GENeSYS-MOD TÜRKİYE: QUANTITATIVE SCENARIOS FOR LOW CARBON FUTURES OF THE TURKISH MACRO ENERGY SYSTEM

by

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To my beloved father, mother and brother…

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ABSTRACT

GENeSYS-MOD TÜRKİYE: QUANTITATIVE SCENARIOS FOR LOW CARBON FUTURES OF THE TURKISH MACRO ENERGY SYSTEM

Global energy consumption is increasing constantly. Countries are most affected economically and environmentally by these changes. A change in the supply-demand balance in the energy sector may result in an increase or decrease in the price of energy and investments made in the energy sector to meet the rising demand are economic effects. Additionally, the sustainability of energy systems is getting more significant as a result of these environmental effects of chosen energy sources. As a result of the changes, energy system models are widely used to create strategic energy policies, environmental goals, and technical advancements. The first oil crisis that occurred in 1973 is defined by excessive price increase and insufficient petroleum supply on the global market. As a result of the crisis, there is an increase in interest in energy supply that is based on multiple sources, energy efficiency, and energy conservation. Consequently, a significant increase in the quantity and complexity of energy system models used for analyzing the change is observed.

The purpose of this thesis is to better provide insights and evaluate how the Turkish energy sector will change over time, as well as to provide the country with the necessary policy decisions based on realistic, meaningful, and reliable findings. In this context, the quantitative scenarios for low-carbon futures of the Turkish energy system are analyzed at aggregated (country level) and regionally disaggregated (NUTS-1 level) levels. Four different scenarios are used for the future of Turkish energy system. They are quantified and implemented for the Turkish energy system using the open-source, "bottom-up" structure global energy system model, GENeSYS-MOD v3.0. All scenario results at both levels are compared. Disaggregating ensures more investment in photovoltaic technologies, more hydrogen generation and usage by 2050 and integration of electricity and hydrogen storage systems as early as 2025. The insights for the Turkish energy system are improved with the disaggregated model results. The major reason for these differences is the better estimation of regional renewable capacity factors (wind and solar) in the disaggregated level compared to aggregated level.

ÖZET

GENeSYS-MOD TÜRKİYE: TÜRKİYE MAKRO ENERJİ SİSTEMİNİN DÜŞÜK KARBONLU GELECEĞİ İÇİN NİCEL SENARYOLAR

Enerji talebindeki sürekli artışın olduğu küresel bir ortamda ülkeler bu değişikliklerden en çok ekonomik ve çevresel olarak etkilenmektedir. Değişen enerji arz-talep dengesinden kaynaklı olarak enerji fiyatlarında artış ya da azalış göstermesi ve artan talebin karşılanması için enerji sektörüne yapılan yatırımlar ekonomik etkilerdir. Bunların yanı sıra tercih edilen enerji kaynaklarının çevreye etkilerinden dolayı son zamanlarda enerji sistemlerinin sürdürülebilirliği önem kazanmıştır. Yaşanan değişimler dolayısıyla stratejik enerji politikaları, çevresel hedefler ve teknolojik yenilikler geliştirmek için enerji sistem modelleri kullanılmaktadır. 1973 yılında gerçekleşen ilk petrol krizi dünya petrol piyasasındaki arz yetersizliği ve fiyatlardaki fazla artışın olduğu dönemdir. Bu dönem sonrasında enerji arzının çeşitli kaynaklara dayalı olması, enerji verimliliği ve tasarrufu konularına olan ilgi artmıştır. Böylece değişimin incelenmesi amacıyla kullanılan enerji sistemi modellerin sayısında ve karmaşıklığında hızlı bir artış gözlemlenmiştir.

Bu tezin amacı, Türkiye'nin enerji sektörünün zaman içinde değişimini daha iyi anlamak, analiz edebilmek ve sonuçta elde edilen gerçekçi, anlamlı ve güvenilir sonuçlar ile ülke için gerekli politika kararlarının verilmesini sağlamaktır. Bu bağlamda, Türkiye enerji sistemi düşük karbonlu geleceğine ilişkin nicel senaryoları toplu (ülke düzeyinde) ve bölgesel olarak ayrıştırılmış (NUTS-1 düzeyi) düzeylerde incelenmiştir. Geleceğin Türkiye enerji sistemi için dört farklı olay örgüsü kullanılmıştır. Açık kaynaklı, “bottom-up” yapıda kurulmuş küresel enerji sistemi modeli GENeSYS-MOD v3.0 Türkiye enerji sistemi için nicelleştirilmiş ve uygulanmıştır. İki düzeyde tüm senaryoların sonuçları karşılaştırılmıştır. Ayrıştırma, 2050 yılına kadar fotovoltaik teknolojilerine daha fazla yatırım yapılmasını, daha fazla hidrojen üretimi ve kullanımını ve 2025 gibi erken bir tarihte elektrik ve hidrojen depolama sistemlerinin entegrasyonunu sağlar. Bölgesel olarak ayrıştırılmış model sonuçlarıyla Türkiye enerji sistemine ilişkin içgörüler iyileştirilmiştir. Bulunan farklılıkların ana nedeni bölgesel yenilenebilir kapasite faktörlerinin (rüzgar ve güneş) ayrıştırılmış düzeyde, toplu düzeye kıyasla daha iyi tahmin edilmesidir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

BEV	Battery electric vehicle
CO_2	Carbon-dioxide
°C	Degree celsius
CCS	Carbon capture and storage
DT	Directed transition
EU	European union
GD	Gradual development
GENeSYS-MOD	Global energy system model
GHG	Greenhouse gas
gpkm	giga passenger-kilometers
gtkm	giga tonne-kilometers
GW	Gigawatt
GWh	Gigawatt hours
IAM	Integrated assessment model
ICE	Internal combustion engine
NUTS	The nomenclature of territorial units for statistics
OCGT	Open cycle gas turbine
OSeMOSYS	Open Source Energy Modelling System
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule
PV	Photovoltaic
RES	Renewable energy sources
SC	Societal commitment
TF	Techno friendly
TWh	Terawatt hours

1. INTRODUCTION

Energy is crucial for the country's economic growth, external dependency, competitiveness, and sustainability. Currently, many factors contribute to an increase in energy consumption, including the development of the economy, industry, transportation sectors and growth in the population. The dependence of countries on the supply of energy increases as energy demand increases. A reliable and secure energy supply is crucial for nations. For this reason, the concepts of sustainability, energy efficiency and reliability must be used to guide energy policy and infrastructure investments.

Modern societies depend on their energy systems to provide for the supply, distribution, and usage of energy. Its significance is growing as it enables the efficient and continuous operation of many economic activities including industrial production, trade, transportation, agriculture and service industry. Interest in the sustainability of energy systems is increasing recently as a result of the necessity of dealing with global warming mainly caused by the constant rise in energy demand. Sustainability of the energy system is critical for preventing climate change, accelerating the energy transition and ensuring sufficient energy for future generations.

Currently, great emphasis is placed on achieving consistent and coherent methodologies and quantitative scenario results at different levels of spatial granularity when generating decarbonization scenarios of the European energy system. The spatial system bounds of the presentation of the scenario outcomes for Türkiye in this study are gradually narrowed starting with the pan-European system boundary corresponding with the European appropriate CO_2 content for the 1.5/2.0°C maximum global temperature increases targets. In practice, breaking down aggregate modeling findings to ever-smaller spatial system boundaries is essential to establishing the energy strategy. Also, this resolves the ongoing complaint that too aggregated modeling findings are frequently abstract and useless for real-world decision-making. The related CO_2 pricing, which establishes the financial viability boundaries for the various technology portfolios, must also be carefully considered in order to generate robust scenario findings. Particularly in the analysis of the decarbonization of regional or local energy systems, the significance of the role of the CO_2 price is frequently overlooked or not properly represented. In the process of substituting fossil fuels, this significantly distorts the preferred energy technologies or technology portfolios.

Since around 1953, national, regional, and international energy planning is implemented with energy policy modeling. In order to inform policymakers, national-scale energy models (also known as macro energy systems) often simulate the dynamics and relationships of a country's energy demand and supply. A significant amount of literature on energy modeling is produced as a result of methodological variations and improvements over place and time. According to the analytical approach, energy models can be divided into two, "top-down" and "bottom-up" [1].

For the transformation of the energy sector, Türkiye is taking many types of initiatives and developing policies. Some of these initiatives include making investments in renewable energy sources, projects, and incentives to improve energy efficiency and use local resources. However, because energy systems are so complicated, these actions should be decided after applying the energy system model and considering the findings of the model. Depending on the potentials of renewable energy sources and the domestic energy demands, Türkiye can become a substantial net exporter of energy for the rest of the European area.

In this thesis, using the open-source and bottom-up "Global Energy System Model (GENeSYS-MOD)", the Turkish energy system's low-carbon futures are analyzed. GENeSYS-MOD is a full-fledged macro energy system model. This model is also well documented and published in several scientific publications [2–6]. For the analysis, four quantitative scenarios focusing on various conditions in the European and Turkish energy system of the future are used. The implementation of the four scenarios in GENeSYS-MOD is completed by selecting four pathways from recent studies or ongoing work with the MESSAGEix-GLOBIOM (IAM) [7]. MESSAGEix is a global systems engineering optimization model used for long-term and medium-term energy system planning. The four pathways (i.e., scenarios) developed in openENTRANCE project [8] are described in detail in Chapter 3.3. Briefly, "directed transition" (DT) scenario has a strong incentive-based policy push whereas the "societal commitment" (SC) scenario is characterized by a sustainable society willing to act. On the other hand, the "techno friendly" (TF) scenario focuses on breakthroughs of novel technologies and general technological improvements. Finally, the "gradual development" (GD) scenario is a combination of aspects of all other three scenarios. One of the primary differences between these four scenarios is the carbon prices and their respective developments. By using all quantitative scenarios, GENeSYS-MOD results are compared at the aggregated (country level) and regionally disaggregated levels (NUTS-1 level) of Türkiye. Aggregated results have been already published in [8], which reflects the quantitative consideration of the corresponding scenarios described in [9]. These consistent and coherent input/output scenario datasets at pan-European level build the foundation of further scenario building exercises at regional levels for Türkiye.

1.1. OBJECTIVE OF THE THESIS

In this thesis, the quantified scenario results for low-carbon futures of the Turkish energy system at aggregated (national, i.e., NUTS-0) and regionally disaggregated (regional, i.e., NUTS-1) levels are introduced. It is aimed to obtain more precise results by dividing Türkiye into 12 sub-regions according to the NUTS-1 level. In this context, the main objectives of this study are to ensure that more investments are made in cost efficient and suitable technologies, that more renewable energy is used and produced, and that renewable energy technologies and storage technologies become widespread for each region in the Turkish energy system. Because aggregated modeling results are frequently abstract and less worthy for real-world decision making, they need to be divided into ever-smaller system boundaries. With the obtained disaggregated modeling results, it is possible to develop a realistic energy strategy.

1.2. OUTLINE OF THE THESIS

In Chapter 2, a literature review on the Turkish energy system is introduced. In Chapter 3, the GENeSYS-MOD, scenarios and disaggregation process are introduced. In Chapter 4, model results and comparative analyses of the GENeSYS-MOD at the aggregated and disaggregated level are presented. Finally, in chapter 5, the outcomes of this thesis are summarized and future research directions are provided.

2. LITERATURE REVIEW

Energy policy modeling has been a frequently applied tool in global, national and regional energy planning since the early 1970s. Energy models at the national scale (i.e., macro-energy systems) typically mimic the dynamics and relationships of a nation's energy demand and supply to provide guidance for policy makers. These dynamics and relations are often influenced by many external parameters. The methodological diversities and developments over the past four decades have generated a wide literature on energy modeling.

The demand for energy in Türkiye is increasing every year. A large amount of investment is needed to ensure the energy transition and meet the demand. The correct evaluation of this investment amount is important to achieve the targeted results in the long term. In this direction, many studies were carried out in order to better understand and analyze Türkiye's energy sector, determining the policy options that support the energy transition, making short and long-term plans for the realization of these options and also to predict how the energy sector will develop in the future.

A systematic literature review of energy systems can be found in [11]. The focus of this thesis is analyzing the energy system of Türkiye. In the articles for Türkiye that are published so far, energy system modeling is not applied. Auto-regression [12], forecasting [13–17] and machine learning techniques [18] are all used in publications for the assessment of the consumption of energy. Additionally, there are theses that analyze the findings of current energy system models [19–21] and develop new energy system models [22,23].

Beeck [1] evaluated the classification methods available in the literature and presented nine approaches for energy system modeling. One of these approaches is the analytical approach. Accordingly, energy modeling methodologies are classified as “top-down” or “bottom-up” as the two main approaches. Top-down energy models consider the entire economy and evaluate the general impact of policies related to energy and/or climate change. There are not many technical components in these models. On the other hand, bottom-up models enable an extensive assessment and possible future technological advancements in the energy sector. In summary, while "top-down" models use an economic approach and aggregated data, "bottom-up" models use an engineering approach and disaggregated data.

Another study aims to determine the real cost of electricity generation by adding external costs based on the scenarios created within the scope of strategies to achieve national CO_2 emission reduction targets and to show the effects of these scenarios on the electricity price [19]. Scenarios are divided into ordinary and ideal. The ordinary scenarios consider the capacity factor and assume that there will be no change in capacity, while the ideal scenario assumes that the capacity may change by opening a new plant or closing the existing plants. Electricity generation optimization was made using the Answer-TIMES modeling approach with a bottom-up structure. Based on 2015 reference year, the amount of electricity to be produced until 2035 has been optimized. Changes in the total cost and CO_2 emissions are analyzed based on different scenarios. As a result of these examinations, it is evaluated that the most cost-effective way of sustainability is to use renewable energy resources and that CO_2 emissions can only be reduced by using these sources. It has been concluded that the external cost should be considered for sustainability and the CO_2 emission target can be achieved by including the external costs.

Yılmazer [20] apply the “MARKAL” modeling system, which is a long-term energy supply-demand balance modeling system, and the “MARKAL-TURKEY” model to better understand and analyze the energy sector. In this study, the “MARKAL-TURKEY” model is remodeled and expanded. Using this model, a reference scenario and other scenarios are analyzed in terms of total costs and effectiveness in emission reduction. Türkiye’s energy system with reality is prepared and 30 alternative scenarios are derived. Results for cost, fuel consumption and CO_2 emissions of each scenario are presented. CO_2 emission reduction policies, carbon capture and storage (CCS) technologies and nuclear power generation are key issues addressed in the scenario analysis conducted. For example, scenarios with an increase in fuel prices have high costs. This is due to Türkiye's high dependence on imported energy.

Another study [21] is based on the current framework of the MARKAL-TURKEY model with a bottom-up structure. In addition, the number of industrial types is increased, and the technological details of the industrial sector are expanded. Using this model, a reference scenario and other scenarios are analyzed in terms of total costs and efficiency of CO_2 emission reduction. Other scenarios are created with the CO_2 emissions or applying a tax per ton of emitted CO_2. Scenarios that reduce CO_2 emissions by raising taxes often yield better unit CO_2 reduction costs than scenarios that directly limit CO_2 emissions. It has been concluded that reducing CO_2 emissions to a certain extent does not bring high costs. This thesis provides that the unit CO_2 reduction costs of the scenarios that reduce CO_2 emissions through taxes are lower than the scenarios that directly limit CO_2 emissions.

The Boğaziçi University Energy Modeling System (BUEMS) model is proposed by Işık [22]. It is aimed to reach meaningful and reliable results by including mechanisms and relations that will realistically represent the Turkish energy sector with a model that has a large-scale energy-economy-environment modeling system. Scenarios are analyzed to provide how the Turkish energy system behaves under alternative policy options that will reduce emissions until 2052. These scenario analyses are Business as Usual (BAU), Carbon Emission Tax, and Carbon Emission Bound.

Karalı [23] develops and analyzes a novel large-scale bottom-up optimization model. The Macro Module and the Bottom-Up Module are the two parts of the modeling framework. The Bottom-Up module covers the entire energy system, from the demand side to the energy supply side. The Macro module, on the other hand, establishes a feedback mechanism between the energy sector and the demand for energy from all of the economy's sectors and sub-sectors. In this approach, the price of energy is connected with the GDP, total production, consumption, and investments, as well as several other important economic variables. These two modules can work independently because each provides a different purpose. By comparing the results of the baseline scenario with the results obtained by MARKAL using the same data set and scenarios, the new modeling platform is validated.

In [24] energy system with five scenarios (namely, base, the low demand, the domestic resource, the carbon cost and the balanced policies), are analyzed for the period between 2020-2030. Unlike the previous studies, in the balanced policies scenario, a holistic approach is followed by supporting the carbon cost scenario with the domestic resource scenario. Each scenario has different advantages and disadvantages. For example, in the carbon cost scenario, while the average carbon intensity is reduced thanks to the carbon cost, a large increase in the cost of imported fuel is expected as the tendency to use other fuels increases. To alleviate these major disadvantages in the balanced policies scenario, the carbon cost scenario is supported by the domestic resource scenario.

The optimal power capacity development for the years 2020–2030 is modeled and examined in the study done by SHURA [24] under five scenarios. By identifying Türkiye's power generation capacity as the optimal point, it is hoped to contribute to long-term energy system planning in Türkiye. This is the first study on Türkiye's energy production capacity. According to the findings of the investigation, each scenario offers distinct advantages and disadvantages. Under the carbon cost scenario, for instance, while the average carbon intensity reduces as a result of the carbon cost, a significant increase in the price of imported fuel is predicted as the tendency to use other fuels rises. The carbon cost scenario is supported by the domestic resource scenario in order to reduce these significant disadvantages in the case of balanced policies. According to the findings of all scenarios, it has been determined that renewable energy sources will be the production technology that will produce the most growth in meaning. Additionally, it is defined that adopting a holistic approach, in which various targets are evaluated together, will be advantageous rather than handling energy targets one at a time and attempting to implement them, will be beneficial.

In TEO (Turkey Energy Outlook) prepared by IICEC (Istanbul International Centre for Energy and Climate), an energy model is created with a comprehensive, holistic and bottom-up approach and two scenario analyses are carried out until 2040 [25]. The first scenario is the reference scenario in which the existing policies are assumed to continue and there are long-term, difficult, and unmet targets. The second scenario, the alternative scenario, is cost-effective and includes additional policy options. In both scenarios, an increase in renewable energy and an increase in efficiency in energy production consumption and conversion are observed towards 2040. Thanks to the stronger policy targets it contains, this change occurred faster and at a higher rate in the alternative scenario. When both scenarios are analyzed, they recommend 10 policies and it is stated that after 2040, Türkiye can meet its energy needs and become an exporter instead of an importer of technologies and energy.

All studies on Türkiye focus on the entire national system, but various regional factors, such as capacity factors and regional demand, are not considered. In the study for Norway, the dataset is divided into five Norwegian bidding regions to provide a more detailed understanding of the Norwegian energy system at the regional level [26]. This thesis contributes to the discussion by analyzing the results at the aggregated and regionally disaggregated levels of Türkiye obtained using the GENeSYS-MOD energy system model with high level of sectoral, temporal and spatial detail. The settings for this study are based on the disaggregation method used in Norway. The aggregate modeling results from this study are divided into progressively smaller spatial system boundaries as a response to the findings that the results of aggregate modeling are frequently abstract, useless, and insufficient for actual policy decisions.

Our focus in this thesis is to provide insights and analyze the changes in Türkiye's energy sector and to make necessary policy decisions for the country with realistic, meaningful and reliable results. In this thesis, we present both aggregated and disaggregated level results for Turkish energy system.

3. GLOBAL ENERGY SYSTEM MODEL

The Open Source Energy Modeling System (OSeMOSYS) [27] is expanded in the Global Energy System Model (GENeSYS-MOD) by the addition of new functionalities including storage and transportation [2]. For instance, existing technologies included in OSeMOSYS are updated and a new function is added to increase the share of cost-effective renewable energy sources. By using this model, it is aimed to meet the region's energy demand and provide a secure energy supply at the lowest system cost by considering certain limits and increasing interrelationships within sectors, such as heating, and power. As a result, low-cost alternatives for safe energy sources are obtained without exceeding the parameters of energy demands, available capacity and CO_2 emission constraints.

Figure 3.1 shows a general view of the different technologies and their connections. Energy generating technologies and energy conversion technologies are the two categories of technology examples shown with nodes. Examples of production technology include wind, solar, and geothermal energy, whereas conversion technologies include heat pumps and storage. Energy carriers such as electricity or fossil fuels, as well as more abstract elements such as energy carrier needs or land areas, are the connecting factors between technologies. Technologies may have multiple fuel inputs or multiple fuel outputs. Fuels can be used or transformed through technologies. For each region and year, three primary energy demands—electricity, heating, and transportation—are given as parameters. By applying demand constraints, the model aims to ensure that this demand is satisfied in a cost-effective way. The project ‘Open ENergy TRansition ANalyses for a low-carbon Economy’ – openENTRANCE develops an open, transparent and integrated modelling platform for assessing low-carbon transition pathways [8]. The platform will gather a suite of state-of-the-art modelling tools and data for covering the multiple dimensions of a green and clean energy transition.

