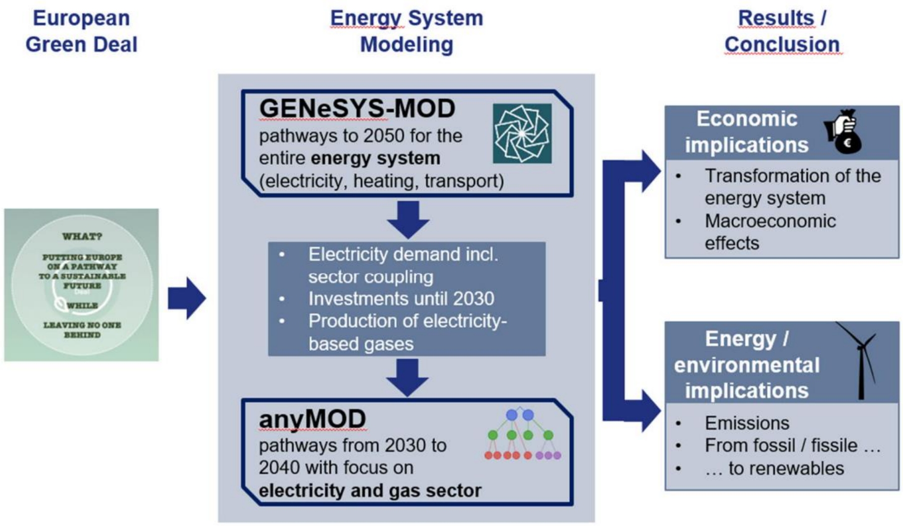

Figure 19 The hybrid modelling approach [44]

The assumptions are based on the 'Societal Commitment' storyline of the open Entrance project [45]. Some of the key assumptions of this story line are the increased participation of the society in switching to a smart life style, with advanced digitalization and circular economy. The communities and policy makers are working together to achieve the climate neutrality. Very High and ambitious carbon pricing has supported the policy push. Significant increase in the electrification of the energy and transport system, with no new disruptive technological novelty to accelerate the transition climate neutrality. Increased investment by the end users in green and energy efficient technologies to reduce the consumption of energy. Heavy Carbon tax is added to the fossil fuels, which maintains its price high although its demand has reduced significantly. [45]. Detailed storyline of this scenario can be found in the appendix.

Emission trends

Significant emission reductions with respect to the emissions in 2015 is noticed in this study. From the fig. 20, with the Power/electricity sector decarbonized faster, zero emission trend is followed by transport, building and industry sector. The net zero emissions in 2040 is achieved without any Carbon capture technology.

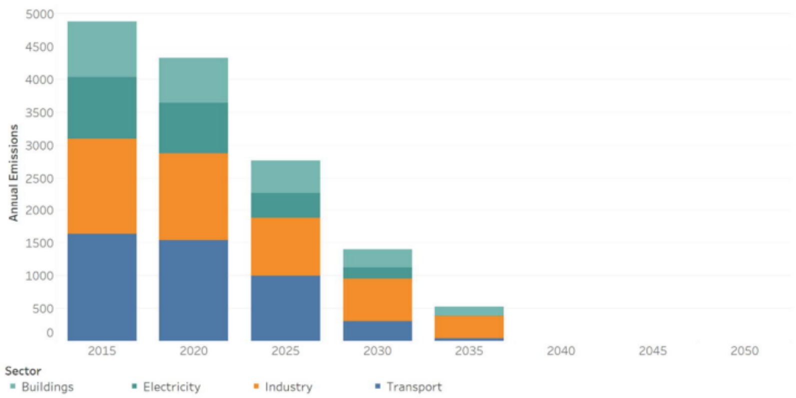

Figure 20 CO_2 emission from the Power sector and the end use sectors (Mt CO_2 eq.) [44]

Energy mix

This scenario is in accordance with the 'societal commitment' scenario of the Openentrance[45], a very ambitious decarbonization scenario. As we can see in the fig. 21 the energy mix is completely decarbonized by 2040, and all the fossil fuels are replaced by an energy mix dominated by renewable energy technologies- wind (offshore and onshore) and photovoltaics. In order to balance this increased electricity production, increased electrification is necessary across all the sectors. Scaling up of H2 production is necessary for 2 reasons: a) to balance the increased production of electricity in the energy system, b) using H2 as fuel where direct electrification is not possible. Increased electrification of the end use sector, also reduces the final energy demand due to the fact that technologies consuming electricity are more efficient than the ones that consume fossil fuels.

In the fig. 22, we can notice the decrease in final energy demand from 80,000 PJ (2015) to 35,000 PJ (2050), a reduction of 56% in energy demand. This is due to the rapid electrification of the end use sector. Increased electrification and sector coupling of the end use sector is important to meet the ambitious climate targets. In the transport sector, the fossil fuel cars are replaced with Electric vehicles, and in the freight transport the share of rail transport is increased from 20% to 40%, with biofuels and H2 playing a key role in its decarbonization. In the building sector, the low temperature heat demand(<200°C) is met with heat pump. In the industry sector, the low temperature heat demand is also met with heat pump, while the high temperature heat demand (>200°C) is met by using H2, biofuels and other synthetic fuels. With increase in vRES in the energy system, significant capacity addition of Storage systems is needed to balance the intermittency of the vRES. In fig. 23, we can observe the share of Storage in providing electricity is ~20% (1000GW) in 2050. The offshore wind capacity is 350 GW and the photovoltaic capacity is ~2500 GW in 2050.

The decarbonization achieved comes with significant macroeconomic effects. While the decarbonization brings in an addition cost of €222billion, the emission savings achieved in 2030 is 15 Gt CO_2 eq., which accounts to closely €1,300 billion of negative externalities cost. The emission savings achieved in 2050 is more than 60 Gt CO_2 eq.

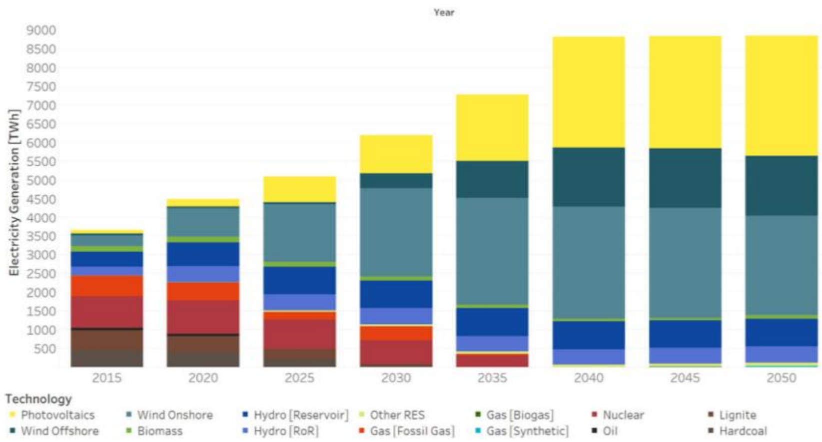

Figure 21 Electricity generation in Europe from 2015 to 2050 [44]

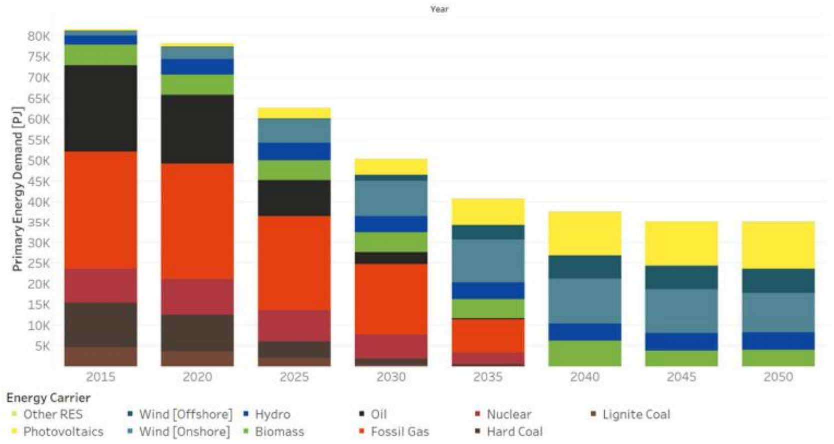

Figure 22 Primary energy demand (2015-2050) [44]

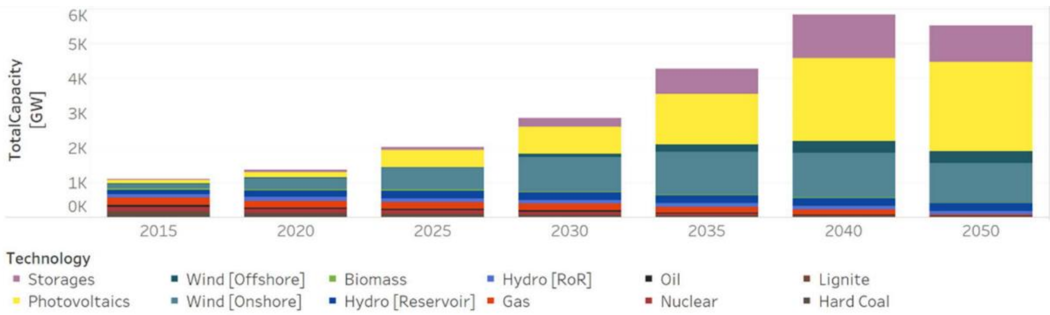

Figure 23 Electricity generation capacity (2015-2050) [44]