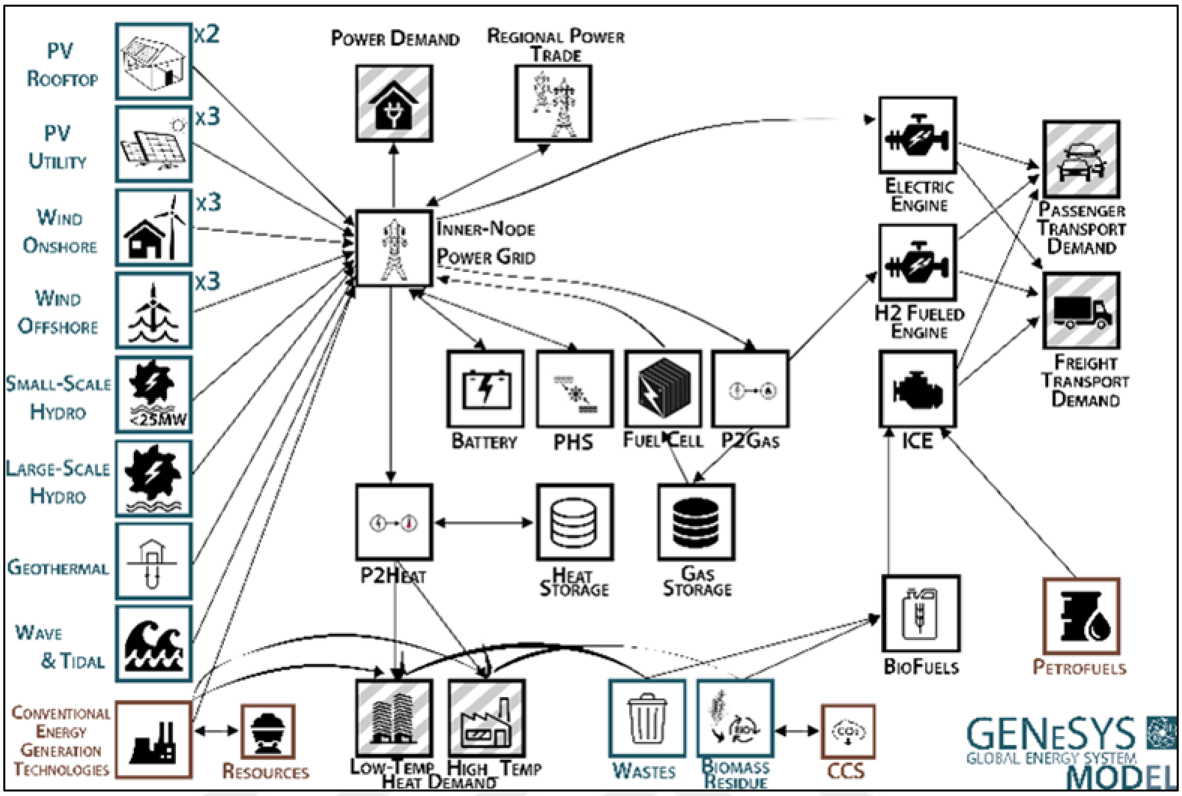

Figure 3.1. Model structure and available technology options for GENeSYS-MOD [4]

GENeSYS-MOD is a linear model with a focus on sector coupling and time-dependent cost minimization of the entire system. Various data points are used as inputs to the model. On the left side of the Figure 3.2, there are inputs. The model structure is in the center, while the outputs are on the right. For instance, demand time series data points are one of the model's common inputs. the amount of mobility required at certain times. Another key component in renewable potentials is to include how many gw of installed capacity can be deployed in a specific region. Additionally, biomass availability plays a significant impact. Additionally, weather information is crucial, particularly as we investigate highly renewable energy sources, which implies that a lot of weather data is actually required. Additionally, that is fed into the model. Because the model is always started in a base year with the pre-existing system and that is then optimized for the future, the capacity in the base year is required to understand where the model is starting from. Additionally, political targets must be included. for instance, the deadline for phase-out of fossil fuels, renewable energy goals, and CO_2 emission limits. The last important data point is about fuel prices. Cost data is crucial to the computation and the outcomes because it is a cost-optimizing model.

The model optimizes different sectors of the energy system. Typically, the sectors electricity, heat in both building and industry and transportation are considered. After that, heat and transportation are divided into additional categories. Applications for industrial and building heat are classified as low temperature, medium temperature, and high temperature. Transportation demand is divided into passenger and freight transport. On the supply side, various technologies are taken into consideration. So, in addition to conventional energy sources such as fossil fuels or nuclear power, there are also renewable energy sources. All of them result in various fuels. Then either directly or indirectly they get into demand of any sector. There is a significant level of sector coupling. Demand changes can be seen on both the primary energy side and the final energy side of sectoral demands. Additionally, there are time series for technological investments, renewable energy production, the phase-out of fossil fuels at specific points in time, and ultimately, CO_2 emissions as an output.

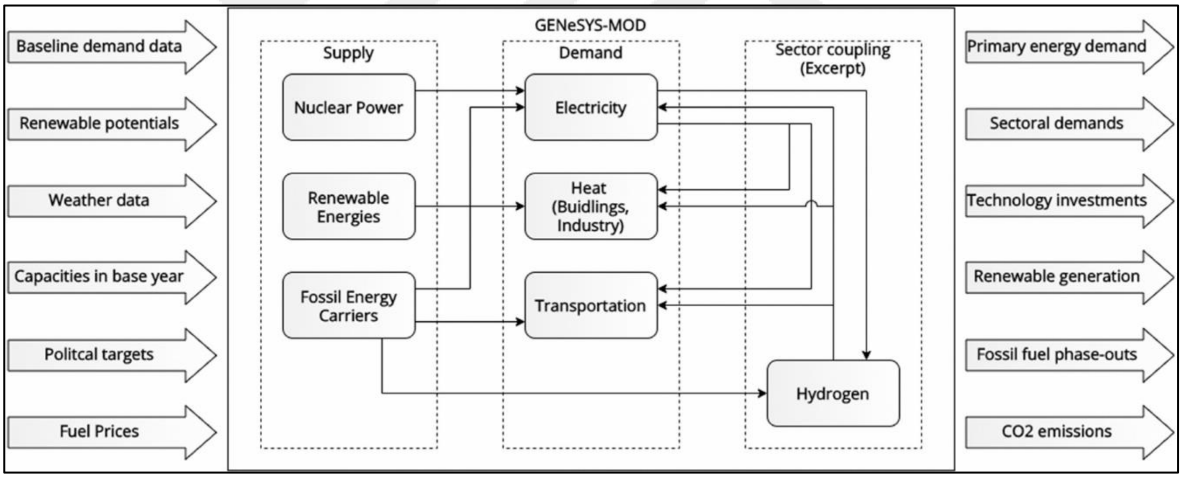

Figure 3.2. Simplified structure of GENeSYS-MOD

3.1. MATHEMATICAL MODEL OF GENeSYS-MOD

This section describes the mathematical model used in GENeSYS-MOD [28].

Sets:

$Daylytimebracket(lh)$	set of splits a single day into brackets day/night
$Daytype(ld)$	set of days weekday/weekend
$Emissions(e)$	set of emissions produced by the different technologies

$Fuel(f)$	set of energy carriers
$Modaltype(mt)$	set of the modal split in the transportation sector
$Mode\ Of\ Operation(m)$	set of input-output combinations for different modes
$Region(r)$	set of regions
$Season(ls)$	set of yearly seasons (e.g., summer/winter)
$Storage(s)$	set of storage technologies
$Technology(t)$	set of technologies that processes energy in any form
$Timeslice(l)$	set of combination of ls, ld and lh
$Year(y)$	set of modeled years

Parameters:

$AccumulatedAnnualDemand_{f,r,y}$: Amount of demand that can be satisfied at any time of the year, not time-slice dependent.

$CapacityToActivityUnit$: Conversion factor of capacities [GW] into activity [PJ]. Assumes provision of 1 [GW] over one year.

$Conversionls_{l,lh}$: Assigns DailyTimeBracket to time-slice.

$Conversionls_{l,ld}$: Assigns DayType to time-slice.

$Conversionls_{l,ls}$: Assigns Season to time-slice.

$ModalSplitByFuelAndModalType_{f,mt,r,y}$: Assigns the share of a mean of transportation for one demand fuel

$TagTechnologyToModalType_{mt,t}$: Links technology production by mode of operation to model type

$TechnologyFromStorage_{m,r,s,t}$: Technologies that can use a fuel from a storage.

$TechnologyToStorage_{m,r,s,t}$: Technologies that can provide a fuel for a storage.

$TradeCapacity_{y,Power,r,rr}$: Upper limit of the power trade for each time slice

$TradeCosts_{f,r,rr}$: Variable costs for trading a fuel between regions.

$TradeLossBetweenRegions_{y,f,r,rr}$: Percentage loss of traded fuel from one region to another. Used to model losses in power transmission networks

$TradeRoute_{f,r,rr,y}$: Tags possible trade routes between regions.

$YearSplit_{l,y}$: Share of a time-slice in one year.

Decision variables:

$DemandSplitByModalType_{f,mt,r,y}$: Assigns the share of a mean of transportation for one demand fuel

$DiscountedCapitalInvestment_{r,t,y}$: Cost of building new capacities of technologies Maintaining. Investment in new capacity of technology t, discounted through the parameter DiscountRate.

$DiscountedOperatingCost_{r,t,y}$: Cost of maintaining capacities or using them. Annual OperatingCost of technology t, discounted through the parameter DiscountRate.

$DiscountedSalvageValue_{r,t,y}$: The salvage value of technologies that have exceeded their operational life or being replaced. Salvage value of technology t, discounted through the parameter DiscountRate.

$DiscountedTechnologyEmissionsPenalty_{r,t,y}$: Annual cost of emissions by technology t, discounted through the DiscountRate

$Export_{y,l,Power,r,rr}$: Exported fuel from region r to region rr in timeslice l

$Import_{y,l,Power,r,rr}$: Imported fuel from region rr to region r in timeslice l

$NetTrade_{y,l,f,r}$: Difference between export and import from region r to region rr in timeslice l

$ProductionSplitByModalType_{f,mt,r,y}$ *:* Share of production of fuel f in region r and year y that will be provided by modaltype mt.

$RateOfActivity_{l,m,r,t,y}$: Intermediate variable. It represents the activity of technology t in one mode of operation and in time slice l, if the latter lasted the whole year. | Energy (per year)

$RateOfProductionByTechnology_{f,l,r,t,y}$: Sum of the RateOfProductionByTechnologyByMode over the modes of operation.

$RateOfStorageCharge_{ld,lh,ls,r,s,y}$: Intermediate variable. It represents the commodity that would be charged to the storage facility s in one time slice if the latter lasted the whole year. It is a function of the RateOfActivity and the parameter TechnologyToStorage. | Energy (per year)

$RateOfStorageDisharge_{ld,lh,ls,r,s,y}$: Intermediate variable. It represents the commodity that would be discharged from storage facility s in one time slice if the latter lasted the whole year. It is a function of the RateOfActivity and the parameter TechnologyFromStorage.

$TotalDiscountedCost_{r,t,y}$: Sum of the TotalDiscountedCostByTechnology over all the technologies

$TotalDiscountedTradeCosts_{r,y}$: Discounted costs for trading fuel f from regions r to rr

$TotalTradeCosts_{l,r,y}$: Undiscounted costs for trading fuel f from regions r to rr in time slice l

$$\text{Min} \quad \sum_{r}\sum_{t}\sum_{y} TotalDiscountedCost_{r,t,y} + \sum_{r}\sum_{y} TotalDiscountedTradeCosts_{r,y} \tag{3.1}$$

$$\text{s.t.} \quad \begin{aligned} &TotalDiscountedCost_{r,t,y} \\ &= DiscountedOperatingCost_{r,t,y} \\ &+ DiscountedCapitalInvestment_{r,t,y} \\ &+ DiscountedTechnologyEmissionsPenalty_{r,t,y} \\ &- DiscountedSalvageValue_{r,t,y} \end{aligned} \quad ,\forall\, r,t,y \tag{3.2}$$

$$\begin{aligned} &\sum_{l}\sum_{m}\sum_{t}(RateOfActivity_{l,m,r,t,y} \\ &\quad \cdot TechnologyFromStorage_{m,r,s,t} \\ &\quad \cdot Conversionls_{l,ls} \cdot Conversionld_{l,ld} \\ &\quad \cdot Conversionlh_{l,lh}) \\ &\quad = RateOfStorageDischarge_{ld,lh,ls,r,s,y} \end{aligned} \quad ,\forall\, ld,lh,ls,r,s,y \tag{3.3}$$

$$\begin{aligned} &\sum_{l}\sum_{m}\sum_{t}(RateOfActivity_{l,m,r,t,y} \\ &\quad \cdot TechnologyToStorage_{m,r,s,t} \\ &\quad \cdot Conversionls_{l,ls} \cdot Conversionld_{l,ld} \\ &\quad \cdot Conversionlh_{l,lh}) \\ &\quad = RateOfStorageCharge_{ld,lh,ls,r,s,y} \end{aligned} \quad ,\forall\, ld,lh,ls,r,s,y \tag{3.4}$$

$$\begin{aligned} &AccumulatedAnnualDemand_{f,r,y} \\ &\cdot ModalSplitByFuelAndModalType_{f,mt,r,y} \\ &= DemandSplitByModalType_{f,mt,r,y} \end{aligned} \quad ,\forall\, f,mt,r,y \tag{3.5}$$

$$\sum_{t}(TagTechnologyToModalType_{mt,t} \cdot \sum_{l}(RateOfProductionByTechnology_{f,l,r,t,y} \cdot YearSplit_{l,y})) = ProductionSplitByModalType_{f,mt,r,y} \quad ,\forall f,mt,r,y \tag{3.6}$$

$$ProductionSplitByModalType_{f,mt,r,y} \geq DemandSplitByModalType_{f,mt,r,y} \quad ,\forall f,mt,r,y \tag{3.7}$$

$$\sum_{f}\sum_{rr}(Import_{f,l,r,rr,y} \cdot TradeRoute_{f,r,rr,y} \cdot TradeCosts_{f,r,rr}) = TotalTradeCosts_{l,r,y} \quad ,\forall l,r,y \tag{3.8}$$

$$\sum_{rr}(Export_{y,l,f,r,rr} \cdot \left(1 + TradeLossBetweenRegions_{y,f,r,rr}\right) - Import_{y,l,f,r,rr}) = NetTrade_{y,l,f,r} \quad ,\forall y,l,f,r \tag{3.9}$$

$$\frac{Import_{y,l,Power,r,rr} + Export_{y,l,Power,r,rr}}{CapacityToActivityUnit \cdot YearSplit_{l,y}} = TradeCapacity_{y,Power,r,rr} \quad ,\forall y,l,r,r \tag{3.10}$$

The objective function (3.1) minimizes the net present cost of an energy system to meet the specified demands for energy carriers and services This equation calculated by summing up the total discounted costs of each technology (t) in each year (y) and region (r) and each region's total discounted trade costs for importing. The total discounted costs are calculated with Equation (3.2). The rates for charging and discharging for each time slice are specified by Equations (3.3) and (3.4).

A modal split for transportation technology is introduced in Equations (3.5), (3.6), and (3.7). Equation (3.5) divides the demand for a specific fuel into multiple demands for each of the specified modal types. To specify which technology can meet this split requirement, modal categories can be applied to technologies in Equation (3.6). In accordance with Equation (3.7), the tagged technologies must generate at least the amount of the split demand. The pre-existing trade variable is divided into separate export and import variables to implement trade expenses in the model. The trade costs for each fuel in Equation (3.8) are then added up to determine the overall trade costs for each time slice, year, and location.

These costs are additionally discounted to the first year of the model run and then added to the overall discounted costs in order to be included in the objective function. Equation 3.9 incorporates trade losses as well as maximal trade capabilities for power trade. The maximum capacity restriction for an electricity trading route is shown in Equation 3.10.

3.2. DATA COLLECTION

The data used in the model are explained in two parts.

3.2.1. Turkish Energy System

Türkiye is located between Middle Eastern and Caucasian countries that export natural gas. The country aims to become a hub for energy and a transmission route to Europe. The four scenarios in GENeSYS-MOD are implemented by choosing four paths from recent studies [10]. They are known as openENTRANCE pathways, and they enable us to understand the motivations, risks, solutions, and outcomes of the energy transition. Figure 3.3 shows the distribution of primary energy supply by sources for Türkiye. According to data from the Ministry of Energy and Natural Resources [29], Türkiye's total energy supply in 2021 is 6673.8 PJ. In the distribution of this supply by sources, natural gas ranked first with 30.8% of the total supply. Natural gas was followed by oil with 27.6% and hard coal with 15.1%.

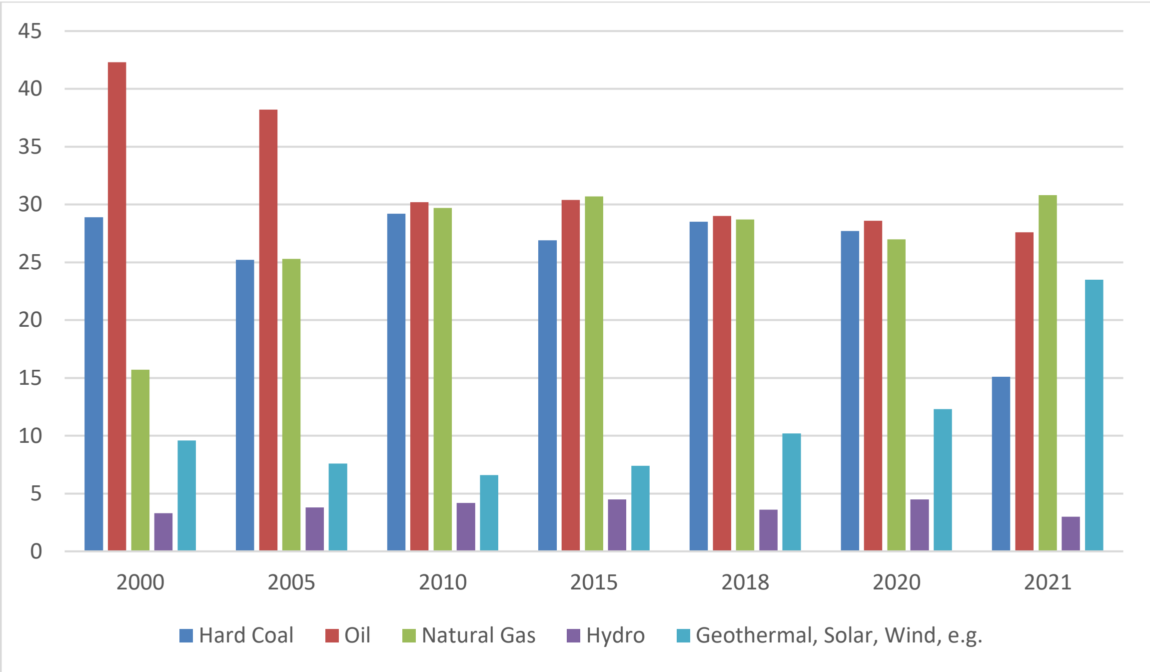

Figure 3.3. Distribution of primary energy supply by sources in 2000-2021 for Türkiye (%)

Generally, the amount of energy supply, generation, import and export is increasing in Türkiye from 2000 to 2021 as shown in Table 3.1. In particular, it is seen that the fastest increase is in exported energy. However, the proportion of supply covered by generated energy is decreasing. In the last 21 years between 2000-2021, Türkiye's total energy supply has increased by 3349.5 PJ by 100.8%. In the last year, while the increase in supply, production, export and import continued, the proportion of supply covered by generated energy decreased.

Table 3.1. Primary energy supply, generation, import, export and 2000-2021, 2020-2021 inceases in Türkiye (PJ)

	2000	2002	2010	2015	2018	2020	2021	2000-2021 Increase (%)	2020-2021 Increase (%)
Supply	3324.3	3228.0	4433.8	5409.3	6012.3	6163	6673.8	100.8	8.3
Generation	1105.3	1021.6	1318.8	1268.6	1662.2	1845.1	1955.2	76.9	6.0
Import	2306.9	2394.9	3542	4722.7	4848.3	4785.1	5204.2	125.6	8.8
Export	67	134	330.8	339.1	255.4	368.4	377.2	463.1	2.4
Gen/Supply (%)	33.3	31.7	29.7	23.5	27.7	29.9	29.3	-12	-2

Figures 3.4 and 3.5 show total power capacity, generation and shares by primary resources in Türkiye [30]. From 2000 to 2021, total power generation and capacity are increasing constantly. In 2008 and beyond, the share of geothermal, wind, solar and other renewables is increasing.

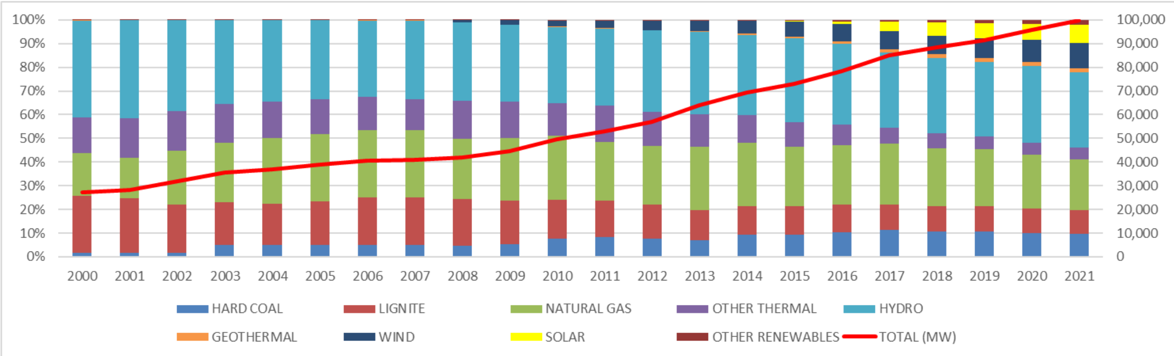

Figure 3.4. Total power capacity (right axis) and its share by primary resources (left axis) in Türkiye

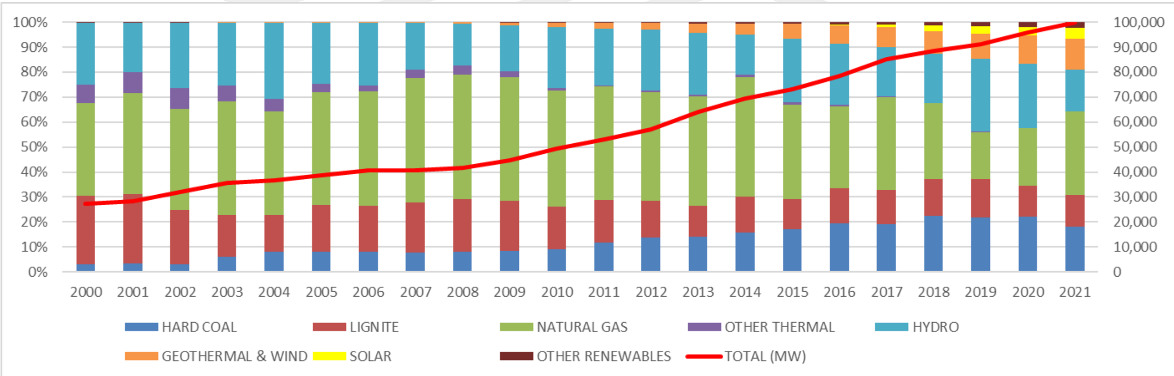

Figure 3.5. Total power generation (right axis) and its share by primary resources (left axis) in Türkiye

As the input of the model, the data is collected mainly from GENeSYS-MOD v3.0 database and The Ministry of Energy and Natural Resources. Hourly generation profiles, hourly load profiles and generation/production costs are provided in the current GENeSYS-MOD v3.0 database. The Ministry of Energy and Natural Resources [31] provides the most recent energy demand statistics for Türkiye's model, however the GENeSYS-MOD v3.0 database provides the most recent information on heat demand. Data on transportation is collected from different sources, including information from the Ministry of Transport and Infrastructure, Ministry of Environment, Urbanization and Climate Change. Installed capacity and generation/production mix by technology and sector are collected from the transparency platform of Energy Exchange Istanbul (EXIST) [32]. The Ministry of Energy and Natural Resources provides data on energy balances [31].

3.2.2. Time Series Data for Disaggregated Turkish Regions

Time series data for wind and solar PV were gathered via the website renewables.ninja. (i.e., capacity factors for each hour in a year). Different from most EU countries, there is no published hourly wind or solar photovoltaic capacity factor data for Türkiye on this website, nor it has any regional disaggregation at NUTS level 1. Only point data is available, which requires coordinates (in longitude and latitude) for each potential location. Hence, an R code has been employed to obtain regional data for Türkiye at NUTS-1 level (the R codes and instructions are available on GENeSYS-MOD-Turkey GitHub repository [33]).

The tool ninja_automator.r that is available on Github and the coordinates of centroids of polygons for NUTS-1 level are used to gather the solar PV and wind time series data from the renewables.ninja website (the Github page of ninja.renewables has the necessary information, but there is an hourly data gathering limit of 50 queries,i.e., 50 locations at once). For offshore wind data, the data on offshore wind potential in Türkiye from the literature, with the first 11 locations selected from [34] and the last 4 locations being selected from [35] is used.

1. Bandırma (TR2)
2. Bozcaada (TR2)
3. Gökçeada (TR2)
4. Burhaniye (TR2)
5. Saros (TR2)
6. Dikili (TR3)
7. Karaburun (TR3)
8. Karasu (TR4)
9. Antalya (TR6)
10. Mersin (TR6)
11. Bafra1 (TR8)

12. Bafra2 (TR8)
13. Inebolu (TR8)
14. Sinop1 (TR8)
15. Sinop2 (TR8)

Then, representative offshore points for these locations were selected from the renewables.ninja website and wind capacity factors have been downloaded. These factors were then averaged for each NUTS-1 level region. These efforts, however, do not complete the hourly onshore wind, offshore wind, and solar PV time series data required for GENeSYS-MOD, which uses multiple categories of each technology within each region, differentiating between optimal (opt), average (avg), and below average (inf) locations. The values in parentheses show the multipliers for capacity factors we have used for each sub technology:

Solar PV: inf (0.7), avg (0.85), opt (1)

Wind Onshore: inf (0.7), avg (1), opt (0.85)

Wind Offshore: shallow (0.85), deep (0.7) and transitional (1)

There are further parameters to consider, but we do not have data sources for run-of-river hydro (RoR) capacity factors at NUTS Level 1 for Türkiye. Additionally, load data is only accessible at the aggregate level. As a result, we used the aggregated Türkiye data that are currently present in the GENeSYS-MOD database for all regions in the remaining hourly time series dataset.

3.3. SCENARIOS

The storyline of the narrative describes a potential energy system for the future. It is crucial that the storylines used for the analysis are selected based on the comparison criteria for the model results. Comparisons can be effectively established when the appropriate storylines are chosen. On the other hand, the results are inaccurate when the models on various subjects are considered separately. Therefore, it is crucial to consider how the models are connected while developing energy and climate models.

In this thesis, the storylines emphasize three uncertainties and more effectively connect climate and energy modeling. Since the storylines are constructed as a combination of at least two (and maybe three) sets of (key) drivers, different combinations of potential outcomes are better analyzed in this way. Three-dimensional topology emerges as a meaningful approach to set scenarios around key drivers and uncertainties of the energy transition. In Figure 3.6, the storylines that combine two dimensions are depicted as purple areas, while the storyline that combines three dimensions is depicted as both an orange dot and an orange cube. The figure also shows that uncertainty and distortions are strongest at areas far from the intersection of the three dimensions.

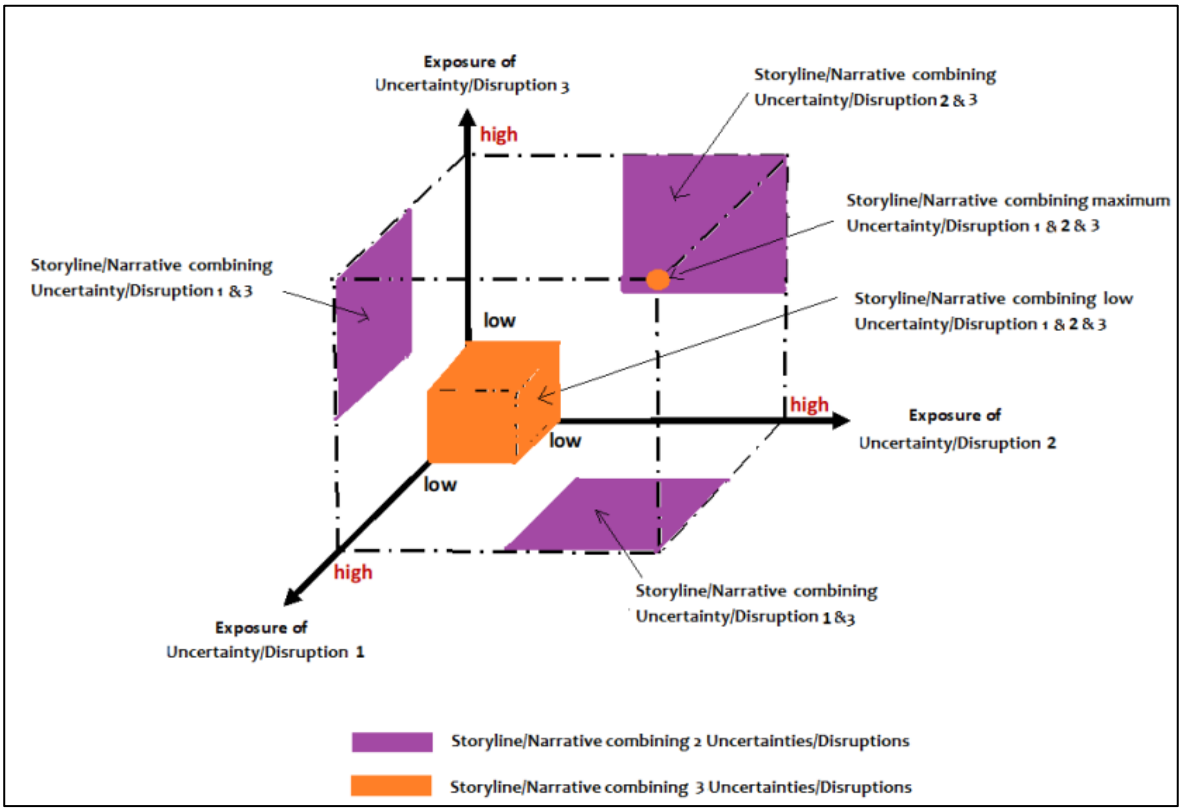

Figure 3.6. Three-dimensional storyline framework

By selecting four pathways from recent studies or ongoing work with the MESSAGEix-GLOBIOM (IAM) [7], four scenarios are implemented in GENESYS-MOD. MESSAGEix is a global systems engineering optimization model used for long- and medium-term energy system planning. In this context, it is crucial to carry out robustness testing and plausibility checks using the "most alike" existing global pathway datasets developed with the MESSAGEix-GLOBIOM IAM. Moreover, an alignment to existing energy system related input datasets used by other studies to support policy making, such as long-term renewable resource potentials per country, is also important to guarantee the comparability of delivered results.

The qualitative storylines are composed of variables related to technological development, policy making and community involvement. The dimensions for the storylines in this thesis—"smart society," "policy exertion," and "technological novelty"—are shown in Figure 3.7. The "smart society" dimension focuses on the participation and awareness of society to take efficient strategies to dealing with climate change. The "policy exertion" is about effective policy actions to lead the energy transition to decarbonization and finally the "technological novelty" is about innovation and technology advancements [10].

The quantitative scenarios used in this thesis are developed in the openENTRANCE project based on a three-dimensional extension of the qualitative storyline topology just mentioned to evaluate low-carbon developments in line with the Paris Agreement climate targets. All scenarios assume widespread use of renewable energy sources as well as demand-side response from people and communities. These are necessary conditions for achieving significant energy and climate policy goals for a low-carbon energy system in the future. Scenario descriptions are not restricted to a particular (geographical) area. For instance, in this thesis, it is only used for Türkiye.

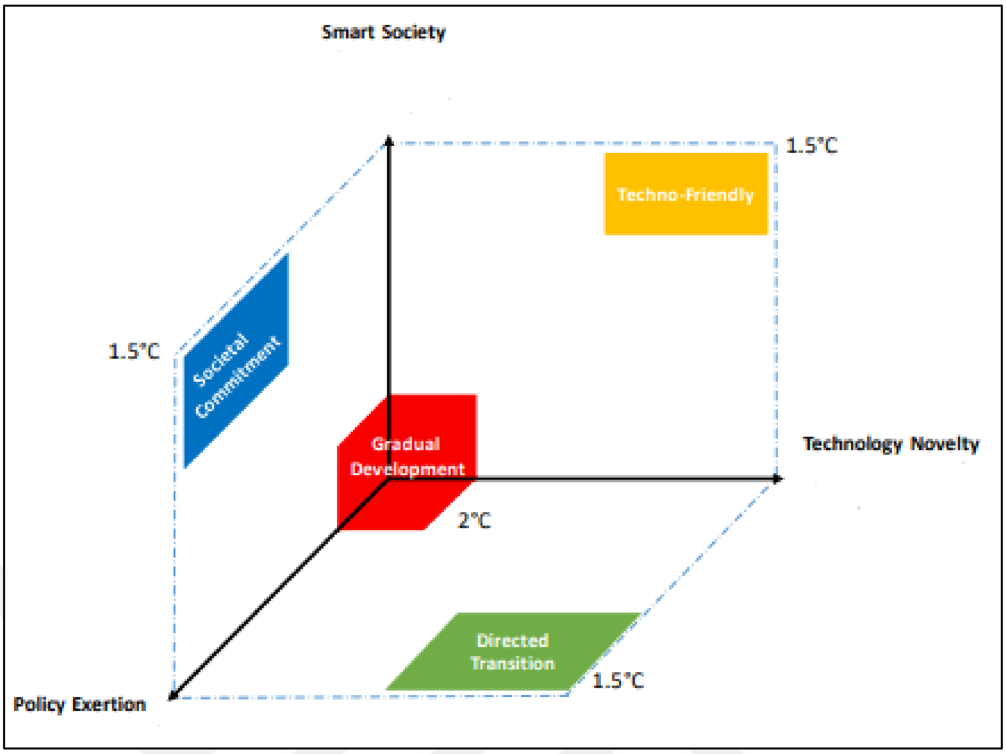

Figure 3.7. Scenarios typology = policy exertion x technological novelty x smart society

The four scenarios can be described as follows (see [2,10] for further information):

- The “directed transition” (DT) scenario has a strong incentive-based policy push and it is enriched with additional aligned initiatives at the Member State level. On both the supply and demand sides, a significant policy push favors specific technological solutions.
- The "societal commitment" (SC) scenario is defined by a sustainable society that is ready to take action as a result of a push for policy made feasible by an ambitious carbon price. There is a strong electrification of the energy and transport system with significant demand side participation. The supply provided by technological innovations is lacking (limited floating offshore wind and limited H2 applications are assumed to be established), instead relying on existing technologies with digitalization.
- The “techno friendly” (TF) scenario focuses on the development of novel technologies and other technical advancements in general (candidates such as floating offshore wind, H_2, CCS are successful and competitive). Large-scale

infrastructure initiatives are accepted by society, which is also generally tech-friendly.

- The “gradual development” (GD) scenario is a combination of aspects of all the other three scenarios. While others have ambitious carbon pricing, this scenario has moderate carbon pricing only (e.g. due to divergent interest groups in politics). Human inertia mitigation policies and continuous policy push are necessary. Moderate market pull only increasing electrification of energy and transport system and limited floating offshore wind is assumed (due to lack of technology novelty)

The carbon costs and their corresponding developments are one of the main distinctions between these four scenarios. Carbon price development for all four scenarios is shown in Figure 3.8. As shown, the carbon price is implemented exponentially, with a low price in the early model periods and a high price in the latter model periods, for the GD, SC, and TF scenarios. In contrast, the DT scenario assumes that the price of carbon will increase linearly. This results in substantially higher carbon prices in the time period between 2025 and 2040 compared to all other scenarios, due to the strong policy measures put in place. Overall, in 2050 SC scenario requires the highest carbon price to reach its 1.5°C compatible pathway goal with 1275€/tCO_2 (mostly due to the absence of carbon dioxide removal technologies being available making a complete carbon neutrality challenging), followed by the DT scenario with a required carbon price of 1000€/tCO_2.

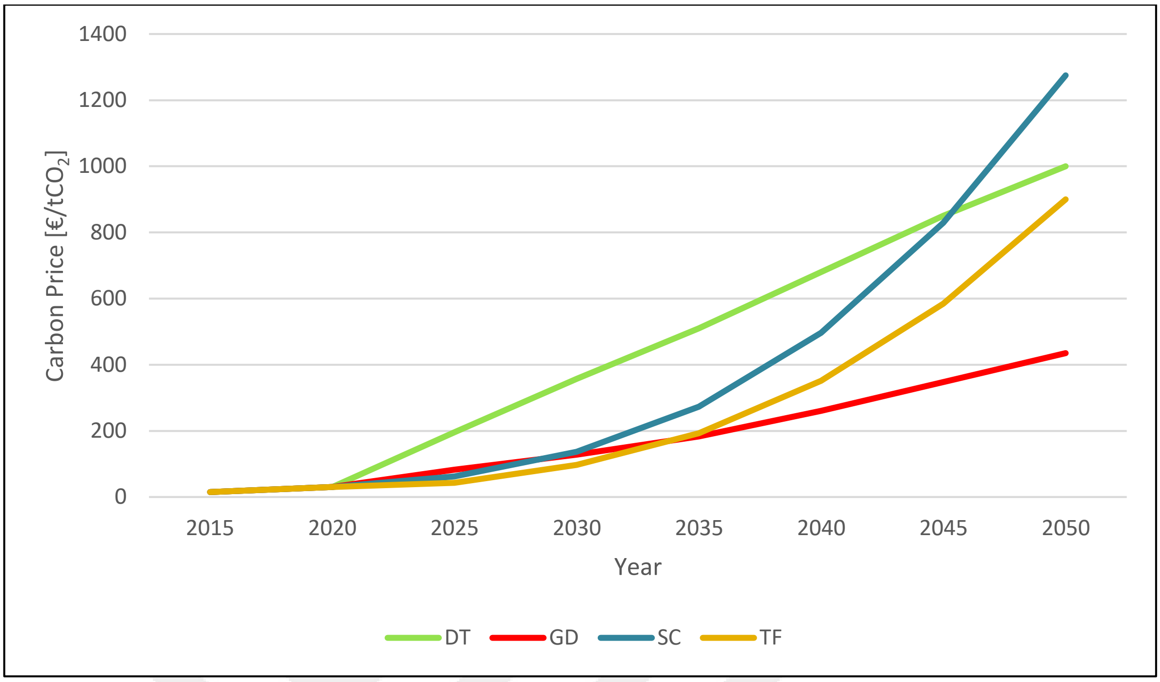

Figure 3.8. Carbon Price in all scenarios from 2015 to 2050

3.4. DISAGGREGATION PROCESS

The analysis of Türkiye is conducted both for Türkiye at a country level (one node) and on a more detailed subnational, power-price region level (12 subregions in NUTS-1 level). Figure 3.9 provides the regionally disaggregated map of Türkiye. The disaggregation process is based on factors such as the population, industrial production, offshore/onshore potential and land area of each region. To account for the differences according to region, it is important to look at the 12 subregions separately when modeling future energy system developments for Türkiye. The transition scenarios, namely Directed Transition (DT), Societal Commitment (SC), Gradual Development (GD), and Techno Friendly (TF) are employed for the analysis both for the aggregate, one node Türkiye model as well as the disaggregated version. The results are obtained using GENeSYS-MOD v3.0. The base year is assumed to be 2015 and the analysis is extended until 2050 with 5-year steps.

To add a new region to the GENeSYS-MOD v3.0 model, the steps in the GENeSYS-MOD Quick-Start Guide [36], Technical Guide [37], and Data Documentation [38] are followed. Because there is no specific disaggregation procedure given in the guide, various problems arose throughout the setup process. In order to solve the problems, initially, a model for Türkiye based on NUTS level 1 that included twelve areas is created. The model's settings are based on the disaggregation method used in Norway [26]. The data that provided in the original model data files is updated and disaggregated according to the following regional data on population, industrial production, onshore wind production, land area, and offshore wind potentials, as seen in the Table 3.2.

Table 3.2. Population, industry, wind potential, and land area per region

Region	Population (%)	Industry (%)	Onshore Wind (%)	Land Area (%)	Offshore Wind (%)
TR1	18.61	29.34	6.47	0.84	0.00
TR2	4.30	5.36	22.84	4.67	78.02
TR3	12.88	13.35	26.51	8.40	0.00
TR4	9.52	16.85	7.82	9.75	0.00
TR5	9.71	10.66	4.48	4.72	0.00
TR6	12.75	8.27	15.91	16.34	3.76
TR7	4.95	3.39	8.91	7.34	0.00
TR8	5.72	3.14	4.60	11.76	18.22
TR9	3.27	1.87	0.21	9.68	0.00
TRA	2.79	0.79	0.00	8.96	0.00
TRB	4.86	1.75	0.58	7.84	0.00
TRC	10.65	5.23	1.66	9.71	0.00

For the disaggregation process, the website renewables.ninja is used to collect data. Due to the lack of relevant data and disaggregated supplies for Türkiye on this website, a regional data gathering approach at the NUTS-1 level is established for Türkiye.

The disaggregation at NUTS-1 level will rely on industry locations for the disaggregation of industrial heat demands, population for the residential heating, electricity demand, transport demand and land area for resource potential, whenever there is no data available for the disaggregated level.

Both an aggregate level and a level of regionally disaggregated data are used in the analysis for Türkiye. The disaggregated level analyzes the nation using 12 subregions at the NUTS-1 level. In Figure 3.9, a map of Türkiye with distinct regions is displayed. Disaggregation is affected by a variety of variables, such as population, industrial output, offshore/onshore potential, and land area. Using GENeSYS-MOD v3.0 and a smaller hourly time series, the analysis is conducted utilizing the four transition scenarios (18-time steps per year). With 2015 as the starting point, the analysis is run through the year 2050.

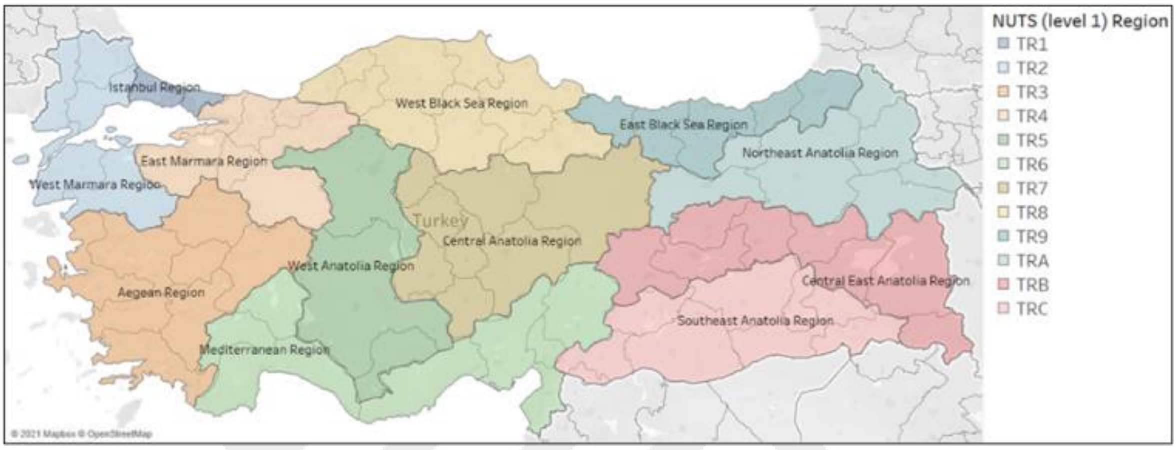

Figure 3.9. Türkiye map with 12 distinct regions according to NUTS1

4. RESULTS

In this chapter, results of the four transition scenarios at aggregated and disaggregated level obtained using GENeSYS-MOD in the thesis are presented. In the first part, mathematical and graphical results for the results achieved from 2015 to 2050 in 5-year steps under all possible scenarios at aggregated and disaggregated level are analyzed and the difference between the two levels is examined. In the second part, the overall results of the levels for each sector are compared.

4.1. MODEL RESULTS AT AGGREGATED AND DISAGGREGATED LEVELS

In this section, results for GENeSYS-MOD v3.0 at the aggregated and disaggregated levels introduced in the previous section are presented. The goal of energy systems is to support economic growth by ensuring many sectors such as trade, transportation, and agriculture operate efficiently and constantly. To analyze the interactions across different sectors, this study considers three primary categories of demand: power, heat, and transportation. The findings are presented in eight subsections. Detailed results are shown in Appendix A and Appendix B.

4.1.1. Power Generation and Use

The detailed demand and supply distribution at aggregated and disaggregated levels provide important findings. Figure 4.1 provides the specifics for power production and use for the results achieved every 5 years from 2025 to 2050 in each scenario at both levels. At the disaggregated level, photovoltaics are used to generate the majority of the power, which is still provided by onshore wind at the aggregate level. On the other hand, most of the aggregated level power usage is due to industry and final demand, while at disaggregated level it is due to industry and final demand as well as electrolysis. The photovoltaics generation in the disaggregated level is much more every year than at the aggregated level. The main reason for the difference in solar photovoltaics and onshore wind generation is the increase in the new capacity investments for solar photovoltaic technologies until 2050 in all scenarios; by contrast, onshore wind capacity increases until

2040 and stabilizes by 2045 and declines slightly by 2050. PV and wind energy replaces fossil fuels in all scenarios as early as 2030. Most of the power generation is provided from solar PV in 2050 in all scenarios, with hydro resources still playing a substantial role. Offshore wind energy production is carried out only in the aggregated level in the DT scenario as of 2040. The trend for installed storage capacities is rising and it is found that there is an upward trend until 2050, especially in disaggregated level. A small portion of the generation is provided by biomass and geothermal. The fossil fuels, including coal and natural gas, are phased out by 2030 in GD, SC, and TF scenarios while a small portion of natural gas is used in DT scenario by 2030. Electrolysis and industry demand continue to increase until 2040 and the disaggregated level shows a higher power consumption for electrolysis in each year for all scenarios. It can be stated that the extra power generated at disaggregated level (specifically from solar) has also increased usage of electrolysis, i.e., hydrogen production. On the other hand, the demand for transport is significant in SC, lower in TF, and almost identical in GD and DT scenarios at both levels. Higher power generation from photovoltaics in the disaggregated model is mainly used in electrolyzes for hydrogen production.