3.4 "How to reach the new Green Deal targets" [46]

The paper focusses on addressing the question of which sector contributes to the most in achieving the green deal targets. This is done by comparing three scenarios: one where the share of the ETS sector is more, one where the share of ESR (non-ETS) sector is more and the third one is the optimal scenario

The modelling approach is done by using two models, **TIMES PanEU** and **NEWAGE**. TIMES PanEU is mainly used to study the impact European Green Deal is having on the energy system accounting for the fact that TIMES PanEU consists of high level of technological details. NEWAGE is mainly concerned with analysing the macroeconomic impact with regards to the burden sharing.

For the different ratio of burden sharing, three scenarios which are created on the basis of European Green Deal's climate neutrality targets: a) Optimal (OPT) scenario where the already agreed ratio of ETS and ESR sectors are determined. B) ETS first: Reaching the 100% emission reduction targets with ETS completely decarbonized in 2050. c) ESR more: Achieving the Green Deal emission targets with increased share of ESR in decarbonizing. The below table summarizes the estimated emission reduction of each sector in the year 2030 and 2050 based on the 2005 emission levels.

Table 4 GHG targets in OPT, ETS first and ESR more scenarios [46]

Year	Scenario	ETS Sector	ESR Sector	Overall GHG
2005	Statistics	2360 Mt	2677 Mt	5037 Mt
2030	OPT ETS first ESR more	−43% −77% −58%	−30% −30% −47%	−55%
2050	OPT ETS first ESR more	−43% −100% −58%	−30% −30% −95%	−100%

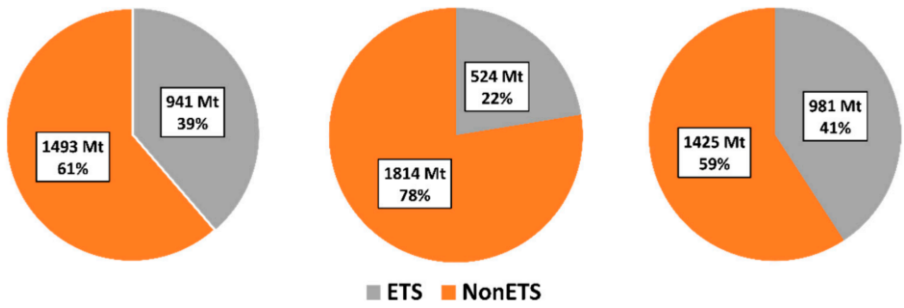

Figure 24 Emission budget share in 2030 for OPT, ETS first and ESR more (from left to right) [46]

Emission

The impact of the emission target depicted in the table 3 and emission budget in fig, 24 can be seen in the fig. 25, where emission reduction in ETS sector in ETS first scenario is ~20% higher than Optimal and ESR more scenario. But the emission reduction in the ESR sector is much lower. There are two main reasons to why the 'ETS first' scenario is not the best scenario on an energy system perspective:

1. The emission reduction from the building sector is cheaper in the Optimal scenario through district heating, but with tighter ETS emission reduction targets the district heating becomes more expensive.

2. With increased ETS targets, the burden on power sector increases to point where the electricity produced is very expensive. This decreases the usage of electricity in the end use sector, leading to lesser electrification of industry, transport and buildings sector.