The capacity for solar photovoltaics and onshore wind increases until 2040 in all scenarios and stays constant afterwards. The hydropower resources are already widely used in Türkiye and the results show that not much capacity is added, since significant amounts of existing potentials are already being used such as photovoltaics and onshore wind. The electrolysis and demand for industry are the main components of power usage until 2050 and they keep rising until 2040 and stay constant afterwards. The final energy demand is an exogenous input and therefore similar to the aggregated level.

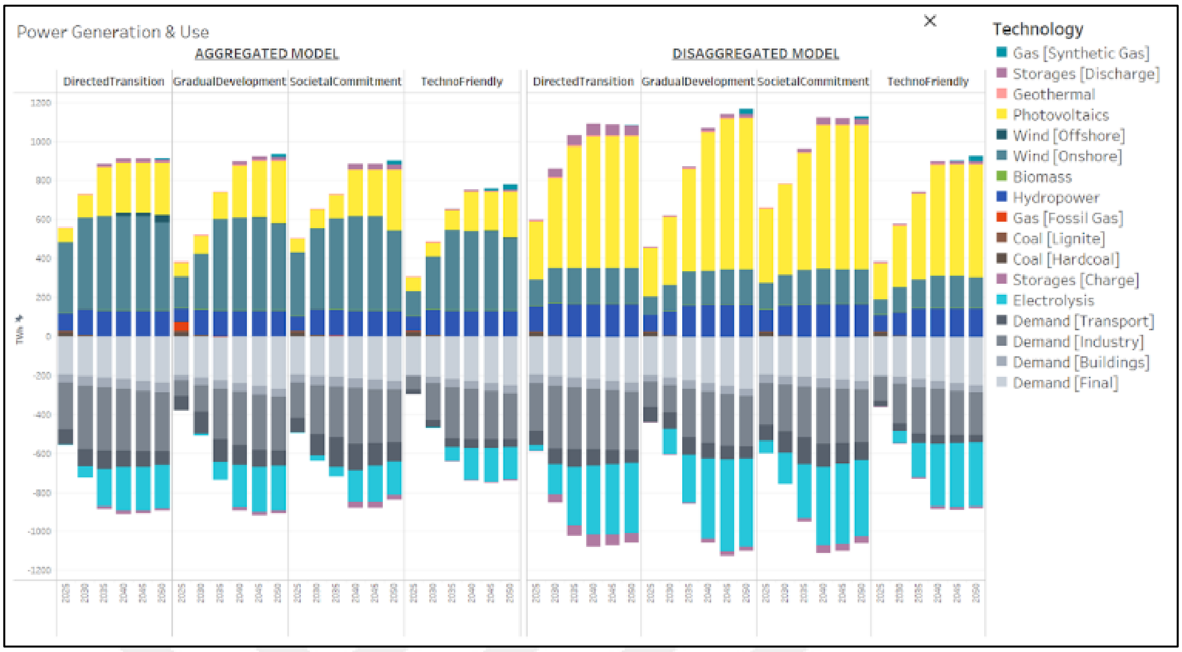

Figure 4.1. Power generation & use at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

Table 4.1 and Table 4.2 show the relative difference between model results of total power generation and use of the four scenarios for the results achieved from 2025 to 2050 in both aggregated and disaggregated level results. The difference between the two levels is greatest in the SC scenario and lowest in the DT scenario. The electrolysis in PV usage during manufacturing is the primary cause of the difference between the two levels in the SC scenario. At the disaggregated level compared to the aggregate level, power generation and use are higher each year in all scenarios. The biggest difference between the two levels in terms of power generation is photovoltaics and then onshore wind. The largest relative difference in power consumption between the two levels is due to electrolysis in each year.

Table 4.1. Relative difference between model results of power generation & use for aggregated and disaggregated level for DT and GD scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) ('-' indicates that aggregated level result is zero)											
	Directed Transition						**Gradual Development**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	-	-	-	-	-	93	-	-	-	-	-	57
Storages [Discharge]	-	-	261	247	258	266	-	-	-	10	19	27
Geothermal	52	29	8	-6	-21	-33	52	29	8	-6	-21	-33
Photovoltaics	312	292	149	163	163	154	256	273	295	167	172	145
Wind [Offshore]	-	-	-	-100	-100	-100	-	-	-	-	-100	-100
Wind [Onshore]	-62	-61	-62	-62	-62	-59	-45	-52	-63	-64	-63	-60
Biomass	0	0	0	0	0	0	0	0	0	0	0	0
Hydropower	39	22	23	23	23	22	13	-6	18	21	21	20
Gas [Fossil Gas]	-	-	-	-	-	-	-98	-	-100	-	-	-
Coal [Lignite]	0	0	-	-	-	-	0	0	-	-	-	-
Coal [Hardcoal]	0	0	-	-	-	-	0	0	-	-	-	-
GENERATION	**7**	**18**	**17**	**20**	**19**	**19**	**21**	**20**	**18**	**19**	**24**	**25**
Storages [Charge]	-	-	261	247	258	266	-	-	-	10	19	27
Electrolysis	29,200	155	59	60	61	63	-	932	160	92	107	97
Demand [Transport]	-8	-10	-6	-4	-6	-4	7	-23	-21	-21	-20	-19
Demand [Industry]	4	0	-1	-1	-2	-1	61	2	-4	-5	-7	-7
Demand [Buildings]	1	-6	-3	-3	-3	-9	27	0	-1	-1	-3	-7
Demand [Final]	0	0	0	0	0	0	0	0	0	0	0	0
USE	**7**	**17**	**16**	**18**	**18**	**18**	**18**	**20**	**17**	**19**	**23**	**21**

Table 4.2. Relative difference between model results of power generation & use for aggregated and disaggregated level for SC and TF scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)											
	Societal Commitment						**Techno Friendly**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	-	-	-	-	-	-38	-	-	-	-	-79	-15
Storages [Discharge]	-	-	-	28	20	22	-	-	220	108	172	126
Geothermal	52	29	8	-6	-21	-33	52	29	8	-6	-21	-33
Photovoltaics	443	406	402	211	214	140	160	342	346	184	191	150
Wind [Offshore]	-	-	-	-	-	-	-	-	-	-	-100	-100
Wind [Onshore]	-58	-63	-62	-62	-63	-57	-40	-54	-64	-59	-59	-57
Biomass	0	0	0	0	0	0	0	0	0	0	0	0
Hydropower	43	15	21	23	22	22	13	-7	7	7	7	6
Gas [Fossil Gas]	-	-	-	-	-	-	-100	-	-	-	-	-
Coal [Lignite]	0	0	-	-	-	-	0	0	-	-	-	-
Coal [Hardcoal]	0	0	-	-	-	-	0	0	-	-	-	-
GENERATION	**32**	**20**	**32**	**27**	**27**	**25**	**25**	**19**	**14**	**20**	**19**	**18**
Storages [Charge]	-	-	-	28	20	22	-	-	220	108	172	126
Electrolysis	31,850	496	468	148	125	131	-	1,490	147	101	87	100
Demand [Transport]	7	-1	-10	-10	-10	-10	6	0	0	-2	-2	-4
Demand [Industry]	20	-5	0	-1	0	0	87	7	-9	-9	-9	-9
Demand [Buildings]	7	-1	1	0	-2	-3	55	14	0	0	0	-7
Demand [Final]	0	0	0	0	0	0	0	0	0	0	0	0
USE	**22**	**19**	**32**	**26**	**25**	**26**	**22**	**17**	**14**	**20**	**18**	**19**

Figure 4.2 shows the regional power production results in 2050 under all possible scenarios in disaggregated level. The solar radiation levels are better in southern regions and wind availability is considerably larger in northwestern regions. Therefore, solar and wind generation for 2050 occurs in these regions accordingly. On the other hand, Northwestern regions have a substantial amount of onshore wind capacity, however offshore wind capacities are not utilized. In all scenarios, significant hydro resources are located in eastern and southeastern regions. Natural gas-based generation resources are usually located in western regions but are no longer utilized by 2050. The coal-based generation resources are located in central regions as they are located close to coal mines.

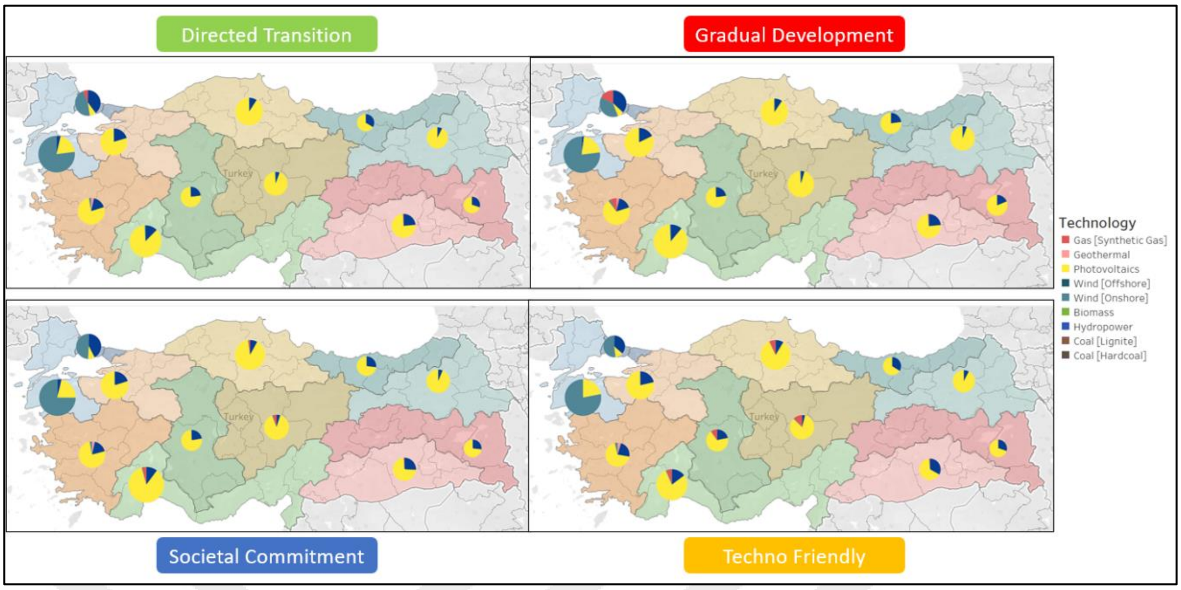

Figure 4.2. Power generation in 2050 at disaggregated level in each scenario

4.1.2. Hydrogen Production and Use

Renewable energy is converted to hydrogen by electrolysis. Hydrogen, the smallest molecule known, does not emit CO_2 when burned. It can be used immediately or stored in pressurized tanks and retrieved when supply runs low. There are technologies in which excess renewable energy obtained from wind, solar or hydro is stored for use first and then converted into other energy carriers such as methanation (i.e., synthetic gas).

Figure 4.3 shows hydrogen production and use for the results achieved every 5 years from 2025 to 2050 in each scenario at aggregated and disaggregated levels. Hydrogen is significantly required in the transport sector (freight, passenger) followed by industry, buildings, and other sectors. Nearly half of the hydrogen produced at both levels is used for road freight transportation. The heating of buildings and industries are the other most common uses.

As seen in Figure 4.2, hydrogen production reaches a significant level in 2040 and accelerated production and usage by 2035. Increases in the solar photovoltaics capacity in the disaggregated level due to regional availability (i.e., capacity factors) led to more opportunities for hydrogen production through electrolysis. Hence, more hydrogen production is observed at the disaggregated level. The demand in the disaggregated scenario is different while the demand from transport is still significant and the share of demand from other sectors differs considerably. For example, in both models, demand from transport is higher in DT and GD scenarios than in SC and TP scenarios. Methanation is one of the technologies used to store extra renewable energy from the wind, sun or water before converting it to other energy carriers. When using hydrogen, it goes through a methanation process using CO_2 to convert hydrogen to methanation (energy-to-methane). The disaggregated level includes greater methanation technology.

The simplest method of generating power or electricity through gas combustion using hydrogen is known as an open-cycle gas turbine (OCGT). Since using OCGTs typically results in higher greenhouse gas (GHG) emissions, it's critical to consider alternative power-generation options in order to increase efficiency and lower GHG emissions. In the aggregated level, natural gas-based power plant technology is used instead of Hydrogen Open Cycle Gas Turbine-based power plant for hydrogen use in SC and TF scenarios at disaggregated level.

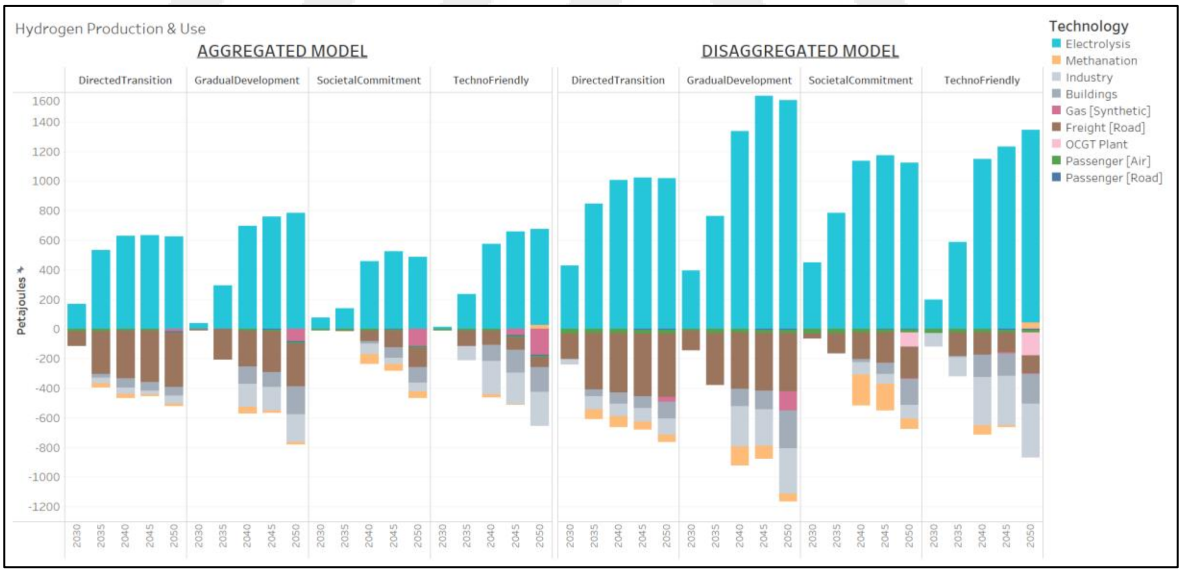

Figure 4.3. Hydrogen production & use at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

Tables 4.3 and 4.4 represent the relative difference between model results of hydrogen production and usage for all scenarios for the outcomes obtained from 2025 to 2050 at aggregated and disaggregated levels. In the SC and GD scenarios, the relative difference between the levels is bigger, whereas it is smaller in the DT scenario. It can be stated that, the relative difference tends to get decrease over time. Additionally, hydrogen generation and usage are higher at the disaggregated level in each year and technology for all scenarios.

Table 4.3. Relative difference between model results of hydrogen generation & use for aggregated and disaggregated level for DT and GD scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)									
	Directed Transition					**Gradual Development**				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	155	59	60	61	63	935	161	92	107	97
Methanation	-	113	194	344	222	-	-	184	427	182
Industry	-	135	87	235	101	-	-	74	52	61
Buildings	-	90	21	39	91	-	-	4	25	38
Freight [Road H2]	74	30	25	21	18	1,305	71	54	41	35
Passenger [H2]	102	118	137	214	149	-	-	136	88	77
Gas	-	-	-	-	97	-	-	-	-	57
Hydrogen OCGT	-	-	-	-	-	-	-	-	-	-
GENERATION	**155**	**59**	**60**	**61**	**63**	**935**	**161**	**92**	**107**	**97**
USE	**112**	**53**	**43**	**49**	**47**	**1,410**	**84**	**61**	**54**	**49**

Table 4.4. Relative difference between model results of hydrogen generation & use for aggregated and disaggregated level for SC and TF scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)									
	Societal Commitment					**Techno Friendly**				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	497	468	148	125	131	1,486	148	101	87	100
Methanation	-	-	207	273	75	-	-	273	171	68
Industry	-	-	17	67	51	-	36	44	54	57
Buildings	-	-	28	3	70	-	-	37	-2	20
Freight [Road H2]	-	1,989	147	83	62	-	55	56	55	77
Passenger [H2]	168	173	137	104	102	131	118	137	90	78
Gas	-	-	-	-	-97	-	-	-	-79	-98
Hydrogen OCGT	-	-	-	-	-	-	-	-	-	-
GENERATION	**497**	**468**	**148**	**125**	**131**	**1,486**	**148**	**101**	**87**	**100**
USE	**468**	**919**	**118**	**93**	**46**	**856**	**52**	**55**	**29**	**31**

Figure 4.4 shows the regional hydrogen production and use results in 2050 under all possible scenarios. In the eastern regions, methanation levels are higher, while in the northwest, electrolysis is much more. Hydrogen use for freight transport is greater in the west.

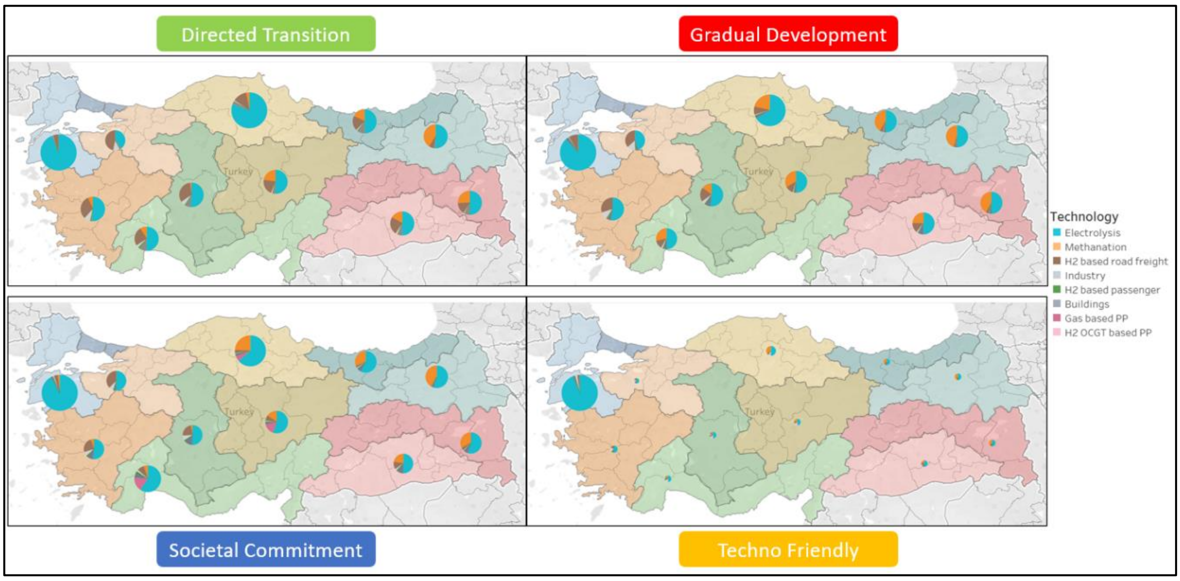

Figure 4.4. Hydrogen generation and use in 2050 at disaggregated level in each scenario

4.1.3. Power Dispatch

Figure 4.5 shows the power dispatch in Türkiye in 2050 for each possible scenarios at both aggregated and disaggregated level. Biomass is almost constant in all results throughout the year. Power is used with electricity demand at the beginning and end of the year and with building heat in the middle of the year. Power generation with direct electricity is only available in the DT scenario in both models.

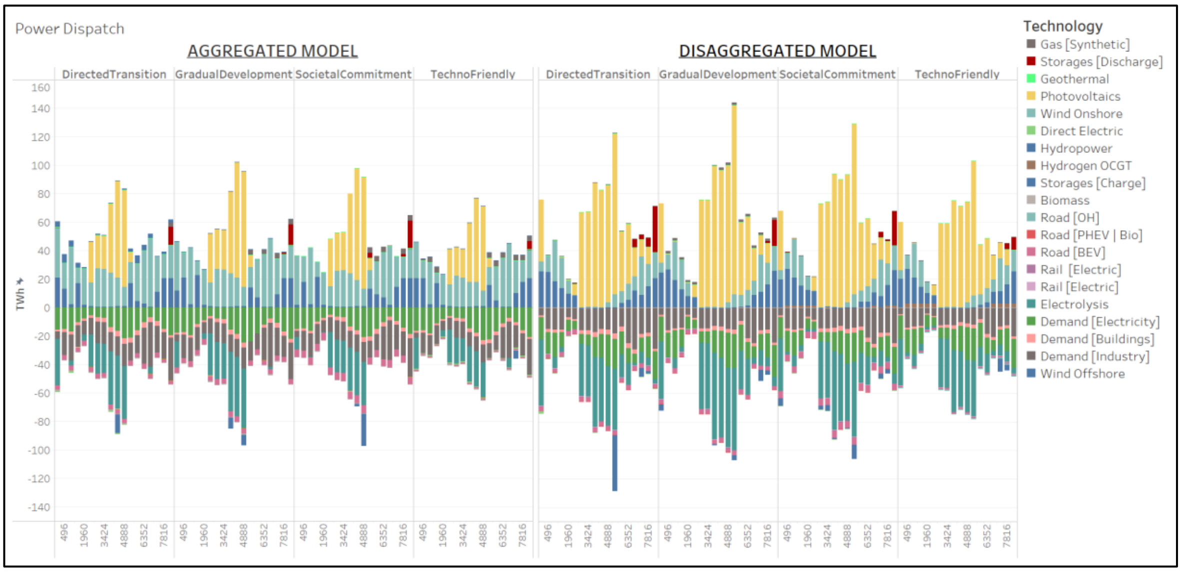

Figure 4.5. Power dispatch at the aggregated and disaggregated level results in 2050 in each scenario

Total generation and use are both more at the disaggregated level. At the disaggregated level, photovoltaics are used to generate the majority of the power in 2050, which is still provided by onshore wind at the aggregate level. On the other hand, most of the power usage is due to industry, final demand and electrolysis at both levels. The biggest difference between the two levels in terms of power generation is photovoltaics and then onshore wind. As in section 4.1.1, Figure 4.1, hourly dispatch results in Figure 4.5 confirms that solar power is mainly used in electrolysis to produce hydrogen.