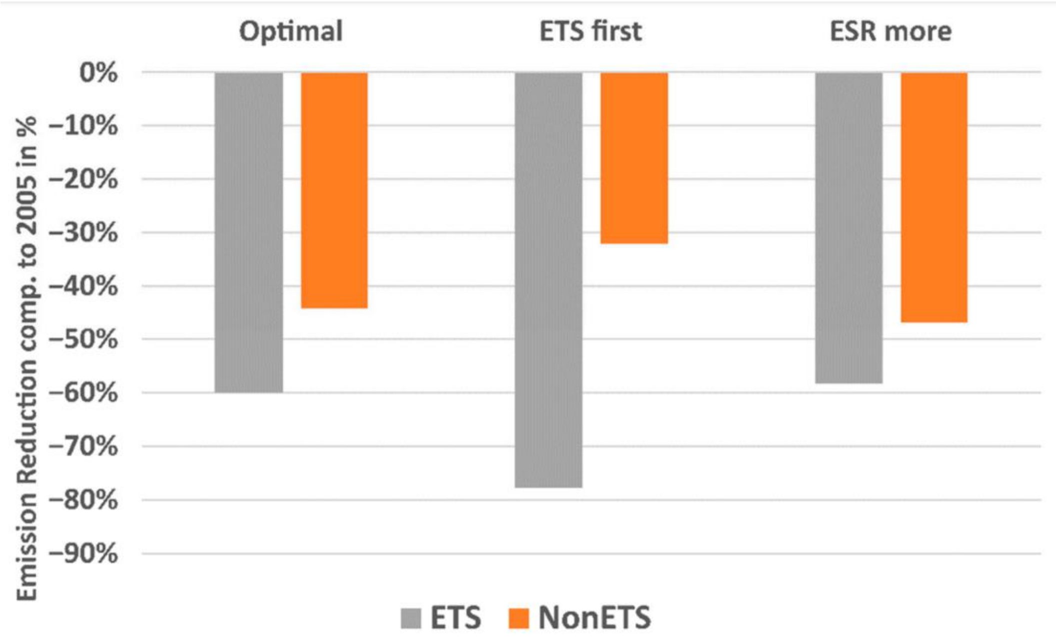

Figure 25 GHG emissions (2030) [46]

Energy Consumption:

With the increase in ETS emission reduction targets, the gas power plants cannot be operated in 2030. The Gas-powered plants were responsible for providing heat to the building sector until 2030, and then replaced by large scale Heat pump. This leads to usage of direct combustion of gas in the buildings, leading to reduced usage of Heat and increased usage of Gas. We can notice a significant reduction in the usage of Heat in building sector from 12% in Optimal scenario to 8% in ETS first scenario.

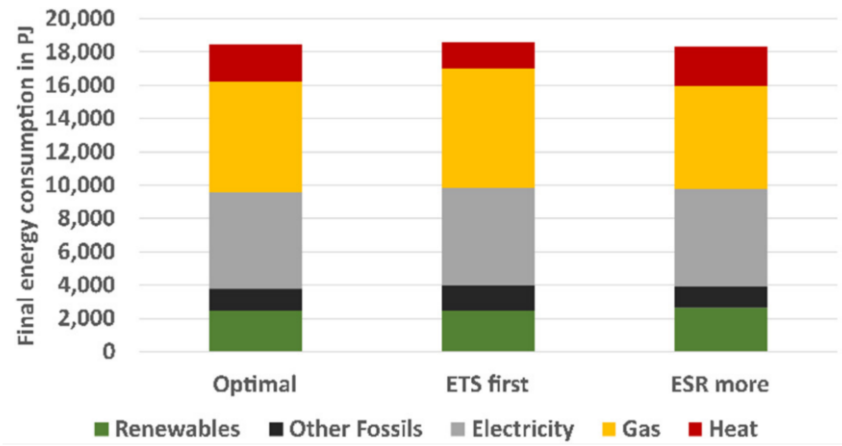

Figure 26 Final energy consumption in Buildings sector (2030) [46]

Similarly, with the increased electricity cost the electric vehicles seems less appealing. In the Optimal scenario, we can observe an early electrification of the transport sector with 33 million battery powered electric vehicles on road by 2030. The electricity share in final energy consumption in the optimal scenario is 15%, but just 11% in ETS first scenario. The 4% difference is met by the fossil fuels in ETS first scenario. This has led to nearly 100 TWh of less electricity consumption in ETS first scenario, compared to ESR more and Optimal scenario. For a cost-efficient reduction of the emissions, ESR sector should play a critical role with emission ratio of 39% to 61% for ETS to ESR.

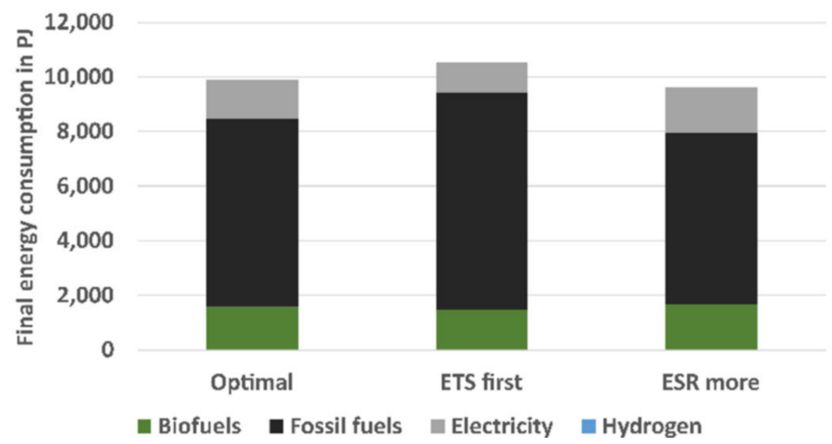

Figure 27 Final energy consumption in Transport sector (2030) [46]

Chapter 4

Results

In the study “Make the European Green deal real”, net zero emission was achieved in 2040. This is way earlier than the targets of European Green Deal. With Electricity sector decarbonized by 2035 due to the increased penetration of Renewable energy systems. The model has been able to achieve the climate goals by having very high carbon prices (€1200/ton CO_2 in 2050) which increased over time. The share of electricity from Renewable energy in 2030 is 82%, which is higher than the EGD target of 65% for 2030. The capacity of offshore wind in 2050 is 350 GW, while EGD target in RED 2 was estimated to be 300 GW. The Solar Photovoltaic generation capacity in 2030 is ~750 GW, while the expected generation capacity is 600 GW in EU Solar Energy strategy which is in line with EGD.

While the Energy Efficiency directive to reduce final energy consumption is 9% in 2030 from 2020 levels, here the model has achieved 35% reduction from 2020 levels.

In the study “Tightening EU ETS targets in line with the European Green Deal”, the author tries to achieve the European Green Deal goals by increasing the EU ETS sector targets from 2.2% to 4.26%. There is a noticeable decrease in carbon emissions, eventually reaching negative emission in 2050. With the decrease in emissions, the carbon price per ton increases up to €350/ton CO_2 in 2050.

There is significant increase in capacity addition in the AMB scenario, as compared to REF scenario. The offshore wind capacity is just 66 GW, while the onshore capacity is 833 GW in 2050. The Photovoltaic capacity in 2030 is ~750 GW, which meets the EU Solar strategy target of 600 GW. The H2 electrolyser capacity is 50GW, higher than the Green Deal target of 40 GW of electrolysers in EU by 2030. The H2 electrolyser capacity is close to 360 GW in 2050. The Nuclear Power capacity is ~62 GW in 2030, and phased out completely by 2050.

Rapid phase out of Coal and increase in the usage of H2 and BECCS has fostered the transformation to a carbon neutral power system by mid-century.

In the study "How to Reach the New Green Deal Targets", the emphasis on finding the perfect balance between ETS and non ETS sector (ESR) to achieve the climate neutrality by 2050 with minimum burden on the member states. It was found that, the emission reduction target for ETS sector should be 58% from 2005 levels and 47% for ESR sector from 2005 levels. The new Green Deal targets for the ETS sector are -61% emission from 2005 levels, and -40% from 2005 levels for ESR sector. The optimal burden sharing between ETS and ESR to achieve the 2030 climate goals is close to the burden sharing proposed by European Green Deal.

In the study, "Greenhouse Gas Abatement in Europe", the share of Renewable energy technology in the Power sector is much higher than the European Green Deal targets. The offshore wind capacity is 410 GW in 2050, while the EGD target is to achieve 300 GW in 2050. Similarly, the Photovoltaic capacity is 1796 GW in 2050, and 640 GW in 2030 while the EU Solar Strategy for 2030 is 600 GW. The Photovoltaic capacity is higher than the ambitious target of 600 GW by the EU Solar strategy. The installed capacity of electrolysers is 45 GW in 2030, achieving the EGD target of 40 GW by 2030. The H2 will only be produced through electrolysis after Steam reforming being phased out after 2030. The reduction in energy consumption from 2020 is 16% in 2030. This reduction is higher than the 9% reduction target by Energy Efficiency directive.

Chapter 5

Conclusion

The purpose of this thesis was to conduct a comparative analysis on the current literature on the implementation of European Green deal into the Energy System, focussing on decarbonizing the Power sector. It was focussed on analysing the constraints and assumptions that were considered in order to achieve the green deal targets.

After choosing 4 different energy system modelling scenarios, and understanding its modelling approach to implement the green deal targets to achieve climate neutrality, the characteristics of the final energy mix was compared with the technology capacity targets of the Green Deal in 2030 and 2050.

The results show that achieving the green deal targets for the power sector is considered possible by as early as 2040 with increased penetration of Renewable energy systems, Storage capacities and high carbon taxes. Since the power sector comes in the EU ETS sector, ambitious ETS targets can foster the transition to a carbon neutral society much earlier than 2050. The LRF of 4.26% brings the net emissions in ETS sector to 0 in 2040, while the carbon price increases to €200/ton CO_2 eq. The carbon price remains in this window due to the presence of Carbon Capture technologies. In scenarios where the Carbon Capture technologies were not present, the Carbon price was as high as €1200/ton CO_2 eq. The Carbon Capture technologies are less preferred while modelling a carbon neutral system, as it slows down the phasing out of Natural Gas from the energy system. This is the reason why CCS technologies appears only towards the mid of the century and not earlier.