4.1.4. Total & New Power Capacity

Figures 4.6 and 4.7 display the total and new power capacity in Türkiye the results achieved every 5 years from 2025 to 2050 at aggregated and disaggregated levels under every possible scenario. Figure 4.6 demonstrates the significant increase in total capacity at both levels between 2025 and 2035. While solar and onshore wind are the main causes of this in aggregated, solar is in the disaggregated level. In addition, these figures also show that offshore wind capacity at both levels is only available in the DT scenario. In both levels, there is almost no additional capacity for natural gas, biomass and lignite. Solar, which has a higher capacity at the disaggregated level, and onshore wind, which has a higher capacity at the aggregated level, are the two technologies with the largest differences in total capacity.

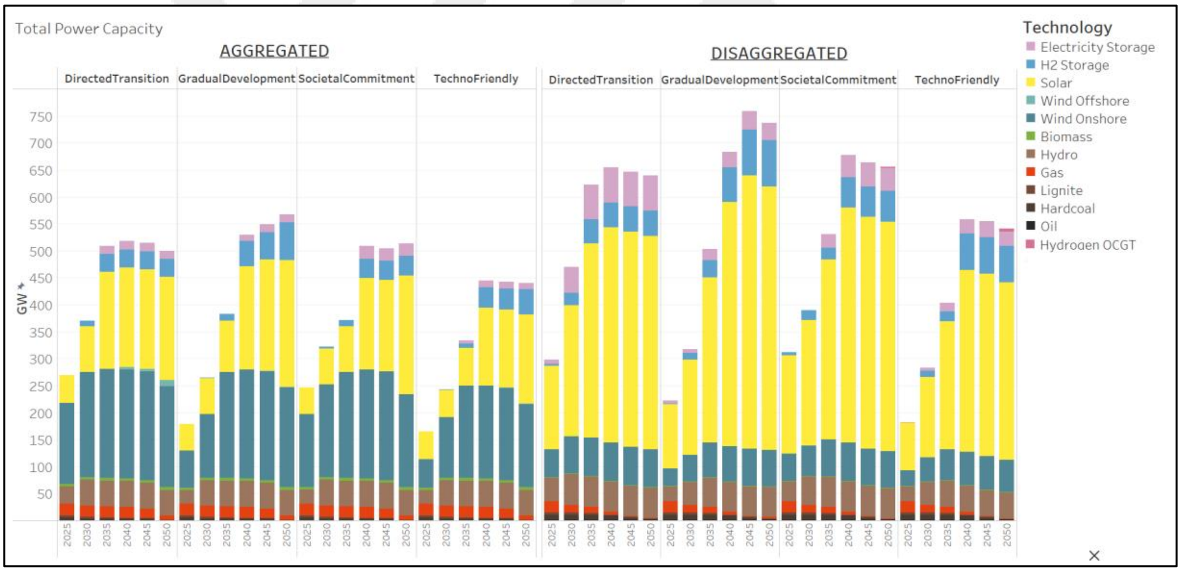

Figure 4.6. Total power capacity at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

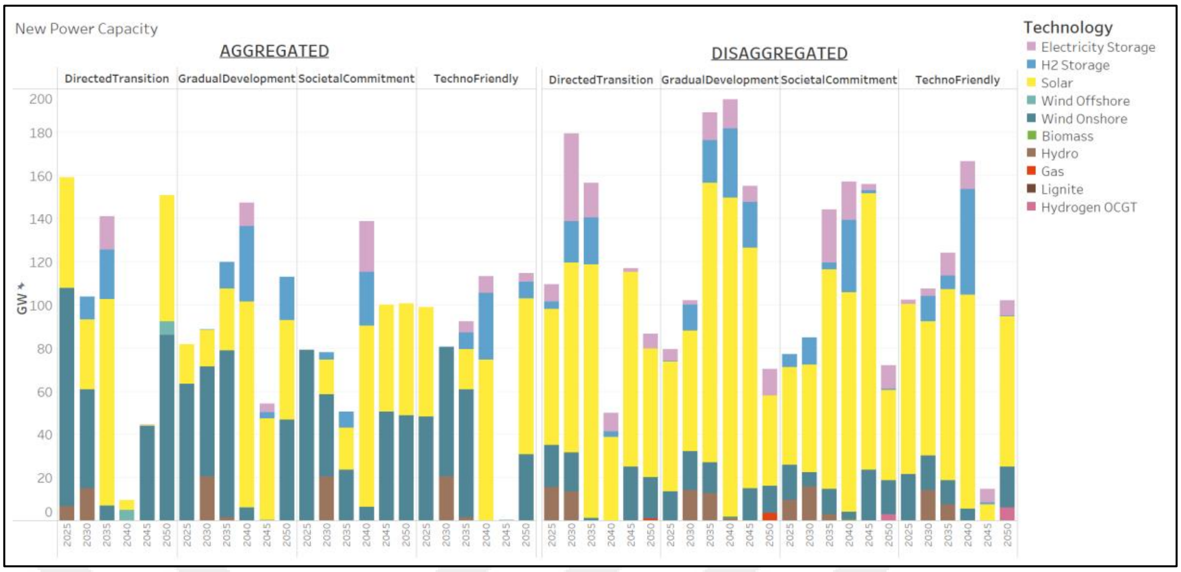

Figure 4.7. New power capacity at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

Table 4.5 and Table 4.6 show the relative difference between model results of new power capacity of the four scenarios for the results achieved from 2025 to 2050 in both aggregated and disaggregated level results. At the disaggregated level, new capacity results are higher almost every year. Wind onshore and offshore new capacity results are higher in the findings obtained for each year of each scenario at the aggregated level, whereas electricity storage and solar are generally higher in the disaggregated level.

Table 4.5. Relative difference between model results of new power capacity results at the aggregated and disaggregated level for DT and GD scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)											
	Directed Transition						**Gradual Development**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen OCGT	-	-	-	-	-	-	-	-	-	-	-	-
Electricity Storage	-	-	4	-	1,600	-	-	-	-	21	95	-
H2 Storage	-	83	-5	-	-	-	-	5,900	58	-8	631	-100
Solar	23	171.6	23	760	45,050	2	226.6	232	350	55	137.4	-9
Wind Offshore	-	-	-	-100	-	-100	-	-	-	-	-100	-
Wind Onshore	-81	-61	-83	-	-43.5	-78	-78.9	-65	-81	-90	-	-73
Biomass	-	-	-	-	-	-	-	-	-	-	-	-
Hydro	129.9	-11	-	-	-	-	-	-31	861.5	-	-	-
Lignite	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	**72**	**183.01**	**-61**	**660**	**46,606**	**-176**	**148**	**6036**	**1,188**	**-22.1**	**763.2**	**-182**

Table 4.6. Relative difference between model results of and new power capacity results at the aggregated and disaggregated level for SC and TF scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)											
	Societal Commitment						**Techno Friendly**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	-	-	-	-	-	-	-	-	-	-	-	-
Hydrogen OCGT	-	-	-	-	-	-	-	-	-	-	-	-
Electricity Storage	-	-	-	-24	-	-	-	-	106	65	-	78
H2 Storage	-	273.5	-57	33	-	-	-	-	-17	59	-	-99
Solar	-	213.2	424.7	22	158.5	-19	55	-	370	33	-	-3
Wind Offshore	-	-	-	-	-	-	-	-	-	-	-100	-
Wind Onshore	-79	-83	-50.8	-48	-54	-68	-55	-73	-81	-	-	-39
Biomass	-	-	-	-	-	-	-	-	-	-	-	-
Hydro	-	-22	-	-	-	-	-	-31	462	-	-	-
Lignite	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	**-79**	**381.4**	**316.6**	**-17**	**105**	**-87**	**-0.6**	**-79**	**840**	**157**	**-100**	**-63**

4.1.5. Passenger and Freight Transport

The passenger and freight transport for both aggregated and disaggregated level results achieved every 5 years from 2025 to 2050 are shown in Figures 4.8 and 4.9. In general, road has the highest proportion of both, followed by rail and ship or air. However, while the proportion of rail increases over time, the share of others decreases.

In air passenger transport and ship freight transport hydrogen and bio-fuel is used as fuel instead of conventional fuel in almost every scenario after 2030 since biofuel and hydrogen cause less emissions. However, the total energy used for air and ship transport at both levels is decreasing from year to year. While electric rail transport increases at both levels and in each scenario for freight and passenger transport, it is higher at aggregated level in both. Internal combustion engines (ICEs) power vehicles using common, oil-derived fuels such as gasoline or diesel. Thus, ICE cars release more pollutants into the atmosphere. When they are utilized frequently, they release harmful gases and chemicals into the atmosphere. So, they are not used after 2030. While hydrogen powered cars are only available in passenger transport after 2045, they are used in freight transport from 2030.

Before 2035, mostly ICE and PHEV vehicles were used in passenger transport and then BEV powered vehicles took their place. In contrast to the other scenarios, in the TF scenario PHEV and PHEV bio vehicles are not used in both models in this case.

Before 2035, ICE and PHEV vehicles were used as well as BEV for the road in Freight Transport, and then hydrogen powered vehicles took their place. The only exception here is the TF scenario. In this scenario, unlike the others, OH powered vehicles are mostly used instead of ICE vehicles after 2030.

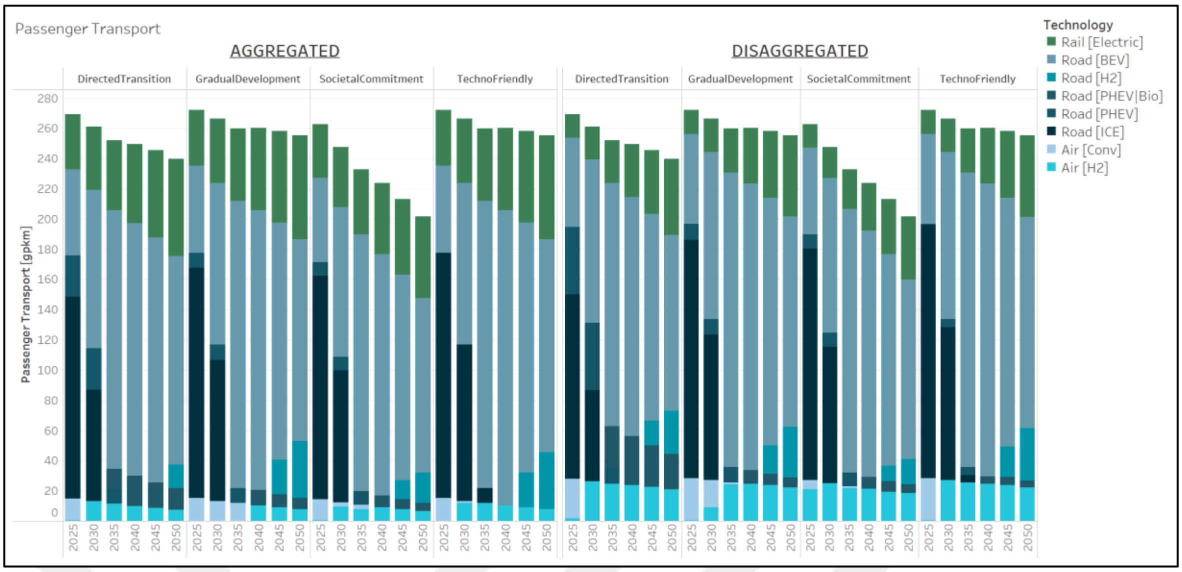

Figure 4.8. Passenger transport at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

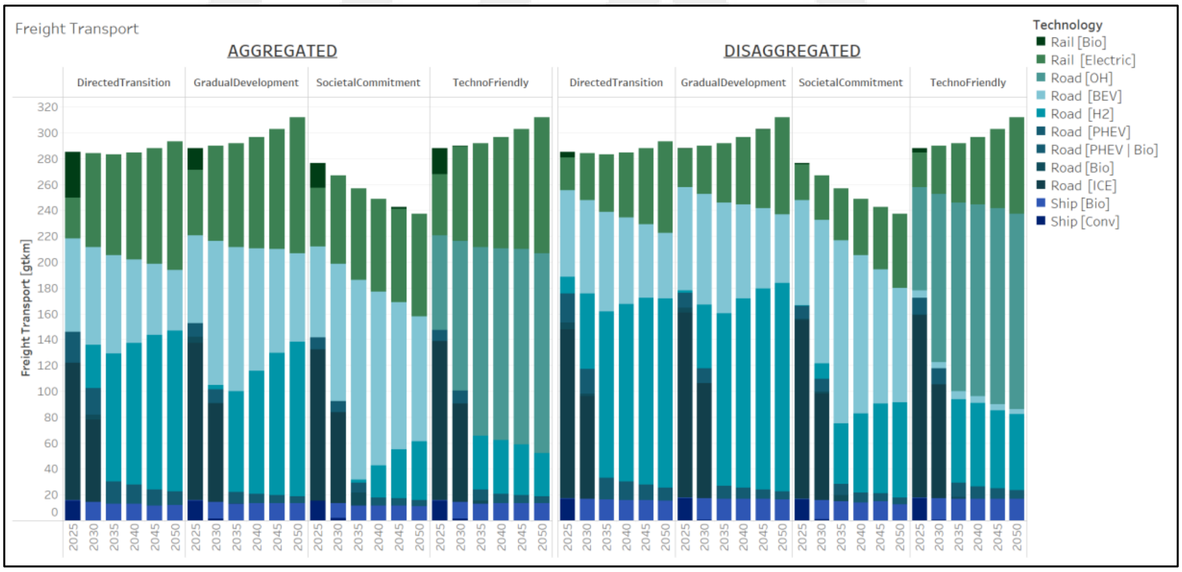

Figure 4.9. Freight transport at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

Table 4.7 and Table 4.8 show the relative difference between model results of passenger and freight transport of the four scenarios for the results achieved from 2025 to 2050 in both aggregated and disaggregated level results. The biggest differences in passenger transport are seen in rail electric and air H_2. In the results for each year of each scenario, rail electric is used more frequently at the aggregate level, and air H_2 is used more frequently at the disaggregated level. Both rail technologies are used more frequently overall in freight transport.

Table 4.7. Relative difference between model results of passenger and freight transport at the aggregated and disaggregated level for DT and GD scenarios

		RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) ('-' indicates that aggregated level result is zero)											
		Directed Transition						**Gradual Development**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PASSENGER	Rail [Electric]	-57	-48	-39	-32	-27	-22	-57	-48	-39	-32	-27	-22
	Road [BEV]	4	3	-6	-5	-16	-16	3	3	3	3	4	4
	Road [H2]	-	-	-	-	-	84	-	-	-	-	-17	-11
	Road [PHEV|Bio]	-	-	107	63	64	63	-	-	-	-13	-13	-12
	Road [PHEV]	63	63	2	-	-	-	3	3	3	-	-	-
	Road [ICE]	-9	-19	-	-	-	-	4	3	-	-	-	-
	Air [Conv]	81	-	-	-	-	-	85	36	-89	-	-	-
	Air [H2]	467	103	119	136	160	186	-	-	-	137	162	190
FREIGHT	Rail [Bio]	-88	-	-	-	-	-	-98	-	-	-	-	-
	Rail [Electric]	-20	-50	-43	-39	-34	-29	-41	-50	-43	-40	-34	-28
	Road [OH]	-	-	-	-	-	-	-	-	-	-	-	-
	Road [BEV]	-7	-5	1	4	4	8	17	-23	-23	-23	-23	-23
	Road [H2]	-	75	31	25	21	18	-	1,309	71	54	41	35
	Road [PHEV|Bio]	-	-	-24	-5	-6	-6	-	-	-	15	14	15
	Road [PHEV]	-6	-5	15	-	-	-	16	16	15	-	-	-
	Road [Bio]	-	-53	-	-	-	-	-20	-100	-100	-	-	-
	Road [ICE]	23	24	-	-	-	-	18	17	-	-	-	-
	Ship [Bio]	0	19	28	25	36	30	-33	28	28	26	26	22
	Ship [Conv]	11	-	-	-	-	-	12	-64	-	-	-	-

Table 4.8. Relative difference between model results of passenger and freight transport at the aggregated and disaggregated level for SC and TF scenarios

		RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) ('-' indicates that aggregated level result is zero)											
		Societal Commitment						Techno Friendly					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
PASSENGER	Rail [Electric]	-57	-48	-39	-33	-27	-23	-57	-48	-39	-32	-27	-22
	Road [BEV]	3	3	3	2	3	3	3	3	3	-1	-1	-1
	Road [H2]	-	-	-	-	-19	-15	-	-	-	-	-11	-8
	Road [PHEV|Bio]	-	-	-	3	3	2	-	-	-	-	-	-
	Road [PHEV]	3	3	3	-	-	-	-	-	-	-	-	-
	Road [ICE]	4	3	-	-	-	-	3	-2	-53	-	-	-
	Air [Conv]	-54	-100	-58	-	-	-	85	-100	-	-	-	-
	Air [H2]	6,833	169	173	138	157	182	-	130	117	137	162	188
FREIGHT	Rail [Bio]	-94	-	-	-	-100	-	-83	-100	-	-	-	-
	Rail [Electric]	-39	-50	-43	-39	-34	-28	-44	-50	-43	-40	-34	-29
	Road [OH]	-	-	-	-	-	-	10	13	0	0	0	-2
	Road [BEV]	16	5	-9	-9	-9	-9	-	-	-	-	-	-
	Road [H2]	-	-	2,032	147	83	62	-	-	55	56	55	77
	Road [PHEV|Bio]	-	-	-	15	16	15	-	-	-	26	25	28
	Road [PHEV]	16	16	16	-	-	-	52	25	15	-	-	-
	Road [Bio]	-	-	-53	-	-	-	-	-	-30	-	-	-
	Road [ICE]	18	17	-	-	-	-	15	16	-	-	-	-
	Ship [Bio]	-	28	28	24	26	14	-33	28	28	26	26	24
	Ship [Conv]	8	-39	-	-	-	-	12	-64	-	-	-	-

4.1.6. Building and Industrial Heat

Building and industrial heat are represented in Figures 4.10 and 4.11 for both aggregated and disaggregated level findings achieved every 5 years from 2025 to 2050. While heat pumps are mostly used in building heating, direct electricity is mostly used in industrial heating. However, for building heating, direct electricity is only an option in the DT scenario. In the two graphs, it is seen that for the use of natural gas decreases from year to year in each scenario, the use of hydrogen increases to reduce emissions, especially in the disaggregated model. For the same reason, hard coal and oil are both used very little until 2030, and then not used at all.

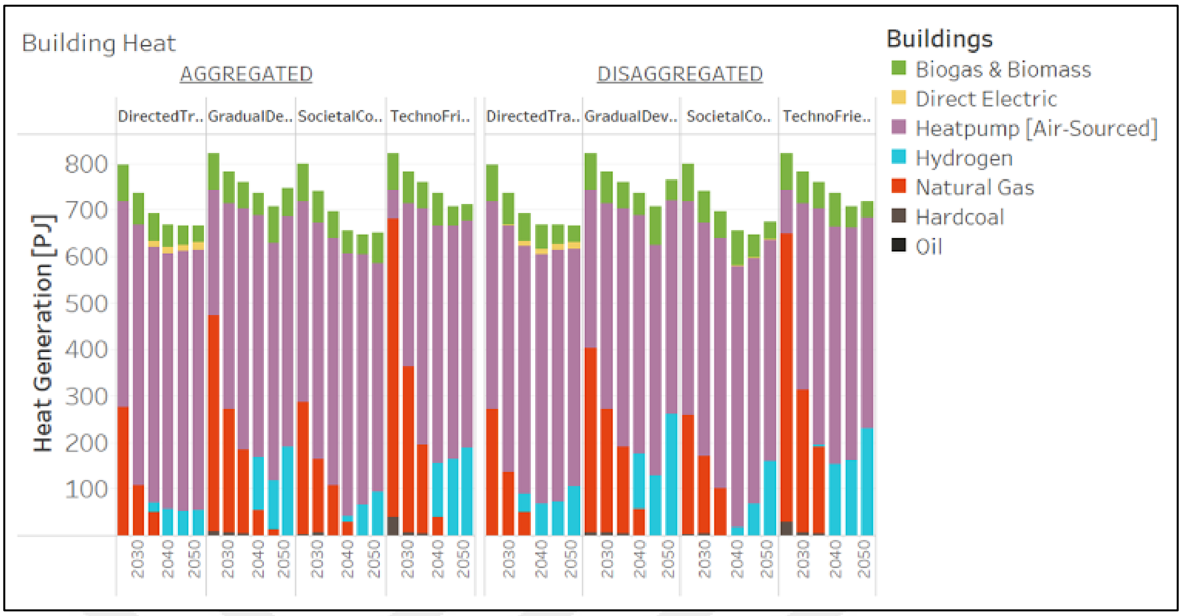

Figure 4.10. Building heat at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

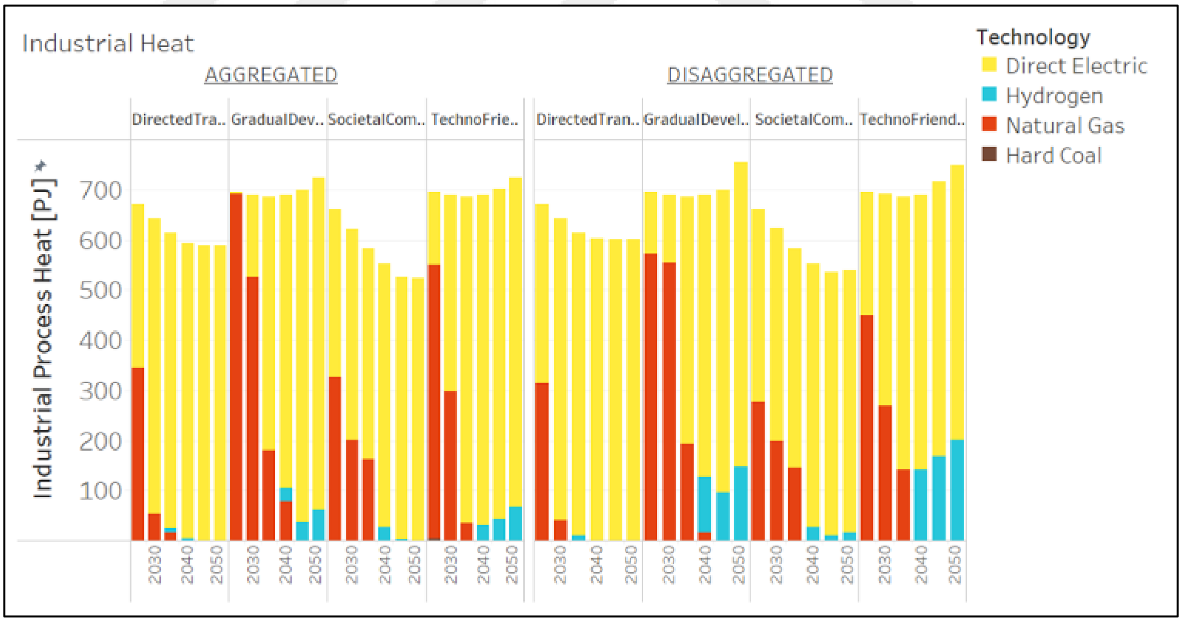

Figure 4.11. Model results for industrial heat at the aggregated and disaggregated levels from 2025 to 2050 in each scenario

Table 4.9 and Table 4.10 show the relative difference between model results of total building and industrial heat of the four scenarios for the results achieved from 2025 to 2050 in both aggregated and disaggregated level results. Hydrogen is generally used more at disaggregated level in both sectors. In contrast, natural gas is more used at disaggregated level generally in both sectors. Between the two levels in both sectors, they represent the most significant difference.

Table 4.9. Relative difference between model results of building and industry heat at the aggregated and disaggregated level for DT and GD scenarios

		RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)											
		Directed Transition						**Gradual Development**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	0	0	0	9	0	0	0	0	0	0	7	-30
	Direct Electric	-	-	-18	-15	-5	-5	-	-	-	-	-	-
	Heatpump [Air-Sourced]	1	-5	-3	-3	-3	-9	26	0	-1	-1	-3	-7
	Hydrogen	-	-	91	22	39	92	-	-	-	2	22	36
	Natural Gas	-2	27	1	-	-	-	-15	0	2	5	-100	-
	Hardcoal	-	-	-	-	-	-	-1	0	0	-	-	-
	Oil	0	-50	-40	-	-	-	0	0	0	0	-	-
INDUSTRY	Direct Electric	9	2	2	2	2	2	3,219	-17	-3	-4	-9	-8
	Hydrogen	-	-	51	-82	-	-	-	-	-	308	160	139
	Natural Gas	-9	-25	-99	-	-	-	-17	5	8	-78	-	-
	Hard Coal	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.10. Relative difference between model results of building and industry heat at the aggregated and disaggregated level for SC and TF scenarios

		RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) (‘-’ indicates that aggregated level result is zero)											
		Societal Commitment						**Techno Friendly**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	0	0	0	49	18	-47	0	0	0	3	10	0
	Direct Electric	-	-	-	-	-	-	-	-	-	-	-	-
	Heatpump [Air-Sourced]	7	-1	1	0	-2	-3	53	14	0	0	0	-7
	Hydrogen	-	-	-	29	3	69	-	-	-	32	-2	22
	Natural Gas	-10	4	-6	-100	-	-	-3	-14	-3	-100	-	-
	Hardcoal	-7	-5	-	-	-	-	-28	0	0	-	-	-
	Oil	-	-	-	-	-	-	20	0	0	-	-	-
INDUSTRY	Direct Electric	15	1	4	0	0	0	68	7	-16	-17	-17	-17
	Hydrogen	-	-	-	-5	350	-	-	-	-	362	284	200
	Natural Gas	-15	-1	-9	-	-	-	-17	-10	298	-	-	-
	Hard Coal	-	-	-	-	-	-	-100	-	-	-	-	-

4.1.7. Emissions

The emissions for both aggregated and disaggregated level results are displayed in Figure 4.12. At both levels, transportation in Türkiye is the primary reason for current emissions. Industry emits the second highest amount of emissions. In the transportation and other sectors, it is seen that the emission is approaching 0 in every scenario in 2040 at both levels by ensuring the use of fuels that cause less emission as seen in Figures 4.8, 4.9, 4.10 and 4.11. Emissions reach zero first in the DT scenario, where the price of carbon increases linearly and last in the GD scenario, where the price of carbon increases slowly. The role and significance of CO_2 prices are emphasized in the results of the study D3.2[39].

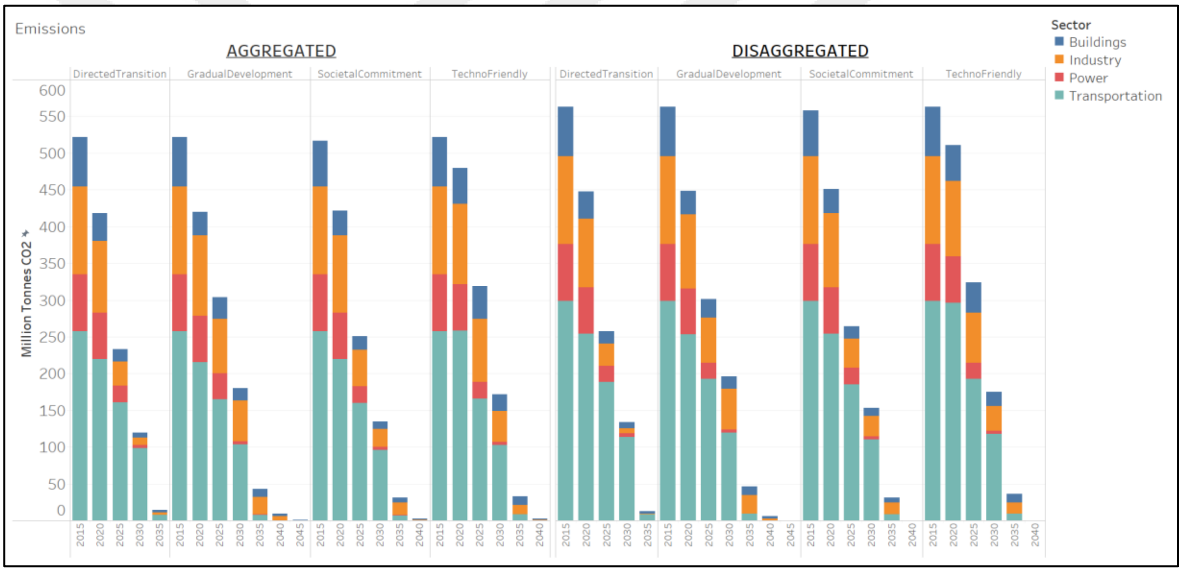

Figure 4.12. Emissions at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

Table 4.11 and Table 4.12 show the relative difference between model results of emissions of the four scenarios for the results achieved from 2025 to 2050 in both aggregated and disaggregated level results. At the disaggregated level, emissions are higher than aggregated level in transportation sector. Buildings sector results vary from year to year, whereas industry and power emission results are higher generally at the aggregated level.

Table 4.11. Relative difference between model results of emissions at the aggregated and disaggregated level for DT and GD scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) ('-' indicates that aggregated level result is zero)											
	Directed Transition					Gradual Development						
	2015	2020	2025	2030	2035	2015	2020	2025	2030	2035	2040	2045
Buildings	0	-1	-2	27	0	0	-2	-15	0	3	6	-100
Industry	0	-5	-8	-32	-97	0	-8	-17	-1	11	-60	-
Power	0	0	0	0	-	0	0	-37	0	-100	-	-
Transportation	16	16	17	16	14	16	17	17	16	5	-	-

Table 4.12. Relative difference between model results of emissions at the aggregated and disaggregated level for SC and TF scenarios

	RELATIVE DIFFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%) ('-' indicates that aggregated level result is zero)											
	Societal Commitment						Techno Friendly					
	2015	2020	2025	2030	2035	2040	2015	2020	2025	2030	2035	2040
Buildings	0	-3	-10	4	-6	-100	0	-1	-6	-14	-3	-100
Industry	0	-5	-19	14	-1	-100	0	-6	-21	-20	22	-83
Power	0	0	0	0	-100	-	0	0	-1	0	-	-
Transportation	16	16	16	15	14	-	16	15	16	15	11	-

4.1.8. Primary Energy

For both aggregated and disaggregated levels, the primary energy demand is shown in Figure 4.13. In contrast to the aggregated level, the disaggregated level has a much larger demand for solar energy while having a significantly lower demand for onshore wind energy. Up until 2035, these energy carriers' energy demand increased quickly at both levels and then stayed nearly steady. Also, by 2050, fossil fuels including gas, oil, and coal will be phased away. The demand for gas has significantly decreased in particular.

At an aggregate level, onshore wind and gas have the highest primary energy demand rates. Photovoltaics has a very high rate at the aggregated level, follows by gas demand. At the disaggregated level, the overall energy consumption is larger. Onshore wind and photovoltaics are the two technologies that affect demand the most significantly. Offshore wind and hydrogen OCGT based power plant technology are two further interesting findings. The demand for hydrogen OCGT based power plant is only seen at the disaggregated level, but the offshore wind demand only exists at the aggregated level.

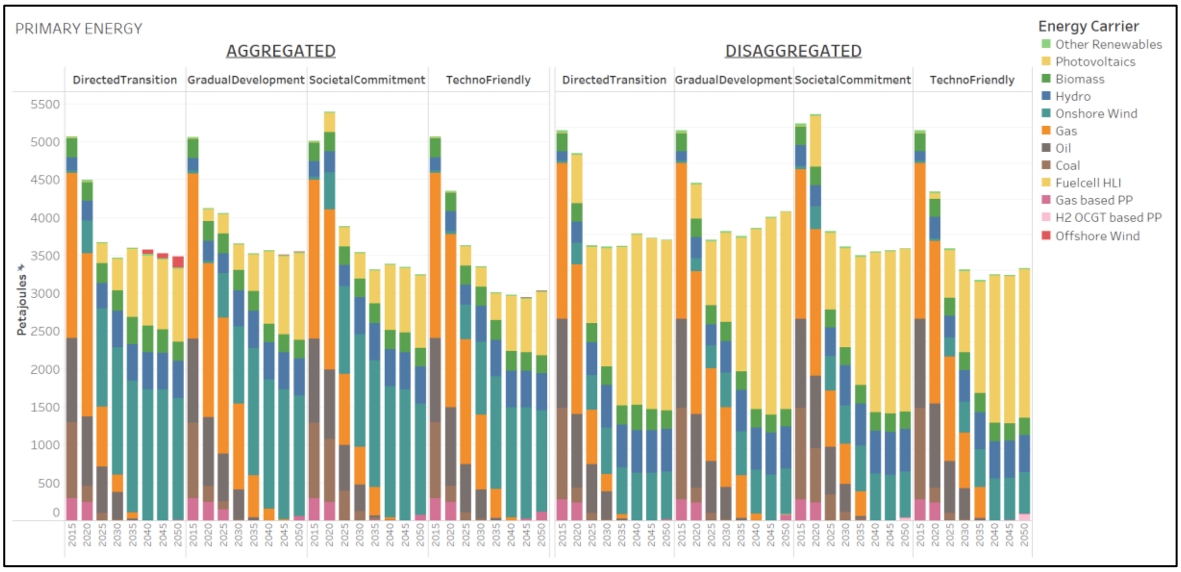

Figure 4.13. Primary energy demand results at the aggregated and disaggregated level results from 2025 to 2050 in each scenario

4.2. COMPARISON OF MODEL RESULTS

The aggregated and disaggregated level results differ in many scenarios. Table 4.8 shows the notable differences. Minor differences are also observed for power dispatch levels in the DT scenario. Plug-In Hybrid Electric Vehicles (PHEV) and Plug-In Hybrid Electric Vehicles fueled with biofuel (PHEV (bio)) levels are not observed in TF scenario in the aggregated level results. Although Battery-Electric Vehicle (BEV) is not detected in TF scenario in aggregated level, there is fewer rail (conventional) in all scenarios in the freight transportation sector. Similar differences are observed for freight transport, residential heat, industrial heat, and hydrogen production and use. Emission levels reach zero by 2040 in disaggregated level results for TF, GD, and SC scenarios. Whereas the emissions in aggregated level results for TF, GD, and SC scenarios are reaching zero beyond 2040.

Table 4.13. The notable differences between aggregated and disaggregated level results

SECTOR	Aggregated	Disaggregated
Power Generation & Use	More onshore wind generation	More solar PV generation and storage
Power Capacity	More onshore wind capacity	More solar PV and storage (electric and H_2) capacity and no offshore wind capacity
Power Dispatch	Minor differences in DT scenario are observed in both	
Passenger Transport	No PHEV and PHEV (Bio)	PHEV and PHEV (Bio) in TF scenario
Freight Transport	No road (BEV) in TF scenario	Less rail (conventional) in all scenarios
Building Heat	No direct electric in SC scenario	In GD, SC and TF scenarios natural gas phase out is by 2035.
Industrial Heat	More natural gas use in all scenarios	More hydrogen use in all scenarios
Hydrogen Production	No power from H_2 (OCGT) in SC and TF scenarios	More hydrogen production and use in all scenarios starting as early as 2025
Emissions	Zero emissions beyond 2040 in buildings in TF, GD and SC scenarios	Zero emissions by 2040 in all scenarios
Primary Energy	In SC and TF scenarios, fossil fuels phase out by 2040.	More from PV source and overall demand has increased slightly in all scenarios, fossil fuel phase out by 2035 in SC and TF scenarios

Table 4.14. Differences between aggregated and disaggregated level results

SECTOR	Aggregated	Disaggregated	RELATIVE DIFERENCE 100*(Disaggregated-Aggregated)/Aggregated (%)
Power Generation & Use	279.5	552.1	97.5
Hydro Production & Use	2,028.4	7,990.3	293.9
Total Capacity	10,216.2	12,826.5	25.6
New Capacity	4,702.7	5,763.7	22.6
Passenger Transport	6,041.6	6,041.6	0.00
Freight Transport	6,810.5	6,810.5	0.00
Building Heat	17,487	17,534.1	0.3
Industry Heat	15,528.2	15,661.9	0.9
Emissions	5,670.8	6,041.1	6.5
Primary Energy	12,1384	134,064.1	10.5

The evaluations that highlight the most significant difference between the two are those that focus on power and hydrogen usage and generation. There is no distinction between the aggregated and disaggregated levels of transportation for both freight and passenger.

5. CONCLUSION

There are various concerns in the energy sector. One of them is ensuring a stable and reliable energy supply while considering overall demand. Also, the energy sector focuses on ensuring equitable access to affordable and clean energy by shifting from fossil fuels to renewable energy sources. Consequently, addressing climate change and lowering greenhouse gas emissions allows for the realization of a future powered by sustainable energy. Particular focus is placed on integrating new technology, increasing energy efficiency across industries, obtaining sufficient funding and attracting investors to clean energy projects. These concerns draw attention to the numerous difficulties the energy industry faces in meeting the rising demand for energy. In this thesis the quantified scenario results of Turkish energy system's low-carbon futures at aggregated and disaggregated levels are introduced.

The aggregated and disaggregated level results show significant differences. However, the dominance of solar PV and wind resources are obvious for both models and for all scenarios. They keep rising until 2040 and reach a point of saturation afterwards. Coal and natural gas phase-outs in the power sector are observed around 2030. The new capacity allocations are observed in the power production map of Türkiye in 2050. On the other hand, the demand for hydrogen will increase significantly by 2040. Hydrogen production and use also provides important insights. Increasing solar PV capacity with lower capacity factor enables more hydrogen production in Türkiye. Significantly more solar PV capacity is installed in the disaggregated level due to regional availability (i.e., capacity factors). The demand for hydrogen mainly comes from the transportation sector.

In particular, when compared to the results at the aggregated level, the disaggregated level has significantly increased the production (and use) of hydrogen. The primary reason for these differences is shown to be the disaggregated level's higher estimation of regional renewable capacity factors (wind and solar) when compared to the aggregated level.

Türkiye has the potential to become a significant net exporter of energy to the rest of Europe, depending on the potential of renewable energy sources and domestic energy needs. Since there are no statistics available for the disaggregated level, the NUTS-1 level disaggregation depends on industry locations for the disaggregation of industrial heat demands, population for domestic heating, electricity and transport demand, and land area for resource potential. When compared to the results of the aggregated level, spatial disaggregation of the Turkish energy system into NUTS-1 level regions with better time series (capacity factor) estimation for solar PV and wind in each region enables more investments in solar PV technologies by 2050, more hydrogen production and use by 2050 and penetration of electricity and hydrogen storage technologies as early as 2025. A more thorough spatial (such as NUTS level 3 regions with 81 provinces) and temporal (such as 72 hours step) disaggregation study can be examined for future research.

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APPENDIX A: DETAILED MODEL RESULTS

Table A.1. Detailed model results of power generation and use at aggregated level for DT and GD scenarios (TWh)

	DirectedTransition						GradualDevelopment					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	15.3
Storages [Discharge]	0.0	0.0	15.1	17.8	15.2	12.9	0.0	0.0	0.0	16.3	18.0	15.3
Geothermal	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Photovoltaics	71.8	117.0	250.2	256.5	256.8	266.8	69.7	93.2	133.4	266.6	285.0	318.1
Wind [Offshore]	0.0	0.0	0.0	17.2	17.3	41.1	0.0	0.0	0.0	0.0	1.2	1.2
Wind [Onshore]	360.1	464.8	480.6	480.6	480.3	446.0	162.0	283.1	467.0	474.7	476.3	442.6
Biomass	0.8	0.7	0.6	0.5	0.4	0.4	0.8	0.7	0.6	0.5	0.4	0.4
Hydropower	91.3	135.4	134.7	134.7	134.7	135.4	72.6	131.6	134.7	134.7	134.7	135.4
Gas [Fossil Gas]	0.0	0.0	0.0	0.0	0.0	0.0	41.8	0.0	0.2	0.0	0.0	0.0
Coal [Lignite]	13.0	2.6	0.0	0.0	0.0	0.0	13.0	2.6	0.0	0.0	0.0	0.0
Coal [Hardcoal]	16.7	3.3	0.0	0.0	0.0	0.0	16.7	3.3	0.0	0.0	0.0	0.0
Storages [Charge]	0.0	0.0	15.1	17.8	15.2	12.9	0.0	0.0	0.0	16.3	18.0	15.3
Electrolysis	0.1	59.8	188.2	222.3	222.7	220.4	0.0	12.7	93.8	216.5	229.0	229.3
Demand [Transport]	77.2	88.9	95.1	85.7	77.4	69.4	70.7	109.9	115.4	101.2	87.3	76.3
Demand [Industry]	237.5	321.5	323.1	314.6	311.3	303.3	81.2	135.0	256.4	274.3	286.1	277.5
Demand [Buildings]	41.7	52.4	51.1	51.2	51.8	51.8	24.7	39.9	45.7	45.0	43.5	41.6
Demand [Final]	196.9	204.4	212.2	220.1	228.2	236.6	200.9	212.9	225.7	239.2	253.6	268.8
GENERATION	558.5	728.7	886.0	912.2	909.6	910.3	381.5	519.4	740.7	897.5	920.6	933.1
USE	553.4	726.9	884.7	911.7	906.7	894.3	377.5	510.4	737.0	892.5	917.5	908.9
ALL PROD.	**27.6**						**49.0**					

Table A.2. Detailed model results of power generation and use at aggregated level for SC and TF scenarios (TWh)

	SocietalCommitment						**TechnoFriendly**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	0.0	0.0	0.0	0.0	0.0	20.1	0.0	0.0	0.0	0.0	7.6	32.3
Storages [Discharge]	0.0	0.0	0.0	29.7	28.8	24.5	0.0	0.0	2.5	6.3	5.3	5.7
Geothermal	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Photovoltaics	69.9	92.1	119.2	236.2	235.6	307.8	71.1	71.1	97.3	201.0	196.8	231.0
Wind [Offshore]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.4
Wind [Onshore]	321.7	413.0	466.4	480.6	480.6	408.5	127.4	268.9	410.8	402.5	406.0	370.6
Biomass	0.8	0.7	0.6	0.5	0.4	0.4	0.8	0.7	0.6	0.5	0.4	0.4
Hydropower	76.4	135.4	135.4	134.7	135.4	135.4	72.6	131.6	134.7	134.7	134.2	135.4
Gas [Fossil Gas]	0.0	0.0	2.2	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Coal [Lignite]	13.0	2.6	0.0	0.0	0.0	0.0	13.0	2.6	0.0	0.0	0.0	0.0
Coal [Hardcoal]	16.7	3.3	0.0	0.0	0.0	0.0	16.7	3.3	0.0	0.0	0.0	0.0
Storages [Charge]	0.0	0.0	0.0	29.7	28.8	24.5	0.0	0.0	2.5	6.3	5.3	5.7
Electrolysis	0.2	26.8	48.8	161.9	184.1	171.2	0.0	3.9	70.2	160.8	174.9	163.7
Demand [Transport]	73.3	109.1	154.2	136.4	117.2	101.8	25.1	36.7	45.6	44.9	41.5	39.2
Demand [Industry]	181.3	252.9	257.6	283.7	274.7	267.3	67.2	191.1	261.4	257.5	248.6	239.9
Demand [Buildings]	40.9	47.5	49.6	52.4	49.9	45.5	5.5	30.5	42.7	41.8	39.7	37.6
Demand [Final]	195.9	202.3	208.8	215.3	221.9	228.5	198.9	208.7	218.9	229.7	240.9	252.7
GENERATION	503.3	652.0	728.5	886.6	885.7	901.5	307.3	483.0	650.7	749.8	756.4	781.5
USE	491.5	638.5	719.0	879.5	876.7	838.7	296.7	470.9	641.3	740.9	751.0	738.8
ALL PROD.	**113.7**						**89.1**					

Table A.3. Detailed model results of power generation and use at disaggregated level for DT and GD scenarios (TWh)