When there are no Carbon Capture technologies present, adding high carbon tax (due to the negative externalities caused due to its combustion) to fossil fuels will reduce its usage. This is the case when the society is very much committed to support the transition to a carbon neutral energy system. This support is in terms of sustainable investment into technologies like Heat pump, Renovating the houses. Also, society's attitude to saving energy by using Shared mobility also reduces the final energy consumption significantly. We can notice a significant reduction in the final energy consumption in 2050, but simultaneous increase in the electricity consumption. This is mainly due to electrification of the end use sectors and usage of electricity to produce H_2 through electrolysis.

For all the development mentioned above to happen, the energy system should be able to accommodate more and more vRES in the coming years. This would involve a substantial investment upgrading the Transmission capacities of the European Transmission network.

Further development of this work can be done by having a more detail analysis of the end use sectors through energy system modelling, and the analysis of shifting from Fossil fuel consuming technologies to technologies that run on electricity. This is for the fact that the energy system final energy demand decreases by more than 50% but the electricity demand increase by 100% in 2050 compared to 2020.

References

[1] “Summary for policymakers - IPCC.” [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf. [Accessed: 20-Jun-2022].
[2] “Synthesis report summary for Policymakers Chapter - IPCC.” [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf. [Accessed: 20-Jun-2022].
[3] “Climate change: Vital signs of the planet,” *NASA*. [Online]. Available: https://climate.nasa.gov/. [Accessed: 20-Jun-2022].
[4] “Paris agreement,” *Climate Action*. [Online]. Available: https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en. [Accessed: 20-Jun-2022].
[5] “The Paris Agreement,” *United Nations Climate Change*. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [Accessed: 20-Jun-2022].
[6] “Adoption of the Paris agreement - Paris agreement text English - UNFCCC.” [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf. [Accessed: 20-Jun-2022].
[7] “A European Green Deal,” *European Commission - European Commission*. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. [Accessed: 20-Jun-2022].
[8] EC–European Commission. "Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions–The European Green Deal." Document 52019DC0640 640 (2019).
[9] “Development of EU ETS (2005-2020),” *Climate Action*. [Online]. Available: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en. [Accessed: 20-Jun-2022].
[10] “Energy and the green deal,” *European Commission - European Commission*. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en. [Accessed: 20-Jun-2022].

[11] “The just transition mechanism: Making sure no one is left behind,” *European Commission - European Commission*. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en. [Accessed: 20-Jun-2022].
[12] “The European Green Deal Investment and JTM explained.” [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_24. [Accessed: 20-Jun-2022].
[13] EC–European Commission. " Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality” Document 52021DC0550 (2021).
[14] EC–European Commission. " Proposal for a directive of the European parliament and of the council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757” Document 52021PC0551 (2021).
[15] EC–European Commission. " Proposal for a regulation of the European parliament and of the council amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement” Document 52021PC0555 (2021).
[16] EC–European Commission. " Proposal for a directive of the European parliament and of the council amending Directive (EU) 2018/2001 of the European Parliament and of the Council, Regulation (EU) 2018/1999 of the European Parliament and of the Council and Directive 98/70/EC of the European Parliament and of the Council as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652” Document 52021PC0557 (2021).
[17] EC–European Commission. " Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions EU Solar Energy Strategy” Document 52021DC0221 (2021).
[18] “Renewable power generation costs in 2020 - executive summary.” [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020_Summary.pdf?la=en&hash=A27B0D0EF33A68679066E30E507DEA0FD99D9D48. [Accessed: 20-Jun-2022].
[19] EC–European Commission. " Proposal for a directive of the European parliament and of the council on energy efficiency (recast)” Document 52021PC0558 (2021).

[20] “Leading the clean industrial revolution - European commission.” [Online]. Available: https://ec.europa.eu/commission/presscorner/api/files/attachment/869507/Industry_Factsheet_EN.pdf. [Accessed: 20-Jun-2022].
[21] “Delivering the European Green Deal,” *European Commission*. [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en. [Accessed: 20-Jun-2022].
[22] “Make transport greener - European commission.” [Online]. Available: https://ec.europa.eu/commission/presscorner/api/files/attachment/869687/Transport_Factsheet_EN.pdf.pdf. [Accessed: 20-Jun-2022].
[23] “Making our homes and buildings fit for a greener future - European commission.” [Online]. Available: https://ec.europa.eu/commission/presscorner/api/files/attachment/869476/Buildings_Factsheet_EN_final.pdf.pdf. [Accessed: 20-Jun-2022].
[24] “Renovation wave.” [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en. [Accessed: 20-Jun-2022].
[25] EC–European Commission. " Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives” Document 52020DC0662 (2020).
[26] Bhattacharyya, Subhes C., and Govinda R. Timilsina. "A review of energy system models." *International Journal of Energy Sector Management* (2010).
[27] Hobbs, Benjamin F. "Optimization methods for electric utility resource planning." *European Journal of Operational Research* 83.1 (1995): 1-20.
[28] “Documentation of limes-EU - Potsdam institute for climate impact research.” [Online]. Available: https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/limes/limes-documentation-april-2020. [Accessed: 20-Jun-2022].
[29] “Isaar – integrated simulation model for unit dispatch and expansion with regionalization.” [Online]. Available: https://www.ffe.de/en/tools/isaar/. [Accessed: 02-Jul-2022].
[30] Böing, Felix, and Anika Regett. "Hourly CO_2 emission factors and marginal costs of energy carriers in future multi-energy systems." *Energies* 12.12 (2019): 2260.
[31] Burandt, Thorsten, Konstantin Löffler, and Karlo Hainsch. *GENeSYS-MOD v2. 0-enhancing the global energy system model: Model improvements, framework changes, and European data set*. No. 94. DIW Data Documentation, 2018.
[32] Leonardgoeke, “Leonardgoeke/anymod.jl: Julia framework for energy system models with a focus on multi-period capacity expansion,” *GitHub*.

[Online]. Available: https://github.com/leonardgoeke/AnyMOD.jl. [Accessed: 20-Jun-2022].

[33] Göke, Leonard. "A graph-based formulation for modeling macro-energy systems." *Applied Energy* 301 (2021): 117377.

[34] Göke, Leonard. "AnyMOD. jl: A Julia package for creating energy system models." *SoftwareX* 16 (2021): 100871.

[35] Hainsch, Karlo, et al. *Make the European Green Deal real: Combining climate neutrality and economic recovery*. No. 153. DIW Berlin: Politikberatung kompakt, 2020.

[36] Loulou, Richard, and Maryse Labriet. "ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure." *Computational Management Science* 5.1 (2008): 7-40.

[37] "ETSAP: Times," *IEA*. [Online]. Available: https://iea-etsap.org/index.php/etsap-tools/model-generators/times. [Accessed: 20-Jun-2022].

[38] "Newage," *NEWAGE | IER Institute of Energy Economics and Rational Energy Use | University of Stuttgart*. [Online]. Available: https://www.ier.uni-stuttgart.de/en/research/models/NEWAGE/. [Accessed: 20-Jun-2022].

[39] "Ier präsentation e 10-2016 [Kompatibilitätsmodus] - set-Nav.eu." [Online]. Available: http://www.set-nav.eu/sites/default/files/common_files/events/20160928_Brussels/20161124_Trondheim/T3-Fahl_Hybrid_Modelling_Docu.pdf. [Accessed: 20-Jun-2022].

[40] Pietzcker, Robert C., Sebastian Osorio, and Renato Rodrigues. "Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector." *Applied Energy* 293 (2021): 116914.

[41] Kigle, Stephan, Michael Ebner, and Andrej Guminski. "Greenhouse Gas Abatement in EUROPE—A Scenario-Based, Bottom-Up Analysis Showing the Effect of Deep Emission Mitigation on the European Energy System." *Energies* 15.4 (2022): 1334.

[42] Guminski, Andrej, Claudia Fiedler, and Stephan Kigle. "Modeling kit and scenarios for pathways towards a climate neutral Europe. eXtremOS summary report." (2021).

[43] "National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism" [Online]. Available: https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18. [Accessed: 20-Jun-2022].

[44] Hainsch, Karlo, et al. *Make the European Green Deal real: Combining climate neutrality and economic recovery*. No. 153. DIW Berlin: Politikberatung kompakt, 2020.

[45] Auer, H., et al. "Storylines for low carbon futures of the European energy system." *Deliverable D7* 1 (2019).
[46] Kattelmann, Felix, et al. "How to reach the new Green Deal targets: analysing the necessary burden sharing within the EU using a multi-model approach." *Energies* 14.23 (2021): 7971.
[47] Pandey, Rahul. "Energy policy modelling: agenda for developing countries." *Energy Policy* 30.2 (2002): 97-106.