	DirectedTransition						**GradualDevelopment**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	0.0	0.0	0.0	0.0	0.0	5.8	0.0	0.0	0.0	0.0	0.0	24.0
Storages [Discharge]	4.0	45.3	54.5	61.8	54.4	47.2	2.6	3.6	9.9	17.9	21.5	19.4
Geothermal	7.3	6.2	5.2	4.5	3.8	3.2	7.3	6.2	5.2	4.5	3.8	3.2
Photovoltaics	295.7	459.0	624.1	674.8	675.7	676.8	247.9	347.2	526.8	712.0	776.1	778.0
Wind [Offshore]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind [Onshore]	135.9	179.2	183.6	184.7	184.7	184.2	89.4	134.8	170.9	172.5	178.3	178.3
Biomass	0.8	0.7	0.6	0.5	0.4	0.4	0.8	0.7	0.6	0.5	0.4	0.4
Hydropower	126.8	165.6	165.6	165.6	165.6	165.6	82.3	123.1	159.4	162.5	162.5	162.5
Gas [Fossil Gas]	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
Coal [Lignite]	13.0	2.6	0.0	0.0	0.0	0.0	13.0	2.6	0.0	0.0	0.0	0.0
Coal [Hardcoal]	16.7	3.3	0.0	0.0	0.0	0.0	16.7	3.3	0.0	0.0	0.0	0.0
Storages [Charge]	4.0	45.3	54.5	61.8	54.4	47.2	2.6	3.6	9.9	17.9	21.5	19.4
Electrolysis	29.3	152.4	299.3	355.3	359.4	358.2	2.2	131.1	244.3	414.8	475.1	452.8
Demand [Transport]	70.8	80.1	89.5	81.9	72.4	66.6	76.0	84.4	91.0	80.3	69.8	61.5
Demand [Industry]	246.6	321.5	318.4	310.6	305.5	299.9	131.1	137.8	245.7	261.3	265.2	258.0
Demand [Buildings]	42.2	49.5	49.5	49.8	50.1	47.2	31.3	39.8	45.3	44.5	42.3	38.8
Demand [Final]	196.9	204.4	212.2	220.1	228.2	236.6	200.9	212.9	225.7	239.2	253.6	268.8
GENERATION	600	862	1034	1092	1085	1083	461	622	873	1070	1143	1166
USE	590	853	1023	1079	1070	1056	444	610	862	1058	1127	1100
ALL PROD	**85**						**134**					

Table A.4. Detailed model results of power generation and use at disaggregated level for SC and TF scenarios (TWh)

	SocietalCommitment						**TechnoFriendly**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas [Synthetic Gas]	0.0	0.0	0.0	0.0	0.0	12.5	0.0	0.0	0.0	0.0	1.6	27.5
Storages [Discharge]	0.0	0.0	16.9	37.9	34.7	29.9	1.1	2.8	8.0	13.1	14.4	12.9
Geothermal	7.3	6.2	5.2	4.5	3.8	3.2	7.3	6.2	5.2	4.5	3.8	3.2
Photovoltaics	379.3	466.2	598.6	733.6	738.8	740.2	185.0	314.2	434.3	571.1	572.5	578.3
Wind [Offshore]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind [Onshore]	135.6	151.3	176.8	182.3	177.8	177.0	76.5	122.8	149.1	164.8	164.6	159.4
Biomass	0.8	0.7	0.6	0.5	0.4	0.4	0.8	0.7	0.6	0.5	0.4	0.4
Hydropower	109.3	155.1	163.8	165.5	165.5	165.5	82.3	122.6	143.8	143.8	143.8	143.8
Gas [Fossil Gas]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal [Lignite]	13.0	2.6	0.0	0.0	0.0	0.0	13.0	2.6	0.0	0.0	0.0	0.0
Coal [Hardcoal]	16.7	3.3	0.0	0.0	0.0	0.0	16.7	3.3	0.0	0.0	0.0	0.0
Storages [Charge]	0.0	0.0	16.9	37.9	34.7	29.9	1.1	2.8	8.0	13.1	14.4	12.9
Electrolysis	63.9	159.8	277.2	401.0	413.7	395.2	2.1	62.0	173.7	322.7	327.2	326.7
Demand [Transport]	78.7	107.9	138.8	122.6	105.7	91.9	26.7	36.8	45.8	44.1	40.7	37.8
Demand [Industry]	217.5	239.8	257.7	281.7	274.3	268.6	125.7	203.7	238.8	234.6	225.7	217.2
Demand [Buildings]	43.7	46.9	50.2	52.3	48.9	44.1	8.5	34.9	42.7	41.7	39.7	34.9
Demand [Final]	195.9	202.3	208.8	215.3	221.9	228.5	198.9	208.7	218.9	229.7	240.9	252.7
GENERATION	662	785	962	1124	1121	1129	383	575	741	898	901	925
USE	600	757	950	1111	1099	1059	363	549	728	886	889	882
ALL PROD	**207**						**126**					

Table A 5. Detailed model results of hydro generation and use at aggregated level for DT and GD scenarios (PJ)

	DirectedTransition					**GradualDevelopment**				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	167.8	531.8	630.3	632.5	626.8	38.3	292.8	696.6	758.5	782.7
Methanation	0.0	31.1	26.5	12.5	15.0	0.0	0.0	45.1	16.8	19.2
Industry	0.0	38.7	43.4	27.2	54.0	0.0	0.0	156.9	161.9	189.1
Buildings	0.0	22.9	62.5	58.1	60.5	0.0	0.0	113.2	99.6	184.7
Freight [Road H2]	98.7	291.0	321.5	348.6	361.7	9.6	207.8	244.9	275.2	289.8
Passenger [H2]	16.1	13.7	11.8	10.0	13.0	0.0	0.0	10.9	15.3	16.7
Gas	0.0	0.0	0.0	0.0	16.9	0.0	0.0	0.0	0.0	83.1
Hydrogen OCGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GENERATION	167.8	531.8	630.3	632.5	626.8	38.3	292.8	696.6	758.5	782.7
USE	114.7	397.5	465.6	456.4	521.2	9.6	207.8	570.9	568.7	782.6
PROD-USE	**634**					**429**				

Table A.6. Detailed model results of hydro generation and use at aggregated level for SC and TF scenarios (PJ)

	SocietalCommitment					**TechnoFriendly**				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	75.1	138.0	459.1	522.6	487.0	12.5	236.9	572.7	657.8	651.9
Methanation	0.0	0.0	69.0	47.8	42.2	0.0	0.0	17.3	4.1	25.3
Industry	0.0	0.0	71.2	41.6	60.4	0.0	97.2	228.5	216.8	230.6
Buildings	0.0	0.0	14.6	72.3	103.5	0.0	0.0	108.7	152.6	167.9
Freight [Road H2]	0.0	6.6	72.7	110.5	131.8	0.0	102.2	96.8	86.3	69.1
Passenger [H2]	11.5	9.6	10.6	12.5	12.4	12.6	11.8	9.8	13.5	14.3
Gas	0.0	0.0	0.0	0.0	115.0	0.0	0.0	0.0	41.7	175.6
Hydrogen OCGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GENERATION	75.1	138.0	459.1	522.6	487.0	12.5	236.9	572.7	657.8	651.9
USE	11.5	16.1	238.0	284.7	465.4	12.6	211.2	461.2	515.1	632.1
PROD-USE	**666**					**299**				

Table A.7. Detailed computational results of hydro generation and use at disaggregated level for DT and GD scenarios (PJ)

	DirectedTransition					GradualDevelopment				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	427.9	845.8	1,007.2	1.020.6	1,018.7	396.5	763.0	1,334.9	1,573.7	1,545.2
Methanation	0.0	66.2	78.0	55.5	48.3	0.0	0.0	127.9	88.5	54.1
Industry	38.3	90.8	81.1	91.2	108.5	0.0	0.0	273.5	246.4	305.3
Buildings	0.0	43.5	75.9	80.5	115.5	0.0	0.0	117.3	124.9	254.8
Freight [Road H2]	172.1	379.6	402.6	421.5	425.7	134.9	355.0	377.2	388.6	391.2
Passenger [H2]	32.5	29.8	28.0	31.4	32.4	10.1	26.4	25.7	28.7	29.5
Gas	0.0	0.0	0.0	0.0	33.3	0.0	0.0	0.0	0.0	130.7
Hydrogen OCGT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GENERATION	427.9	845.8	1,007.2	1.020.6	1,018.7	396.5	763.0	1,334.9	1,573.7	1,545.2
USE	242.8	610.0	665.6	680.0	763.7	145.0	381.4	921.5	877.1	1,165.6
PROD-USE	**1,358**					**2,123**				

Table A.8. Detailed computational results of hydro generation and use at disaggregated level for SC and TF scenarios (PJ)

	SocietalCommitment					TechnoFriendly				
	2030	**2035**	**2040**	**2045**	**2050**	**2030**	**2035**	**2040**	**2045**	**2050**
Electrolysis	448.5	783.2	1,136.6	1,174.7	1,123.8	198.3	586.6	1,149.2	1,230.3	1,300.6
Methanation	0.0	0.0	211.9	178.5	73.8	0.0	0.0	64.6	11.1	42.4
Industry	0.0	0.0	83.3	69.3	91.1	91.4	132.5	328.8	334.4	361.5
Buildings	0.0	0.0	18.7	74.6	175.5	0.0	5.2	149.0	148.8	201.9
Freight [Road H2]	34.5	137.9	179.6	202.1	214.0	0.0	158.3	150.7	133.5	122.0
Passenger [H2]	30.8	26.2	25.1	25.5	25.1	29.1	25.7	23.2	25.6	25.5
Gas	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	8.6	3.6
Hydrogen OCGT	0.0	0.0	0.0	0.0	95.2	0.0	0.0	0.0	0.0	153.5
GENERATION	448.5	783.2	1,136.6	1,174.7	1,123.8	198.3	586.6	1,149.2	1,230.3	1,300.6
USE	65.3	164.1	518.7	550.0	678.1	120.5	321.7	716.2	662.0	825.5
PROD-USE	**2,691**					**1,819**				

Table A.9. Detailed model results of total capacity at aggregated level for DT and GD scenarios (GW)

	DirectedTransition						**GradualDevelopment**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	0	0	15.5	15.5	15.6	15.6	0	0	0	11.1	14.8	14.8
H2 Storage	0	10.5	33.5	33.5	33.5	33.5	0	0.2	12.6	47.4	50.3	70.1
Solar	51.5	83.9	180	184	184	191	50	66.9	95.7	191	207	235
Wind Offshore	0	0	0	4.8	4.8	11.3	0	0	0	0	0.4	0.4
Wind Onshore	150	195	202	202	202	187	67.9	119	196	202	202	186
Biomass	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Hydro	32.6	47.6	47.6	47.6	47.6	47.6	25.9	46.3	47.6	47.6	47.6	47.6
Lignite	3.9	2.9	2.2	1.6	1.2	0.9	3.9	2.9	2.2	1.6	1.2	0.9
Hardcoal	5.2	3.6	3.3	3.3	3.3	0.1	5.2	3.6	3.3	3.3	3.3	0.1
Oil	0.2	0.2	0.1	0	0	0	0.2	0.2	0.1	0	0	0
Demand [Industry]	0	2.3	2.8	2.8	2.8	2.8	0	0	0	0	0	0
Demand [Buildings]	9.1	29.6	29.6	29.6	29.6	29.6	10.5	21.9	25.5	25.5	25.5	15.2
Gas	21.2	21.2	20.6	20.4	17.5	8.1	21.2	21.2	20.6	20.4	17.5	8.1
Subtotal	278	402	542	550	547	533	190	287	409	555	574	582
TOTAL	**2851.4**						**2596.3**					

Table A.10. Detailed model results of total capacity at aggregated level for SC and TF scenarios (GW)

	SocietalCommitment						**TechnoFriendly**					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	0	0	0	23.3	23.3	23.3	0	0	5.2	12.9	12.9	11.7
H2 Storage	0	3.4	10.9	35.9	35.9	35.9	0	0	7.6	38.6	38.6	46.3
Solar	50.2	66.1	85.5	169	169	221	51	51	69.8	144	144	166
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0.4	0.4
Wind Onshore	134	172	196	202	202	172	52.6	113	172	172	172	154
Biomass	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Hydro	27.2	47.6	47.6	47.6	47.6	47.6	25.9	46.3	47.6	47.6	47.6	47.6
Lignite	3.9	2.9	2.2	1.6	1.2	0.9	3.9	2.9	2.2	1.6	1.2	0.9
Hardcoal	5.2	3.6	3.3	3.3	3.3	0.1	5.2	3.6	3.3	3.3	3.3	0.1
Oil	0.2	0.2	0.1	0	0	0	0.2	0.2	0.1	0	0	0
Demand [Industry]	0	0	0.8	1.9	2.4	2.4	0	0	0	0	0	0
Demand [Buildings]	10	20.5	20.5	20.5	20.5	19.2	2.4	15.9	24.7	24.7	24.7	23.2
Gas	21.2	21.2	20.6	20.4	17.5	8.1	21.2	21.2	20.6	20.4	17.5	8.1
Subtotal	257	343	392	531	528	535	167	258	358	470	467	463
TOTAL	**2585.2**						**2183.2**					

Table A.11. Detailed model results of total capacity at disaggregated level for DT and GD scenarios (GW)

	DirectedTransition						GradualDevelopment					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	8.2	49	65.1	65.4	64.5	64.7	5.4	7.4	20.4	28.3	33.8	32.8
H2 Storage	3.3	22.5	44.3	46.8	46.8	46.8	0.2	12.2	31.9	64.1	85.3	85.3
Solar	154	242	360	399	399	396	120	176	306	454	507	489
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0	0
Wind Onshore	51.9	69.8	71	71	70.8	70.6	32.2	50.1	64.5	65.1	68.4	67.6
Biomass	0.5	0.5	0.5	0.2	0.1	0.1	0.5	0.5	0.5	0.1	0.1	0.1
Hydro	43.9	57.3	57.3	57.3	57.3	57.3	28.5	42.6	55.1	56.2	56.2	56.2
Lignite	4.9	4.2	3.6	1.7	1.6	0.8	4.9	4.2	3.6	1.7	1.6	0.8
Hardcoal	9.3	9.3	9.3	7.7	4.1	1.3	9.3	9.3	9.3	7.7	4.1	1.3
Oil	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Demand [Industry]	0	0.9	1.4	1.5	1.5	1.5	0	0	0	0	0	0
Demand [Buildings]	16.2	27.6	27.6	27.6	27.6	27.6	14.8	21.4	25.1	25.1	25.1	15.8
Gas	20.3	14.1	10.7	5.2	1	0.9	20.3	14.1	10.7	5.2	1	3.5
SUM	314	499	652	684	676	668	237	339	528	708	783	753
OVERALL	**3492.5**						**3349.1**					

Table A.12. Detailed model results of total capacity at disaggregated level for SC and TF scenarios (GW)

	SocietalCommitment						TechnoFriendly					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Hydrogen OCGT	0	0	0	0	0	2.8	0	0	0	0	0	6.1
Electricity Storage	0	0	24.4	42.2	45.1	42	2.2	5.7	16.4	26.9	29.8	26.1
H2 Storage	6	18.7	21.9	55.2	56.4	57	0	11.7	18.1	67.1	67.9	68
Solar	183	233	334	436	429	425	87.2	149	238	337	337	329
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0	0
Wind Onshore	49.7	56.2	67.7	71	68.4	68	28.8	45.1	56.4	61.9	61.9	59.2
Biomass	0.5	0.5	0.5	0.2	0.1	0.1	0.5	0.5	0.5	0.1	0.1	0.1
Hydro	37.8	53.7	56.7	57.2	57.2	57.2	28.5	42.4	49.8	49.8	49.8	49.8
Lignite	4.9	4.2	3.6	1.7	1.6	0.8	4.9	4.2	3.6	1.7	1.6	0.8
Hardcoal	9.3	9.3	9.3	7.7	4.1	1.3	9.3	9.3	9.3	7.7	4.1	1.3
Oil	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Demand [Industry]	0	0	0.1	0.8	0.8	0.8	0	0	0	0	0	0
Demand [Buildings]	13.5	19.4	19.4	19.4	19.4	17.7	3.4	18.6	24.7	24.7	24.7	23.1
Gas	20.3	14.1	10.7	5.2	1	0.2	20.3	14.1	10.7	5.2	1	0.2
SUM	326	410	550	698	684	674	186	302	428	583	579	565
OVERALL	**3341.4**						**2643.6**					

Table A.13. Detailed model results of new capacity at aggregated level for DT and GD scenarios (GW)

	DirectedTransition						GradualDevelopment					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	0	0	0	0	0	0	0	0	0	0	0	0
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	0	0	15.5	0	0.1	0	0	0	0	11.1	3.8	0
H2 Storage	0	10.5	22.9	0	0	0	0	0.2	12.4	34.8	2.9	19.9
Solar	51.3	32.4	95.5	4.5	0.2	58.5	18.4	16.9	28.8	95.5	47	46.3
Wind Offshore	0	0	0	4.8	0	6.5	0	0	0	0	0.4	0
Wind Onshore	101	45.6	7	0	44.1	85.9	63.4	50.9	77.4	6	0	46.6
Biomass	0	0	0	0	0	0	0	0	0	0	0	0
Hydro	6.7	15	0	0	0	0	0	20.4	1.3	0	0	0
Lignite	0	0	0	0	0	0	0	0	0	0	0	0
Demand [Industry]	0	2.3	0.5	0	0	0	0	0	0	0	0	0
Demand [Buildings]	9.1	20.5	0	0	0	0	0.3	11.4	3.6	0	0	0
SUM	168	126	141	9.3	44.4	151	82.1	99.8	124	147	54.1	113
OVERALL	**640.5**						**619.7**					

Table A.14. Detailed model results of new capacity at aggregated level for SC and TF scenarios (GW)

	SocietalCommitment						TechnoFriendly					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	0	0	0	0	0	0	0	0	0	0	0	0
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	0	0	0	23.3	0	0	0	0	5.2	7.7	0	4
H2 Storage	0	3.4	7.5	25	0	0	0	0	7.6	30.9	0	7.8
Solar	0	15.9	19.4	83.9	49.6	51.8	50.8	0	18.8	74.4	0	72.3
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0.4	0
Wind Onshore	79.2	38.2	23.6	6.3	50.6	48.9	48.1	60	59.3	0	0	30.6
Biomass	0	0	0	0	0	0	0	0	0	0	0	0
Hydro	0	20.4	0	0	0	0	0	20.4	1.3	0	0	0
Lignite	0	0	0	0	0	0	0	0	0	0	0	0
Demand [Industry]	0	0	0.8	1.2	0.4	0	0	0	0	0	0	0
Demand [Buildings]	8.8	10.4	0	0	0	0	0.8	13.5	8.8	0	0	0
SUM	88	88.3	51.3	140	101	101	99.7	93.9	101	113	0.4	115
OVERALL	**568.6**						**522.7**					

Table A.15. Detailed model results of new capacity at disaggregated level for DT and GD scenarios (GW)

	DirectedTransition						GradualDevelopment					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	0	0	0	0	0	0.8	0	0	0	0	0	3.4
Hydrogen OCGT	0	0	0	0	0	0	0	0	0	0	0	0
Electricity Storage	8.2	40.7	16.1	8.5	1.7	6.9	5.4	1.9	13	13.4	7.4	12
H2 Storage	3.3	19.2	21.8	2.5	0	0	0.2	12	19.6	32.2	21.2	0
Solar	63	88	117	38.7	90.3	59.6	60.1	56.1	130	148	112	42
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0	0
Wind Onshore	19.5	18	1.2	0	24.9	19.3	13.4	17.9	14.4	0.6	14.8	12.6
Biomass	0	0	0	0.1	0	0	0	0	0	0	0	0
Hydro	15.4	13.4	0	0	0	0	0	14.1	12.5	1.1	0	0
Lignite	0.1	0	0	0	0	0	0.1	0	0	0	0	0
Demand [Industry]	0	0.9	0.6	0.1	0	0	0	0	0	0	0	0
Demand [Buildings]	16.2	11.4	0	0	0	0	4.6	6.5	3.7	0	0	0.9
SUM	126	192	157	49.9	117	86.6	83.8	109	193	195	155	70.9
OVERALL	**727.8**						**806**					

Table A.16. Detailed model results of new capacity at disaggregated level for SC and TF scenarios (GW)

	SocietalCommitment						TechnoFriendly					
	2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gas	0	0	0	0	0	0	0	0	0	0	0	0
Hydrogen OCGT	0	0	0	0	0	2.8	0	0	0	0	0	6.1
Electricity Storage	0	0	24.4	17.8	2.9	11	2.2	3.5	10.7	12.7	6.4	7.1
H2 Storage	6	12.7	3.2	33.3	1.2	0.6	0	11.7	6.3	49	0.8	0.1
Solar	45.5	49.8	102	102	128	41.8	78.6	62.1	88.4	99.1	7.5	69.9
Wind Offshore	0	0	0	0	0	0	0	0	0	0	0	0
Wind Onshore	16.3	6.5	11.6	3.3	23.5	15.9	21.5	16.3	11.3	5.5	0	18.8
Biomass	0	0	0	0.1	0	0	0	0	0	0	0	0
Hydro	9.3	15.9	3	0.6	0	0	0	14	7.3	0	0	0
Lignite	0.1	0	0	0	0	0	0.1	0	0	0	0	0
Demand [Industry]	0	0	0.1	0.6	0	0	0	0	0	0	0	0
Demand [Buildings]	11.8	5.9	0	0	0	0	1.9	15.2	6	0	0	0
SUM	89	90.8	144	158	156	72.1	104	123	130	166	14.7	102
OVERALL	**709.4**						**640.1**					

Table A.17. Detailed model results of passenger and freight transport at aggregated level for DT and GD scenarios (gpkm)

		DirectedTransition						GradualDevelopment					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PASSENGER (gpkm)	Rail [Electric]	36.4	41.7	46.6	52.4	57.7	64.7	36.7	42.6	48.1	54.6	60.7	68.9
	Road [BEV]	57.1	105	171	168	162	138	57.7	107	190	185	157	134
	Road [H2]	0	0	0	0	0	15.6	0	0	0	0	22.8	37.7
	Road [PHEV|Bio]	0	0	13.5	19.8	16.8	14.3	0	0	0	10.1	8.6	7.3
	Road [PHEV]	27.4	27.4	9.8	0	0	0	10.1	10.1	10.1	0	0	0
	Road [ICE]	134	74	0	0	0	0	153	93.3	0	0	0	0
	Air [Conv]	14.5	0	0	0	0	0	15	13.3	11.7	0	0	0
	Air [H2]	0.3	13	11.3	10	8.6	7.3	0	0	0	10.4	9	7.7
	SUM	**269**	**261**	**252**	**250**	**245**	**240**	**272**	**266**	**260**	**260**	**258**	**255**
FREIGHT (gtkm)	Rail [Bio]	35.4	0	0	0	0	0	16.9	0	0	0	0	0
	Rail [Electric]	31.7	72.5	77.8	82.5	89.2	99.8	50.9	73.9	80.3	86	92.7	105
	Road [OH]	0	0	0	0	0	0	0	0	0	0	0	0
	Road [BEV]	72.3	75.9	76.1	64.7	55	46.7	68.1	111	112	94.8	80.6	68.5
	Road [H2]	0	33.4	99	110	120	125	0	3.5	78.1	95	110	120
	Road [PHEV|Bio]	0	0	9	14.8	12.6	10.7	0	0	0	7.4	6.3	5.3
	Road [PHEV]	24.1	20.5	8.4	0	0	0	10.2	10.2	8.7	0	0	0
	Road [Bio]	0	3.8	0	0	0	0	4.9	0.6	0.1	0	0	0
	Road [ICE]	106	63.9	0	0	0	0	122	75.9	0	0	0	0
	Ship[Bio]	0.4	14.2	12.7	12.8	11.5	11.7	0.6	13.1	13.1	13.3	13.3	13.3
	Ship[Conv]	15.3	0	0	0	0	0	15.3	1.4	0	0	0	0
	SUM	218	212	205	202	199	194	221	216	212	211	210	207

Table A.18. Detailed model results of passenger and freight transport at aggregated level for DT and GD scenarios

		SocietalCommitment						TechnoFriendly					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PASSENGER (gpkm)	Rail [Electric]	35.4	39.6	43	47	49.9	54	36.7	42.6	48.1	54.6	60.7	68.9
	Road [BEV]	55.7	99.4	170	160	136	116	57.7	107	190	195	166	141
	Road [H2]	0	0	0	0	13	19.9	0	0	0	0	22.8	37.7
	Road [PHEV|Bio]	0	0	0	7.7	6.5	5.6	0	0	0	0	0	0
	Road [PHEV]	9	9	9	0	0	0	0	0	0	0	0	0
	Road [ICE]	148	87.1	0	0	0	0	163	103	10.1	0	0	0
	Air [Conv]	14.1	3.1	2.6	0	0	0	15	1.6	0	0	0	0
	Air [H2]	0.3	9.3	7.9	8.9	7.6	6.5	0	11.7	11.7	10.4	9	7.7
	SUM	**262**	**248**	**233**	**224**	**213**	**202**	**272**	**266**	**260**	**260**	**258**	**255**
FREIGHT (gtkm)	Rail [Bio]	19.5	0	0	0	1.1	0	20.3	0.2	0	0	0	0
	Rail [Electric]	45.5	68	70.6	72.2	72.2	79.2	47.5	73.7	80.3	86	92.7	105
	Road [OH]	0	0	0	0	0	0	73	115	146	148	152	155
	Road [BEV]	70.1	106	155	134	114	97	0	0	0	0	0	0
	Road [H2]	0	0	2.2	24.8	37.9	45.4	0	0	41.5	41.5	39.2	33.3
	Road [PHEV|Bio]	0	0	0	6.5	5.5	4.7	0	0	0	7.4	6.3	5.3
	Road [PHEV]	9	9	7.6	0	0	0	8.7	10.2	8.7	0	0	0
	Road [Bio]	0	0	10.1	0	0	0	0	0	2.3	0	0	0
	Road [ICE]	117	70.2	0	0	0	0	123	75.9	0	0	0	0
	Ship[Bio]	0	11.6	11.6	11.3	11.6	11	0.6	13.1	13.1	13.3	13.3	13.3
	Ship[Conv]	15.3	1.8	0	0	0	0	15.3	1.4	0	0	0	0
	SUM	212	199	186	177	169	158	148	101	65.6	62.2	58.8	51.9

Table A.19. Detailed model results of passenger and freight transport at disaggregated level for DT and GD scenarios

		DirectedTransition						GradualDevelopment					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PASSENGER (gpkm)	Rail [Electric]	15.6	21.6	28.3	35.4	42.1	50.6	15.8	22	29.2	36.9	44.3	53.7
	Road [BEV]	59.1	108	161	158	137	116	59.7	110	195	190	164	139
	Road [H2]	0	0	0	0	16.6	28.7	0	0	0	0	19	33.5
	Road [PHEV|Bio]	0	0	28	32.3	27.5	23.3	0	0	0	8.8	7.5	6.4
	Road [PHEV]	44.7	44.7	10	0	0	0	10.4	10.4	10.4	0	0	0
	Road [ICE]	122	60	0	0	0	0	158	96.5	0	0	0	0
	Air [Conv]	26.3	0	0	0	0	0	27.7	18.1	1.3	0	0	0
	Air [H2]	1.7	26.4	24.7	23.6	22.4	20.9	0.5	8.8	24.2	24.6	23.6	22.3
	SUM	**269**	**261**	**252**	**250**	**246**	**240**	**272**	**266**	**260**	**260**	**258**	**255**
	OVERALL SUM	**1517.3**						**1572.1**					
FREIGHT (gtkm)	Rail [Bio]	4.4	0	0	0	0	0	0.3	0	0	0	0	0
	Rail [Electric]	25.4	36.5	44.4	50	58.7	71	29.9	37.2	45.7	52	61.5	75.5
	Road [OH]	0	0	0	0	0	0	0	0	0	0	0	0
	Road [BEV]	67.2	72.1	76.8	67	57	50.5	80	85.7	85.8	73	62	52.7
	Road [H2]	12.7	58.3	129	138	145	147	1.9	49.3	134	146	155	162
	Road [PHEV|Bio]	0	0	6.8	14	11.9	10.1	0	0	0	8.5	7.2	6.1
	Road [PHEV]	22.7	19.4	9.7	0	0	0	11.8	11.8	10	0	0	0
	Road [Bio]	5	1.8	0	0	0	0	3.9	0	0	0	0	0
	Road [ICE]	131	79.2	0	0	0	0	143	88.8	0	0	0	0
	Ship[Bio]	0.4	16.9	16.3	16	15.6	15.2	0.4	16.8	16.8	16.8	16.8	16.2
	Ship[Conv]	17	0	0	0	0	0	17.2	0.5	0	0	0	0
	SUM	256	248	239	235	229	222	258	253	246	245	241	237
	OVERALL SUM	**1427.9**						**1479.6**					

Table A.20. Detailed model results of passenger and freight transport at disaggregated level for SC and TF scenarios

		SocietalCommitment						TechnoFriendly					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PASSENGER (gpkm)	Rail [Electric]	15.2	20.5	26.1	31.7	36.5	41.8	15.8	22	29.2	36.9	44.3	53.8
	Road [BEV]	57.6	103	175	163	140	119	59.7	110	195	194	165	140
	Road [H2]	0	0	0	0	10.5	16.9	0	0	0	0	20.4	34.6
	Road [PHEV|Bio]	0	0	0	7.9	6.7	5.7	0	0	0	4.8	5.3	4.5
	Road [PHEV]	9.3	9.3	9.3	0	0	0	0.7	5.6	5.6	0	0	0
	Road [ICE]	153	90.1	0	0	0	0	168	101	4.7	0	0	0
	Air [Conv]	6.5	0	1.1	0	0	0	27.7	0	0	0	0	0
	Air [H2]	20.8	25	21.6	21.2	19.5	18.3	0.5	26.9	25.4	24.6	23.6	22.2
	SUM	**263**	**248**	**233**	**224**	**213**	**202**	**272**	**266**	**260**	**260**	**258**	**255**
	OVERALL SUM	**1381.1**						**1571.5**					
FREIGHT (gtkm)	Rail [Bio]	1.1	0	0	0	0	0	3.4	0	0	0	0	0
	Rail [Electric]	27.8	34.2	40.3	43.7	48	57.2	26.7	37.2	45.7	52	61.5	74.6
	Road [OH]	0	0	0	0	0	0	80.3	130	146	148	152	152
	Road [BEV]	81.1	111	141	122	104	88.5	5.3	4.5	6.4	5.5	4.6	3.9
	Road [H2]	0.4	11.7	46.9	61.3	69.3	73.7	0	0	64.4	64.7	60.6	58.8
	Road [PHEV|Bio]	0	0	0	7.5	6.4	5.4	0	0	1	9.3	7.9	6.8
	Road [PHEV]	10.4	10.4	8.8	0	0	0	13.2	12.7	10	0	0	0
	Road [Bio]	0.8	1.2	4.7	0	0	0	0.1	0	1.6	0	0	0
	Road [ICE]	138	82.2	0	0	0	0	142	87.9	0	0	0	0
	Ship[Bio]	0.4	14.8	14.8	14	14.6	12.5	0.4	16.8	16.8	16.8	16.8	16.5
	Ship[Conv]	16.5	1.1	0	0	0	0	17.2	0.5	0	0	0	0
	SUM	248	233	217	205	194	180	178	122	100	96.3	89.9	86
	OVERALL SUM	**1276.7**						**672.5**					

Table A.21. Detailed model results of building and industrial heat at aggregated level for DT and GD scenarios (PJ)

		DirectedTransition						GradualDevelopment					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	79.8	67.9	57.7	49	41.7	35.4	79.8	67.9	57.7	49	77.7	62.3
	Direct Electric	0	0	14.3	12.2	13.6	16.6	0	0	0	0	0	0
	Heatpump [Air-Sourced]	440	559	548	551	559	559	268	443	517	518	509	494
	Hydrogen	0	0	20.7	56.5	52.6	54.7	0	0	0	114	106	191
	Natural Gas	277	108	49.9	0	0	0	466	265	182	54.9	13.8	0
	Hardcoal	0	0	0	0	0	0	7.2	5.7	2.9	0	0	0
	Oil	0.1	0.2	0.5	0	0	0	0.5	1	0.5	0.2	0	0
	TOTAL	**4224.9**						**4554.4**					
INDUSTRY	Direct Electric	326	589	589	589	589	589	3.7	165	505	584	663	663
	Hydrogen	0	0	7.3	3.8	0	0	0	0	0	27.1	36.9	62.1
	Natural Gas	344	53.4	17.2	0	0	0	691	526	180	77.6	0	0
	Hard Coal	0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL	**3694.9**						**4183.9**					

Table A.22. Detailed model results of building and industrial heat at aggregated level for SC and TF scenarios (PJ)

		SocietalCommitment						TechnoFriendly					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	79.8	67.9	57.7	49.6	42.6	66.3	79.8	67.9	57.7	70.7	41.7	35.4
	Direct Electric	0	0	0	0	0	0	0	0	0	0	0	0
	Heatpump [Air-Sourced]	432	508	533	564	539	491	61.4	351	507	511	500	487
	Hydrogen	0	0	0	13.1	65.5	94.1	0	0	0	116	165	189
	Natural Gas	284	158	107	28.7	0	0	642	357	192	38.8	0	0
	Hardcoal	2.9	5.7	0	0	0	0	38	5.7	2.9	0	0	0
	Oil	0	0	0	0	0	0	0.5	1	0.5	0	0	0
	TOTAL	**4189.3**						**4518.6**					
INDUSTRY	Direct Electric	334	421	421	524	524	524	146	393	650	658	658	658
	Hydrogen	0	0	0	27.5	2.4	0	0	0	0	30.4	43.6	66.8
	Natural Gas	326	200	161	0	0	0	545	298	35.3	0	0	0
	Hard Coal	0	0	0	0	0	0	4.8	0	0	0	0	0
	TOTAL	**3464.1**						**4185.9**					

Table A.23. Detailed model results of building and industrial heat at disaggregated level for DT and GD scenarios (PJ)

		DirectedTransition						**GradualDevelopment**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	79.8	67.9	57.7	53.5	41.7	35.4	79.8	67.9	57.7	49	82.9	43.7
	Direct Electric	0	1.6	11.7	10.4	12.9	15.7	0	0	0	0	0	0
	Heatpump [Air-Sourced]	446	529	532	536	541	510	339	443	513	513	495	461
	Hydrogen	0	0	39.5	68.8	72.9	105	0	0	0	117	129	260
	Natural Gas	272	137	50.5	0	0	0	395	265	186	57.7	0	0
	Hardcoal	0	0	0	0	0	0	7.1	5.7	2.9	0	0	0
	Oil	0.1	0.1	0.3	0	0	0	0.5	1	0.5	0.2	0	0
	TOTAL	**4226.3**						**4571.1**					
		DirectedTransition						**GradualDevelopment**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
INDUSTRY	Direct Electric	356	602	602	602	602	602	123	137	492	561	604	607
	Hydrogen	0	0	11	0.7	0	0	0	0	0	111	96	148
	Natural Gas	315	40.1	0.1	0	0	0	572	553	193	17	0	0
	Hard Coal	0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL	**3732**						**4214.4**					

Table A.24. Detailed model results of building and industrial heat at disaggregated level for SC and TF scenarios (PJ)

		SocietalCommitment						**TechnoFriendly**					
		2025	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BUILDING	Biogas & Biomass	79.8	67.9	57.7	74.1	50.2	35.4	79.8	67.9	57.7	72.6	46	35.4
	Direct Electric	0	0	0	1.5	1.9	3.4	0	0	0	0	0	0
	Heatpump [Air-Sourced]	462	501	539	563	527	476	93.8	401	507	510	500	452
	Hydrogen	0	0	0	16.9	67.6	159	0	0	5.7	154	162	230
	Natural Gas	255	165	101	0	0	0	620	307	186	0	0	0
	Hardcoal	2.7	5.4	0	0	0	0	27.4	5.7	2.9	0	0	0
	Oil	0	0	0	0.1	0	0	0.6	1	0.5	0	0	0
	TOTAL	**4211.6**						**4525.7**					
INDUSTRY	Direct Electric	383	424	436	525	525	525	245	422	544	548	548	548
	Hydrogen	0	0	0	26	10.8	15.5	0	0	0	141	168	200
	Natural Gas	278	199	146	0	0	0	450	269	141	0	0	0
	Hard Coal	0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL	**3492.8**						**4222.8**					

APPENDIX B: REGIONAL MODEL RESULTS

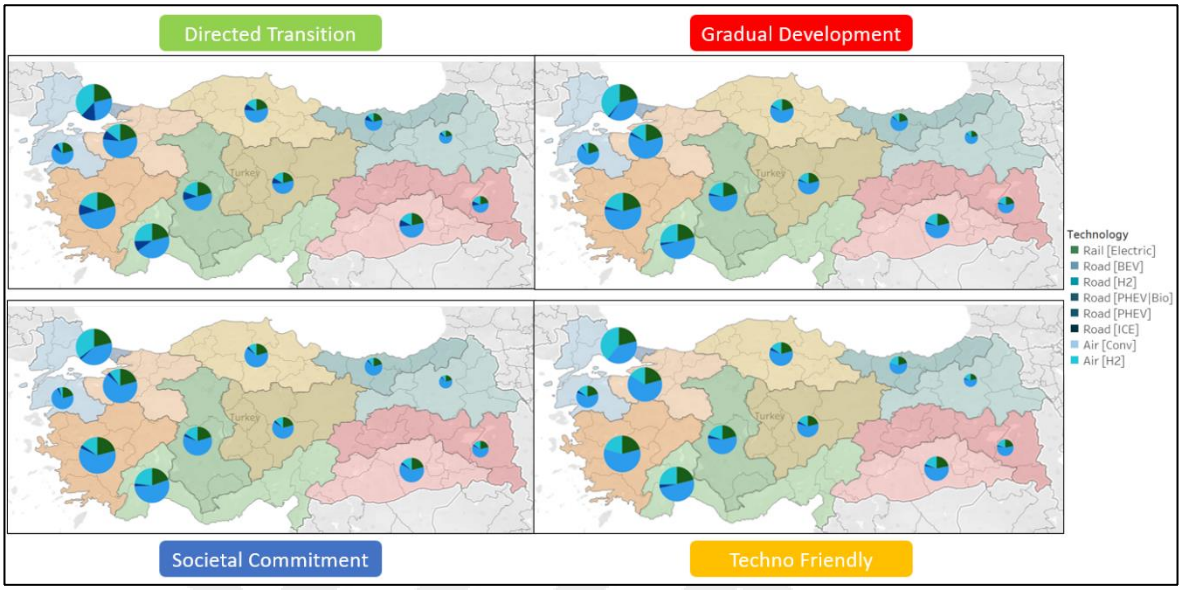

Figure B.1. Passenger transport in 2050 at disaggregated level in each scenario

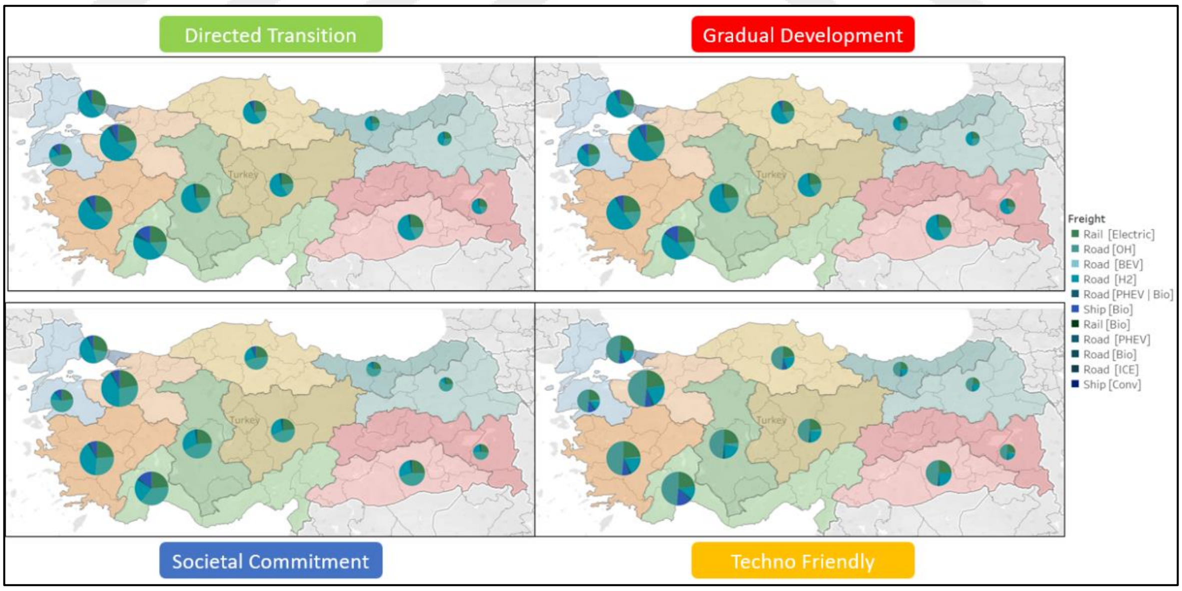

Figure B.2. Freight transport in 2050 at disaggregated level in each scenario

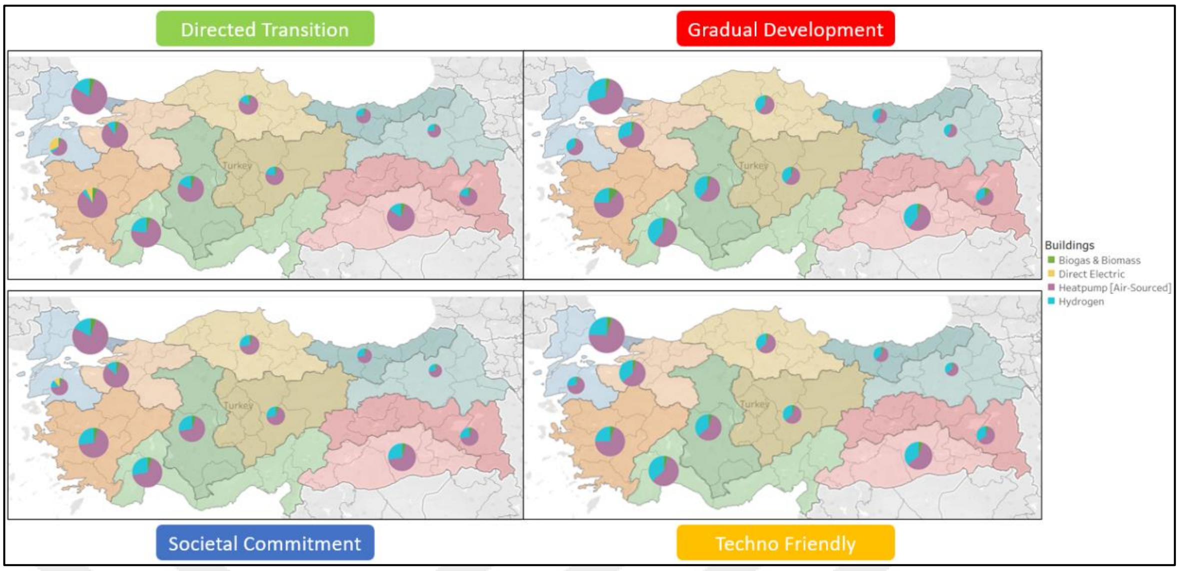

Figure B.3. Building heat in 2050 at disaggregated level in each scenario

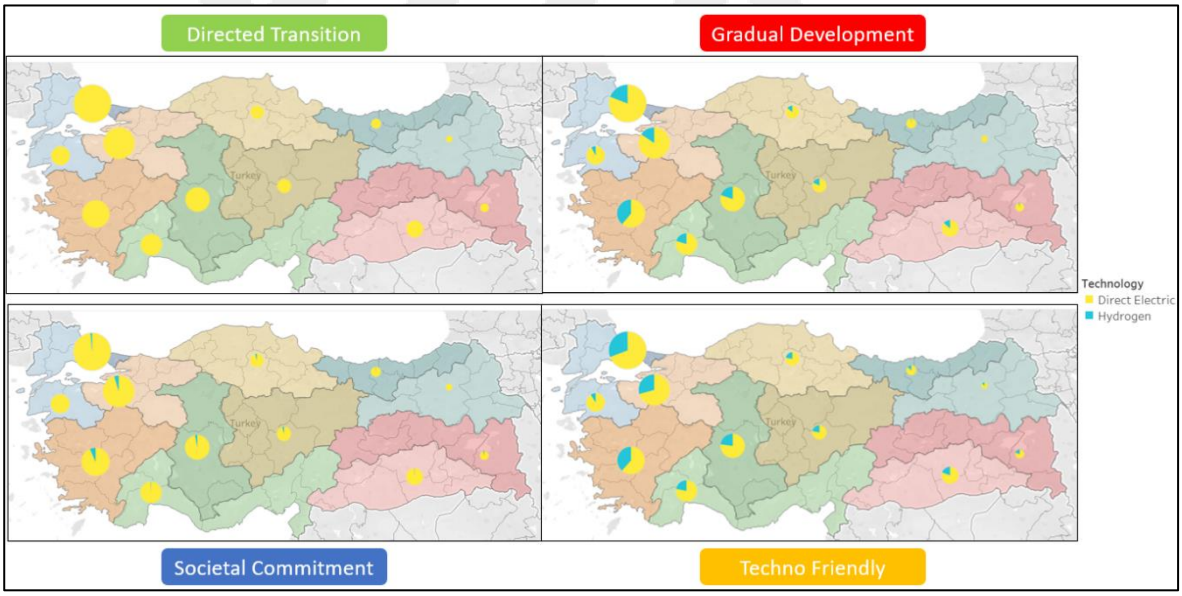

Figure B.4. Industrial heat in 2050 at disaggregated level in each scenario