Appendix

Table 5 openENTRANCE Storyline-Societal Commitment [45]

Storyline features	Societal Commitment
Geopolitics	
General Mood	harmonic geopolitical relationships
Performance of Global Economy/Markets	global economic prosperity
Global/International Climate Policies	coordinated & coherent global climate policies
Markets/Economic Development	
Macro-economic Impact of Energy Transition	
Resource Exploitation	even distribution of resource exploitation (due to recycling chain)
Expected Additional Job Creation	very high
Trade-Offs in Decision Making	
Role of Fossil Fuel Prices	fossil fuel prices increasingly irrelevant, even if low
Role of Carbon Prices	high CO2 Prices trigger technology switch mainly for individuals/communities
Market Actors	
Incumbents versus Entrepreneurs	many new market actors/entrepreneurs on local level
Business Models	completely different compared to the status quo
Circular Economy	
Level of Importance	very important
Net Effect (e.g. Externalities)	not only GHG emission reductions, but also many other externalities
Climate and Energy Policies	
GHG emission reduction targets	approaching minus 80-90% GHG emission reductions (excl. sinks)
Carbon Pricing Ambitions	very ambitious (trading system for all)
Existing/Known Technologies&Services	
Preferable Policy Incentives (if any)	still selective support needed to unlock particular developments
Unlocking Technology Diffusion Barriers	focus on removal of regulatory and administrative barriers
Novel Technologies	
Incentives for Research&Development/Pilots	moderate
Preferable Policy Incentives	market-based instruments (technology-neutral)
Unlocking Technology Diffusion Barriers	focus on removal of regulatory and administrative barriers
Incentivizing Demand Side Participation	very high
Technology Portfolio in Energy & Transport	
Role of Existing/Known Technologies	urgently needed due to limited novel technologies as alternatives
Candidates (Production, Complementary)	RES, PtX, gas, nuc, storage, smart grids, EV
Potential/Competitiveness in Energy Transition	candidates deliver in electricity dominated system with significant lower demand
Advantages/Disadvantanges	incentive to adjust demand & lifestyle / lack of diversification
Role of Novel Technologies	limited applications only
Candidates	floating offshore wind, H2
Potential/Competitiveness in Energy Transition	large-scale electricity production (floating offs. wind) and transport sector (H2)
Advantages/Disadvantanges	contribution to more balanced diversification / no commercial large-scale roll out
Role/Potential/Support of Digitalization	very important
Society's Attitude & Liefestyle	
Life Style	sustainable, cautious, self-disciplined, prudent
Level of Commitment and Cooperation	very high
Willingness to Pay / Invest	very high
Willingness to Unlock Demand Side Flexibilities	very high
Contributions to Circular Economy	very high
Energy Sectors (Electricity, Heat/Cooling, Gas/Fossils)	
Resources	both existing/known resources/raw materials + new ones (need dependent)
Capital (Market-driven, Venture, Private, ...)	market-driven, venture capital, private (high Willingness to Pay/Invest)
Infrastructure/Technologies	
Production/Generation (incl. Complementary)	RES, floating offshore wind (limited), PtX, gas, nuc, energy storage, H2 (limited)
Transmission/Distribution	smart electricity grids, smart gas/H2 grids, local heat grids
Energy Service Delivery	noval smart onsite/local energy managment governed by digitalization
Sub-Sectors (Structure, Demand)	
Industry	very high ambition for demand reduction & fuel switching (partly RES-based H2, PtX)
Commerical/Tertiary	very high ambition for demand reduction & fuel switching (RES, PtX)
Private/Buildings	very high ambition for demand reduction & RES fuel switching (RES, PtX)
Transport Sector in Detail	
Mobility Patterns	multi-modal transport, mainly sharing, public transport, autonomous driving
Capital (Market-driven, Venture, Private, ...)	market-driven, venture capital, private (high Willingness to Pay/Invest)
Infrastructure/Technologies	
Production/Resources	low production quantities/resources due to established sharing/public transport
Supply Chain	combination of global allocation/purchases and local circular/recycling economy
Mobility Service Delivery	low demand on individual mobility services and corresponding infrastructure
Sub-Sectors (Structure, Demand)	
Aviation	electric (short distance), hybrid (long distance)
Fright	electric (light duty vehicles), hybrid/partly RES-based H2 (heavy duty vehicles)
Public Transport	electric, partly RES-based H2
Maritime	electric (light duty vehicles), hybrid/partly RES-based H2 (heavy duty vehicles)
Individuals/Private	electric

Table 5 describes the parameters considered in the 'Societal Commitment' storyline, which is characterised by increased participation of the society in achieving a carbon-neutral society. This storyline involves a change in society's attitude towards energy consumption and choice of technology. This behavioural change will reduce energy consumption, and the willingness to invest in green technology will reduce carbon emissions. The societal commitment storyline is dependent on society's attitude toward having a carbon-free and smart lifestyle in coordination with the public sector. This storyline includes geopolitics, markets and economic development, climate and energy policies, technology portfolio, and society's attitude.